THE EVOLUTION OF THE INNOVATION NETWORK AND THE TECHNOLOGICAL SYSTEM IN A STANDARD DEVELOPMENT ORGANIZATION. THE EXAMPLE OF CELLULAR TELECOMMUNICATIONS

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ABSTRACT OF THE DISSERTATION

The Evolution of the Innovation Network and the Technological System in a Standard Development Organization.
The Example of Cellular Telecommunications

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Standard developing organizations (SDOs) are voluntary inter-organizational collaborations with the goal to develop jointly compatibility standards for complex modular technological systems. This dissertation examines the evolution of the innovation network and technological system in a SDO with the perspective of complementing micro and macro level. The dissertation is rooted in the multidisciplinary complex system theory and draws on a broad range of literature from management, sociology, biology and physics with the common theme of bipartite network analysis.

The innovation network is conceptualized as a bipartite network with ties between organizations and innovations to which they contribute. I show that technical capital, resources in the SDO and their match between organization and innovation, rather than social capital, network position, drive the tie formation in the innovation network. To answer the question of emerging order in an innovation ecology without formal hierarchy I borrow from the literature of ecological mutualistic networks. I show that a nested order emerges based on a parsimonious process of matching resources, that leads to a rather stable system over more than ten years.

The evolution of the technological system in the SDO environment departs from the established life cycle model and is best described by a life spiral model with continuously increasing system performance rather than punctuated equilibria. The key distinction to market-based technological evolution is the coordinated and designed development process within the SDO, that allows to introduce new services and change core parts of the system based on architectural knowledge. As a consequence the development process follows a gradual change model with changing tempo. Furthermore the evolution is characterized by simultaneity of innovation types that identifies the SDO as ambidextrous organization with separation of exploitation and exploration on project level.

The research context is Third Generation Partnership Project (3GPP) in the cellular telecommunications industry with data from 1992 to 2011.

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Dedication

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Table of Contents

Abstract ii

Acknowledgements iv

Dedication vi

List of Tables x

List of Figures xii

1. Systems, Networks and Standard Developing Organizations 1

1.1. Systems and Networks 1

1.2. Standard Developing Organizations 10

2. Tie Formation in a Two-mode Network — is it Technical or Social Capital that Matters? 19

2.1. Introduction 19

2.2. Interorganizational Tie Formation and Network Orchestration 21

2.3. Data and Methods 33

2.4. Results 41

2.5. Discussion 46

2.6. Appendix: Robustness tests 52

3. Order without Hierarchy — the Innovation Ecology of a Standard Developing Organization 65

3.1. Introduction 65

3.2. Ecological Mutualistic Systems 68

3.3. Data and Methods 87

3.4. Results 93

3.5. Discussion 114

3.6. Appendix 122

4. Evolution of Modular Systems — from a Life Cycle to a Life Spiral Model of Technological Change 126

4.1. Introduction 126

4.2. The Life Spiral Model 129

4.3. Data and Methods 141

4.4. Results 147

4.5. Discussion 154

5. "Future is Evolution" — Locus, Tempo and Mode of Evolution in a Technological System 164

5.1. Introduction 164

5.2. Locus, Tempo and Mode of Evolution 166

5.3. Data and Methods 179

5.4. Results 192

5.5. Discussion 212

5.6. Appendix 219

6. Discussion and Outlook 223

6.1. The triad of organizations, technology and innovations 223

6.2. Theoretical contributions 224

6.3. Empirical contributions 229

6.4. Managerial implications 230

6.5. Limitations 231

6.6. Future research 233

Appendix A. The Analysis of Two-mode Networks 236

A.1. Introduction 236

A.2. Two-mode network and projections to one-mode networks 239

A.3. Two-mode networks 248

Appendix B. A nestedness measure for individual nodes 253

Bibliography 258

List of Tables

2.1. Correlation matrix 40

2.2. Basic statistics. 41

2.3. Logistic regression for tie formation of the firm-innovations dyad 43

2.4. Mediation of SDO resources by number of ties and network position (I) 44

2.5. Robustness test: include all present organizations 54

2.6. Robustness test: exclude small firms 55

2.7. Robustness test: exclude large firms 56

2.8. Robustness test: Release-6 only 57

2.9. Robustness test: Release-7 only 58

2.10. Robustness test: Release-8 only 59

2.11. Robustness test: Release-9 only 60

2.12. Robustness test: Release-10 only 61

2.13. Robustness test: alternative match measures 63

3.1. Measures used in the structural analysis of the innovation network. . . . 89

3.2. Results of OLS regression of structural parameters over months 112

4.1. Overview of releases and variables of LSM. 144

4.2. Results of regressions of LSM 148

5.1. Correlation between pleiotropy and counts of all CRs 193

5.2. Correlation between pleiotropy and counts of only functional CRs. 194

5.3. Persistent top 10 specifications and their rank in change. 196

5.4. Model transitions with deviations larger than two standard deviations. . 207

5.5. Innovation types for all 3G releases. 211

5.6. Typology of innovations based on new services and implementations . . 213

5.7. Evolutionary models for specification series: phenotype and archotype . 220

5.8. Evolutionary models for specification series 221

5.9. Evolutionary models for 4G-specific specification series 222

List of Figures

1.1. The organizational structure of 3GPP. 14
1.2. The overview of the data of 3GPP. 16
2.1. Example of blockmodel result for the innovation network 48
3.1. Overview of the key topics in the analysis of mutualistic systems 70
3.2. Examples of networks with differing degree of nestedness. 75
3.3. Definition of roles based on modularity 77
3.4. Example of attack tolerance curves (ATC) 83
3.5. Two-mode innovation network at the beginning in July 2001 94
3.6. Basic networks statistics for the innovation network. 95
3.7. The cumulative distribution of the standardized degree: simulated networks 98
3.8. The cumulative distribution of the standardized degree: random networks 100
3.9. Correlation between node and nearest neighbor degree. 101
3.10. Nestedness of innovation, random and simulated networks 102
3.11. Comparison of individual nestedness for both types of simulations . . . 104
3.12. Example of the modularity of the innovation network for December 2010 106
3.13. The distribution of roles of a random network. 108
3.14. Modularity of the innovation, random and simulated networks. 109
3.15. The robustness of the networks under removal of innovations. 110
3.16. The evolution of individual nestedness for selected organizations. . . . 113

3.17. Nestedness of innovation networks and random networks 123

3.18. Nestedness of innovation networks and simulation networks. 124

3.19. Individual nestedness for the innovation network and simulated networks. 125

4.1. Standard development process in SDO environment. 140

4.2. Standard development in SDO environment over time. 141

4.3. Exponential curve of the system performance over all releases. 150

4.4. Logistic curve of the system performance for 2G releases only. 151

4.5. Logistic curve of the system performance for 3G releases only. 151

4.6. The life spiral model for cellular telecommunication system. 153

5.1. Unsampled versus sampled or gradual punctuation 176

5.2. Innovation typology based on novelty of phenotype and genotype. . . . 178

5.3. Overview of specification series 181

5.4. Lineage for a specification with high pleiotropy over all 3G releases. . . 188

5.5. Top 10 pleiotropic specifications. 195

5.6. Top 10 polygenic services. 197

5.7. System trajectory from 2G to 4Gbeyond 199

5.8. Phenotype trajectory for 3G and beyond 200

5.9. Archotype trajectory for 3G and beyond 201

5.10. 24 series trajectory for 3G and beyond 202

5.11. 25 series trajectory for 3G and beyond 202

5.12. 29 series trajectory for 3G and beyond 203

5.13. Ratio of mean step length over time. 205

5.14. Distribution of jumps in standard deviations of the change model. . . . 206

5.15. System trajectory with all CRs and only functional CRs. 208

5.16. Trajectory of 25 series with only functional CRs. 208

5.17. Empirical innovation types 210

5.18. Empirical innovation types based on percentage of novelty 212

6.1. The three-mode network in 3GPP. 225

B.1. Overlap matrix standardized by pairwise minimum degree. 256

Chapter 1

Systems, Networks and Standard Developing Organizations

1.1 Systems and Networks

General system theory, complexity theory, network theory are the theories to explain complex systems, complicated systems, adaptive systems, complex adaptive systems (CAS), self-organizing networks (SON), complexity, self-organization, self-organized complexity, and emergence. Are these different terms and concepts the same? Do they build a nested order that one type of system is a subcategory of another? Are networks the same as systems? Is there are a "new science of complexity" as Kogut (2007) called the multidisciplinary complexity research or is it old wine in new bottles? I provide here definitions and a short review of complex systems and the relevant theory for the context of this dissertation. First I define systems and their different types, second I look in particular at modular systems and then describe the relationship between systems and networks.

1.1.1 Definitions and system theory approaches

Theories of complex systems are not new and depending on the authors' background different waves of interest and catalytic events will be recognized (Amaral and Ottino 2004; Anderson 1999; Andriani and McKelvey 2009; Kogut 2007). One root that found its way into management research, is general system theory by von Bertalanffy (1950). He pointed out the parallel development in several disciplines as physics, biology, medicine, psychology, economics and philosophy in the study of "wholeness" of systems. "A system can be defined as a complex of interacting elements $p_1, p_2 \ldots p_n$. Interaction means that the elements stand in a certain relation, R, so that their behavior in R is different from their behavior in an another relation R'" (von Bertalanffy 1950, page 142). von Bertalanffy's system definition includes the two basic ingredients of a system, its elements, components or parts and the interaction or relationship between them. It also foresees that the elements can have several relationships with different behavior. These relationships determine the structure and dynamics of the system. He further noted the important difference between physical and biological systems: biological systems are open systems that exchange energy and material with the environment, while many systems studied in physics are closed systems (Von Bertalanffy 1950). The difference between open and closed systems can be interpreted in a hierarchy of systems, where the open system is part of a larger system with interactions to the other elements of this system (Boulding 1956).

The general definition of a system includes the trivial case of a systems with only one element, non-interacting elements as well as the other extreme of huge systems with interactions among all its elements. Simon (1962) in his seminal paper on the architecture of complexity and modularity defined a *complex system* as "made up of a large number of parts that interact in a nonsimple way". While it clearly excludes the trivial system of one element and non-interacting elements, the questions remains how large is large and what is exactly nonsimple. For Simon the key distinction was that the properties of the parts and their rules of interaction do not trivially infer the properties of the system and that the system is "more than the sum of the parts". Amaral and Ottino (2004) clarified further complex systems by contrasting them to simple and complicated systems. A *simple system* has few parts with well understood rules, for example the pendulum, which is a system of one. However, they also pointed out the need to distinguish between the complexity of the dynamics of a system and the system itself: the pendulum shows chaotic dynamics when the driving force is periodic, and yet it is a simple system.

Complex systems can be divided into two groups: complicated and complex adaptive. A *complicated system* has many parts with well-defined roles and well-understood rules as in the example of an airplane with more than one million parts. A key attribute of complicated systems is their limited adaptability to changes of the environment. A *complex adaptive system* (CAS) is "a system with a large number of elements, building blocks or agents, capable of interacting with each other and with their environment" (Amaral and Ottino 2004, page 148)[1] . In addition to Simon's definition CAS are adaptable and can self-organize without any coordination or organization principle from outside. Amaral and Ottino contrasted the complicated system of an airplane with a flock of geese where any goose can take the role of the lead goose. It is not the size of the system, but the interaction that defines the complexity. Self-organization means that no single component controls the behavior of the systems, but that components act on the local information they receive from their interactions (Anderson 1999). In the literature the distinction between complicated and complex system is not well defined. Often complex systems refer to both types and the attributes of adaptability and self-organization are explicitly referred to as CAS.

The key property of CAS is that order is an emergent property of the system level by the interaction of its components. This emergence is what von Bertalanffy called "wholeness" and Simon "more than the sum of the parts". The term emergence goes actually back to the first wave of system discussion in the late 19th century until the

[1] Amaral and Ottino (2004) used this actually as definition of complex system. This more narrow definition is however not commonly adopted in the literature and I use the distinction of complex systems into two groups. In particular modularity, introduced in the next section, applies to both types of complex systems.

1920s within philosophy and the debate whether a system can have properties that the parts do not have or an effect can have properties not contained in its antecedents (Lovejoy 1927). In complexity theory emergence, "the arising of novel and coherent structures, patterns, and properties during the process of self-organization in complex systems" (Goldstein 1999, page 49), is the fundamental property of complex systems.

Now, as most of the key terms above are defined, two questions remain to be answered: Is there an organizing principle to reduce complexity? What are the tools to study complex systems? The first question was answered by Simon with the concept of modularity and is introduced in the next section. The answer to the second question was already given by von Bertalanffy with the system of simultaneous differential equations. However, this is one of several ways and an increasingly popular approach is network theory, where systems are described and analyzed as networks.

1.1.2 Modular Systems

Simon introduced two major, interrelated concepts, to reduce complexity: hierarchy and nearly decomposability. In the hierarchical structure of systems, a system consists of components or subsystems, which can be systems on their own and their components can be systems until the last level is reached. The key concept of modules and nearly decomposable systems is that the interaction between components within a module or subsystem is much stronger than between components of different modules. The short-term behavior of subsystems is independent of each other, while for the long-term behavior the interdependence matters. Simon exemplified this with the example of a building consisting of separate rooms, which are further divided into cubicles and temperature adjustment through walls: First cubicles within rooms adjust to one temperature, then the building temperature is adjusted across rooms.

Simon's seminal paper has spurred in the last two decades a growing literature on modularity by management scholars (Campagnolo and Camuffo 2010), addressing a variety of questions such as: (1) costs and benefits of modularity and when systems will be modular rather than integral (Baldwin and Clark 1997, 2000; Fleming and Sorenson 2001; Garud and Kumaraswamy 1995; Langlois and Robertson 1992; Schilling 2000); (2) the impact on transaction costs and the related vertical and horizontal relationships (Baldwin 2008; Langlois and Robertson 1992; Langlois 2006); (3) strategic flexibility (Sanchez 1995; Worren et al. 2002); and (4) the relationship of technological and organizational structures, the non-hierarchical governance forms, and alliance governance (Garud and Kumaraswamy 1995; Hoetker 2006; Sanchez and Mahoney 1996; Schilling and Steensma 2001; Tiwana 2008).

A technology or technological system is a "man-made system that is constructed from components that function collectively to produce a number of functions for users" (Murmann and Frenken 2006, 936). It is a mechanistic system, but like all other systems it is hierarchic (Simon 1962). That is, a technological system consist of one or more levels of subsystems (e.g., larger, higher-order subsystem and smaller, lower-order subsystem) until the level of basic component (Murmann and Frenken 2006). A complex system has a large number of parts (subsystems and components) that interact. The ways a system's parts interact with each other constitute the interfaces of the system (Fixson and Park 2008). According to the property of "near decomposability" of complex systems (Simon 1962), within subsystem linkages are stronger than across subsystem linkages, indicating that more intra- than inter-subsystem interactions occur (Murmann and Frenken 2006; Ulrich 1995). Most technological systems are complicated, modular systems with rather well defined interaction rules and limited adaptability to their environment (Amaral and Ottino 2004).

Garud and Kumaraswamy (1995) described how the integrity, modularity and upgradeability of technological systems and their organizations lead to economies of substitution allowing for faster development. According to these authors, substitution is the exchange of some components, while others are retained. Integrity is the smooth interaction of the system components to provide the desired functionality. Modularity is the decoupling of the system (as above), and upgradeability is the easiness of the enhancement of the system performance by improving existing functions and adding new ones. Baldwin and Clark (2000) refined the concept of modularity, defining basic operators that act on modular systems whose combinations describe technical change in the context of industrial and technical structures. They illustrated the impact of modularity on innovation by discussing the key role of IBM's 360 system in setting a standard in the computer industry. Garud and Kumaraswamy discussed organizational systems focusing on the dynamics of simultaneous cooperation and competition of firms in creating open standards in decentralized networks. A large portion of empirical studies of modularity is about computer systems and their components, where the basic architecture is the mainframe (Baldwin and Clark 2000) or the PC (Ethiraj 2007), two rival technologies compete, and components have sponsors (Garud and Kumaraswamy 1993; Garud et al. 2002; Wade 1995, 1996). Whereas researchers generally agree on an increase in the speed of innovation in modular systems, they have not adequately explored how complex open systems evolve in an environment of open standard setting by organizations.

1.1.3 Networks

Network theory is rooted in the mathematical discipline of graph theory and networks are referred to as graphs. "A graph consists of a set of *points* and a set of lines or *edges* connecting pairs of points" (Freeman 1978, page 217). The similarity with the definition of systems is obvious with a set of elements or points and a relationship or connecting lines between them. The definition of a graph puts further the focus on the dyad, the pair of elements or actors, which is often the unit of analysis of social networks. The connecting line is often refered to as tie or edge. The concatenation of ties create a path through the network and relate nodes to each other even if they are not directly connected. The pattern of ties defines the structure or topology of the network, in which actors assume positions, measured in network properties as e.g. centrality (Wasserman and Faust 1994). A network is one way to define a system. In this sense self-organizing networks are the same as CAS as both have the property of self-organization. Both are concepts to study self-organization and self-organized complexity.

Networks can be characterized by their nodes and ties (Wasserman and Faust 1994). In technical networks nodes can be airports in an air transport system, routers as in the internet (Guimer et al. 2007) or base station and switches in a cellular telecommunications network. In biological networks nodes can be species or molecules or proteins (Milo et al. 2002). In social networks the elements are actors, who can be either individuals, groups or organizations and their relationships as friendship, working or alliance relationship (Ahuja 2000; Wasserman and Faust 1994). Actors can have attributes that distinguish them from each other. Ties are undirected when the relationship is symmetric as in an individual acquaintance relationship or directed for instance friendship ties on facebook. In many networks only the presence or absence of a tie is considered, so-called binary networks (for instance a paper is cited or not), while in weighted networks the ties have weights that measure the strength of the relationship (e.g. the frequency of communication among acquainted individuals). Networks are presented either in matrices, where the matrix size is defined by the number of actors and the element a_{ij} is the tie weight between node i and j, as lists of ties or as graphs with nodes and connecting ties.

So far I have described one-mode networks, where nodes are all of the same type as individuals or organizations and ties possible between all nodes. Another class of networks are two-mode or bipartite networks that consist of two different types of nodes, where ties are only allowed between nodes of different types (Borgatti and Everett 1997). Examples are affiliation networks where an actor is member of or affiliated with an entity as directors and board membership (Baum and Wally 2003), scholars and scientific papers (Newman 2001b) or delegates in a SDO meeting (Leiponen 2008). All networks studied in this dissertation are bipartite networks: the innovation network with a contributing tie between organizations and innovations (chapter 3 and 4), the SDO meeting network between individual delegates participating in a set of meetings (chapter 2) and the phenotype-genotype matrix between services and implementation of the cellular system (chapter 5). In appendix A I describe in more detail the methods used for the analysis of bipartite networks.

The interest in network analysis has two areas: the formation of network ties and resulting network evolution and the influence of networks on outcome as performance. In both streams actors' network attributes as centrality or other measures play an important role and are subject to theory development (Borgatti and Halgin 2011). An example is the literature of knowledge access within alliance networks, where the centrality of a focal firm positively influences the access to knowledge by its position (Ahuja 2000). A new perspective started with Watts and Strogatz (1998)'s seminal paper on small worlds and is coined *post-1998* network analysis (Latapy et al. 2008). The detection of the small world property i(each node can be reached via a few intermediate nodes) in many real world networks was an important finding of Watts and Strogatz. Subsequent work (Baum and Wally 2003; Kogut and Walker 2001; Uzzi et al. 2007) revealed similar structure across a variety of different, large networks. Even more influential than the small word property itself was the chosen approach of the comparison of the empirical network attributes with those of an appropriate random network. First, it introduced the benchmark of a random network as null model and the test whether a network attribute is beyond what can be expected by chance. Second, it allowed to compare the properties of very different types of networks and the structural similarity between them. It is the post-1998 network analysis that ties in the multidisciplinary of the early system research and findings that hold across many disciplines. This is exemplified by scale-free networks that follow a power law distribution of their degree (the number of nodes they are connected to) over many order of magnitudes (Barabasi and Albert 1999).

While the underlying theory for each field will depend on the specific context, the tools in analyzing networks are universal and allow accumulation of knowledge and cross-disciplinary exchange. Network analysis provides a multidisciplinary language to describe and study complex systems and their structure. For instance in network language emergence is associated with the formation of a giant component of a network, the component in which the majority of the network elements are connected, which can be described as a phase transition (Boisot and McKelvey 2010; Guimera et al. 2005; Kogut 2007). Another example is the ubiquitous power law, a finding already discussed by von Bertalanffy (1950). Scholars know now much more about the underlying processes as well as their implications (Andriani and McKelvey 2009; Newman 2005), understand why power laws are truncated and the reason for the break-off (Jordano et al. 2003; Kogut et al. 2007) and are able to determine the parameters of the curve and the empirical problems (Clauset et al. 2009).

In summary, I use network analysis to study the complex systems of the innovation network and technological system in 3GPP. In particular I use methods developed across disciplines and network concepts to examine the two systems of this dissertation. I will use throughout the dissertation the terms system and network interchangeably. I draw the relevant specific theory from the context and include theory of inter-organizational networks, mutualistic ecological networks and evolution of complex technological systems and refer to them in the according studies of this dissertation.

1.2 Standard Developing Organizations

The development of modular technical systems with interaction between modules requires compatibility standards to guarantee the system functionality. Committees or SDOs provide this coordination. I first provide an overview of the literature on SDOs in general, then describe 3GPP, the SDO under study and its data.

1.2.1 Literature on SDOs

The literature on standard setting by committee or organization with a strong economic focus based on network externalities of compatibility standards for complex technological systems (Besen and Farrell 1994; Katz and Shapiro 1986) has gradually gained currency in the last 25 years. Research on SDOs has examined topics such as factors that drive the decision for a standard (Weiss and Sirbu 1990), forums firms choose to get their standard adopted (Lerner and Tirole 2006); alliances as SDOs for developing standards (Axelrod and Mitchell 1995; Rosenkopf et al. 2001); and factors making firms successful within a given SDO (Leiponen 2008). Recent empirical studies have also investigated the impact of SDOs on patent citations (Rysman and Simcoe 2008), the benefit of participation for small firms in SDOs (Waguespack and Fleming 2009), the influence of social capital and status on the promotion within the SDO (Fleming and Waguespack 2007) and how employee mobility affects social capital and influence in SDOs (Dokko and Rosenkopf 2010).

Standards can be distinguished based on their function and type (Tassey 2000). I focus on compatibility standards, where the interfaces between different components of a system are defined, and distinguish between two types of standard (Oshri and Weeber 2006): committee-based (de jure); and market-based (de facto). These standards are on the opposite sides of the spectrum along several dimensions (Oshri and Weeber 2006, 267), nature of process (cooperation versus competition); mode of selection (negotiation versus market); efforts (joint versus sole); access to standard licensing (open versus restricted); and access to future development (open versus restricted). Using a simple economic model, Farrell and Saloner (1988) showed that committee-based standard setting can be more efficient than market-based because (1) the market may fail to choose a single standard, and (2) economies of scale due to network externalities will be limited.

The studies using de jure standards often rely on computer, telecommunication, and the internet technologies, which exemplify complex open systems that have high network externalities (David and Steinmueller 1994). In contrast, the studies using de facto standards rely mainly on stand-alone assembled products, whether simple (video recorders) or complex (flight simulators), where manufacturers usually coordinate the compatibility between the subsystems and components. Davies (1997) distinguished between the dynamics of innovation drawn from complex infrastructural networks (telecommunication, electricity supply, transportation) and complex stand-alone products (trains, aircrafts, flight simulators). Davies' case study of the life cycle of cellular mobile communications systems illustrates the difference between de facto and de jure standard setting in the development of the second-generation (digital) systems. In the United States, a preference for the selection of new technologies by market forces and reliance on a de facto standard setting approach resulted in an inadequate cooperation between industry and regulatory players, delay in developing a standard, and the emergence of two incompatible digital standards (Davies 1997). On the contrary, the European

Union's (EU) reliance on a de jure approach by formation of an organization representing cellular system operators and manufactures with backing of all EU nations enabled rapid development of a new standard benefiting the European suppliers in the global mobile markets (Davies 1997).

1.2.2 Third Generation Partnership Project (3GPP)

Here I introduce 3GPP, a SDO for a cellular telecommunication system, that is the research context and data source of this study. I define the organizational form of 3GPP, its members, mission, internal structure and working processes (3GPP 2012, specification 21.900). 3GPP is a partnership, a collaborative activity, between six regional and national SDOs from the European Union, The Unites States, South Korea, Japan (two SDOs) and China. The organizational partners delegate the standard development to 3GPP and endorse the developed standard in their territories. In addition to the territory covered by the organizational partners the standard is adopted in many other countries.

3GPP's purpose is to "prepare, approve and maintain globally applicable Technical Specifications and Technical Reports" for 2G (or Global System for Mobile Communications (GSM)), 3G (or Universal Mobile Terrestrial System (UMTS)) and 4G (or Long Term Evolution (LTE)). 3GPP succeeded 1998 the European Telecommunications Standards Institute (ETSI) that was the SDO for the development of the 2G system and is the European partner SDO of 3GPP. In addition to organizational partners 3GPP members are either market representatives or individual members, which are either firms, research institutes or ministries or federal agencies. Each member of an organizational partner has access to 3GPP. While ETSI had membership limitations in its early days with openness only for European firms, it opened its membership later mainly to North American firms. With the formation of 3GPP the standard setting opened for any national or regional SDO and Asian players, in particular from East Asia, joined. Membership includes commitment to contributions and provides the right of participation. 3GPP also maintains liaison relationships with about fifty other SDOs to coordinate overlapping areas of standardization.

The members of 3GPP as parts and their joint standard development work as relationship among them define 3GPP as a system. Via the open membership and the liaison relationship to other SDOs it exchanges information and in particular resources and technological and market knowledge with its environment making it an open system. The joint standard development work is mainly the participation in meetings and contributions to innovations as more detailed below.

3GPP has a formal working structure with a Project Coordination Group (PCG) and Technical Specification Groups (TSGs) that are further divided into Working Groups (WGs). The PCG defines the general policy and strategy of 3GPP, which includes the definition of the scope of 3GPP, the maintenance of the partnership agreement, approval of TSGs, allocation of resources to TSGs, determination of the overall time frame and work program and handling of appeals. Only the organizational members are part of the PCG. Though PCG defines the general strategy of 3GPP and finally approves the work program, it does not define the specific content as single innovations. The human resources it allocates are not the delegates who develop the specifics of the standard, but mainly handle administrative tasks as writing meeting reports and editing of specifications. PCG provides the framework for the development of the standard, while the development is performed in the TSGs and their WGs via the contributions of the individual members.

3GPP has currently four TSGs, which are further divided in up to five WGs. Figure 1.1 shows the structure of 3GPP. While there were a few adaptation of this structure in the past, the working structure is rather stable during the standard development of

Figure 1.1: The organizational structure of 3GPP.

3GPP. According the mirror principle (Sanchez and Mahoney 1996) the organizational structure follows largely the structure of the technological system. TSG GERAN and RAN cover the radio part of the network development, where the former covers 2G and the latter 3G and 4G. TSG CT covers the core network and the terminal (end user equipment) development. TSG SA, Service & System Aspects, takes a prominent role within the TSGs. Its first WG is responsible for the service definition of the technological system, its second WG has the responsibility to define the architecture of the system and maintain the integrity of the system. They allow a coordinated and designed approach to the evolution of the technological system that differs largely from biological evolution and uncoordinated evolution in a market environment (refer to chapter 4 and 5 for details).

The detailed specification work as is done within the WGs, which cover subtopics of the TSGs. Most of the standard development work is performed during meetings of the WGs, where technical proposals are presented, discussed and decided upon. Approved contributions are carried to the plenary meetings of TSGS where they are finally approved. The development process follows two process: The work item (WI) process and the change request (CR) process. In the WI process individual member organizations make proposals for new features of the technical system. A feature is a "new, or substantially enhanced functionality which represents added value to the existing system." (21.900 specification, page 26). In the following I identify features as the innovations of the system. Each innovation is self-contained, i.e. it can be added to the real system or left out. As a requirement for approval at least four members need to support the WI. In case a WI gets approved it becomes part of the official work plan of 3GPP and specification work starts. In case a new specification is created, first a draft is compiled and when it reaches maturity it underlies the CR process. For each modification a CR has to be prepared that needs to be approved to enter into the standard.

The standard is the full set of specifications and descries the cellular technological system completely with its services, architecture and detailed protocols. The technological system consists of several different network elements and interfaces between them. These interfaces are described in detail in the protocols and the overall system performance and behavior is well understood. It is a complicated system, similar to the example of the airplane (Amaral and Ottino 2004). The standard is published in releases,where the difference to the previous release is the sum of all innovations developed for this release.

In summary: 3GPP is an open system of organizations that develops and maintains the standard for a complicated technological system. The evolution of the technological system occurs via a stream of heterogeneous innovations jointly developed by the member organizations. Though 3GPP has its working structure of PCG, TSGs and their

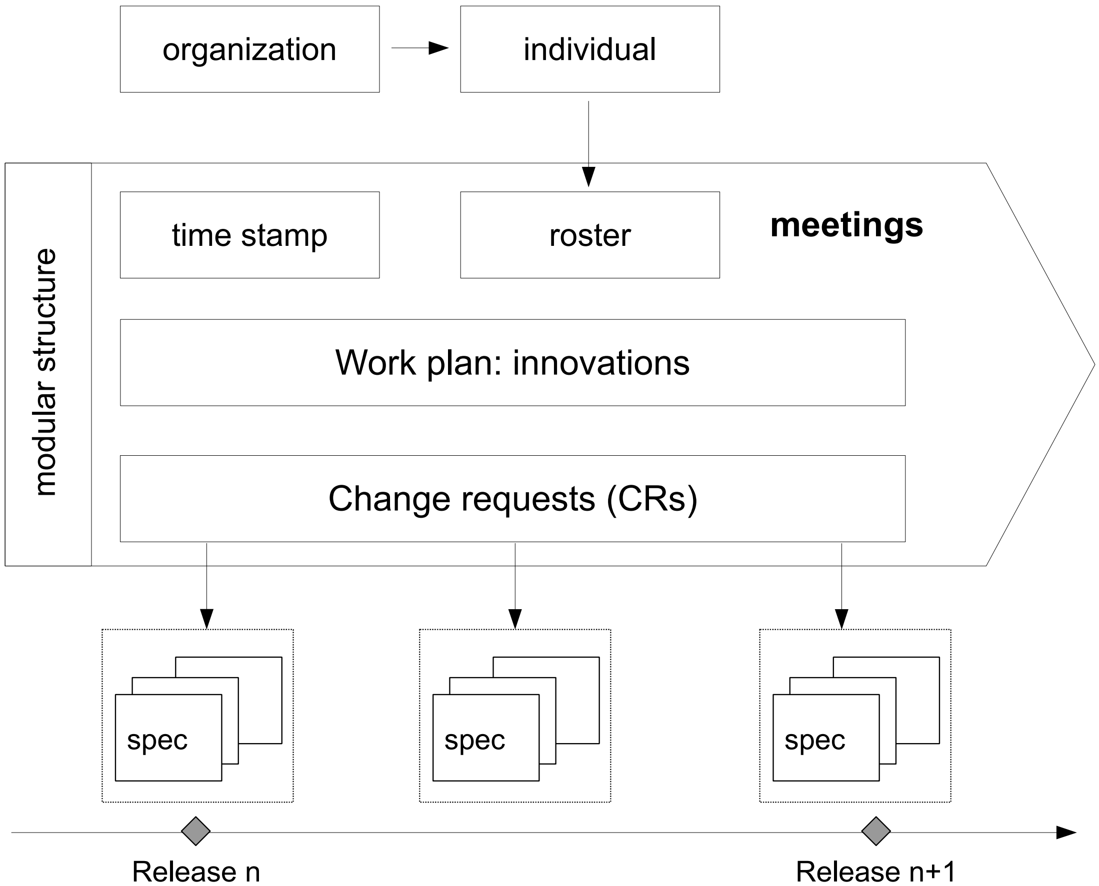

Figure 1.2: The overview of the data of 3GPP.

WGs, and TSG SA as technical coordinator, it is a complex adaptive system without one single authority or individual member organization to define the work program.

1.2.3 Data of 3GPP

The structure and working procedures described in the previous section are reflected in the available data provided by 3GPP. In this section I provide an overview of the data, while the detailed constructions of variables is described in the chapters where they are used for data analysis. An overview of the data structure is shown in figure 1.2 with information on organizations and their delegates, the meetings and the specifications.

3GPP provides the roster of all its member organizations with links to the internet pages of these organizations. In addition it provides the roster of all individual delegates who have participated in meetings after the formation of 3GPP with an unique identifier for each individual, the organization the individual is affiliated with as well as the postal address. These two rosters define the population of organizations and individual delegates and their affiliation.

In the center of the database are the meetings with the modular structure as shown in figure 1.1 mirroring the modular structure of the system. Each meeting is defined uniquely by its WG or TSG and a number. The time of the meeting provides the time stamp for the information related to it and is measured either on a monthly or quarterly level. The meeting report includes the list of participating delegates and their affiliation at the time of the meeting. This information is the basis for the construction of the meeting network, both on individual and organizational level as well as the technological profiles of organizations. The working plan includes all innovations from the beginning of the 3G development with information on the involved working items, their identification numbers, the begin and end of the development, contributing organizations, involved working groups and release. It is the basis for the construction of the innovation network as well as the technological profile of innovations. Part of the work plan is the overall release planning with the release content and time line. The change request database includes all CRs from the beginning of the 2G development with information on meeting it was decided upon, the WI identifier it belongs to, the affected specification, category and status. The WI identifier provides the mapping of CRs to innovations, the category allows the distinction between CRs of the enhancement and error correction modifications.. The number of CRs indicates the change a specification is subject to. Finally approved CRs become part of the new version of the standard. All change requests in a release together with the newly developed specifications define the enhanced functionality of the new release.

The specifications are the result of the development process. 3GPP publishes each quarter an updated status list of all specifications that were developed from 2G onwards with name, version identifier, release, WG, status and creation or update date. The specifications at the release date define the specific release of the standard. The creation date allows the identification of new specifications during a release. Each specification has a primary WG that is responsible for its development and maintenance. Specifications are the results of the staged development process and can be categorized in service, architectural and implementation (or protocol) descriptions of the system. The bundle of all specifications describes fully the technological system and is the basis for the development of real networks components and interfaces as well as requirements by network operators.

In summary: The organizations and the resources they provide in form of delegates and technical proposals are the input into the standard development process. The development mainly takes place during the meetings with the two intermeshed processes of work items and change requests in the development of innovations leading to an innovation network within the meeting network. The result of the process is an updated set of specifications, that define services, architecture and protocols of the technological system.

The upper half of the data, organization and innovation data, are used for the study of the evolution of the innovation network in chapter 3 and 4, the bottom half, innovation and specification data, for the study of the evolution of the technological system in chapter 4 and 5. The innovations are the joint that couples the two perspectives on 3GPP.

Chapter 2

Tie Formation in a Two-mode Network — is it Technical or Social Capital that Matters?

2.1 Introduction

Tie formation of interorganizational networks is largely an endogenous process driven by social capital as trust and access to information about partners, leading to rather dense clusters (Ahuja 2000; Baum and Wally 2003; Chung et al. 2000; Coleman 1988; Gulati 1995a; Powell et al. 2005). Although this process reinforces tie formation among familiar actors, it lacks access to distant knowledge. More exploratory search and benefits from brokerage arise from bridging structural holes (Burt, 1992), leading to shortcuts between dense clusters via bridging ties and resulting in small-world networks (Watts and Strogatz 1998). Two recent streams of research have investigated the emergence of small-world networks. First, Rosenkopf and Padula (2008) and Ahuja et al. (2009) investigated how new entrants and poorly embedded firms connect to a network dominated by a self-reproducing evolution by also taking the attributes of the relationship into account in addition to partner and dyad attributes. Second, Cowan and Jonard (2009) challenged the role of social capital in interorganizational tie formation and posited that the optimal overlap of technical resources in alliance formation can lead to small-world networks.

On the basis of these recent advancements, this study develops a theory of tie formation of the firm-innovation dyad rather than the firm-firm dyad. It reconciles technical resources, social capital, and network orchestration in the framework of a three-mode network of firms, innovations, and technological modularity and their multiple relationships. I address two related research questions: First, what is the importance of technological and social capital in the tie formation process and second, is there a group of hub firms supporting the cohesion of the innovation network via network orchestration (Dhanaraj and Parkhe 2006)? I choose the context of a SDO, a voluntary interorganizational relationship in which members jointly develop a compatibility standard for a technological system via a stream of heterogeneous innovations. SDOs are loosely coupled systems (Oliver 1990; Provan 1983) without a hierarchy or a single, dominant technological sponsor. An innovation is a joint effort among several member firms that have made the decision to contribute to the innovation rather than to collaborate with partners. The resulting innovation network is embedded in the meeting network, where delegates of the member firms present, discuss, and decide on technological proposals (Dokko and Rosenkopf 2010; Leiponen 2008; Rosenkopf et al. 2001).

By examining the tie formation process of the firm-innovation dyad in the framework of a three-mode network, I make several contributions to network theory. First, the novel perspective of the firm-innovation dyad as the unit of analysis emphasizes the decision for the activity and allows accounting for heterogeneity of innovations in the tie formation. It extends the research on relationship attributes (Ahuja et al. 2009; Chung et al. 2000; Rosenkopf and Padula 2008) in firm-firm dyads to the firm-innovation dyad, in particular to the match of technological resources between firm and innovation (Garrette et al. 2009; Sorenson and Stuart 2008), rather than to firm match (Mitsuhashi and Greve 2009). Second, the conceptualization of firms, innovations, and technological modules as a three-mode network with multiple relationships allows the separation of information flows and resource coordination (Gnyawali and Madhavan 2001) and the disentangling and reconciling of technical resources and network embeddedness rather than seeing them as two competing forces (Cowan and Jonard 2009). It shows that the technological resources are the primary force in the tie formation, whereas the network position, the result of past tie formations, does not contribute to the tie formation beyond random networks with the same two-mode degree distributions. Furthermore, the match of technological resources between firm and innovation can be interpreted as an extension of network closure (Coleman 1988) to two-mode dyads and, hence, technological match as a form of network embeddedness. Third, the relevance of the concept of hub firms as network orchestrator (Dhanaraj and Parkhe 2006) is extended to the tie formation, where hub firms are important for network stability and cohesion. Finally, this research has important practical implications regarding openness policies in SDOs (Calderini and Giannaccari 2006; Schmalensee 2009). Although researchers have studied the impact of the members network attributes on their success and influence in SDOs (Dokko and Rosenkopf 2010; Leiponen 2008), the formation of the innovation network itself is not yet understood. This study shows that the network position of firms is driven by their technological resources, which supports the openness of SDOs.

I choose cellular telecommunications as the research context with 3GPP as the focal SDO. 3GPP was a global SDO with 217 contributing organizations in the period from July 2001 to December 2010. In all, 436 innovations were covered. The chapter proceeds as follows: First, I review the literature of tie formation and SDOs and develop the hypothesis of the tie formation of the firm-innovation dyad; then, I describe the methods, including data measurement and analysis; present and discuss the results; and conclude with a discussion of the findings and some implications for future research.

2.2 Interorganizational Tie Formation and Network Orchestration

In this section I develop a theoretical model of tie formation for the firm-innovation dyad in the context of the innovation network in an SDO by drawing on the literature of interorganizational tie formation and network orchestration, as well as SDOs.

The lens of networks accounts for the embeddedness of action in social context and the constraints that networks put on actors (Granovetter 1973). A major debate in the social network theory is whether locally dense networks, which spur trust through repeated interaction and mutual control and provide fine-grained information (Coleman 1988), or structural holes, which are conduits to more-distant, rather unique knowledge via brokerage (Burt 1992), are more beneficial. The evolution of networks reflects this debate, where the creation of new links in dense clusters leads to the reproduction of network structures, while new links to distant partners will change the structure (Walker et al. 1997).

Two established rules of network reproduction support the perspective of locally dense networks: firms are more prone to form ties with firms with which they have existing ties, direct or indirect (Chung et al. 2000; Gulati 1995b; Walker et al. 1997), and past relationships (Gulati 1999; Jensen and Roy 2008; Powell et al. 1996). The rationale behind this is the potential opportunistic behavior of relationship partners in horizontal R&D alliances concerning unwanted knowledge leaks and difficult-to-measure contributions in R&D partnerships. Existing partnerships provide extensive information about the partner and its capabilities and behavior, in particular its trustworthiness. Whereas direct ties provide firsthand, fine-grained information about the partner, indirect ties supply information about reputation, referrals concerning the potential partner, and possibilities of potential misconduct that will spread ex post facto with detrimental effects on future alliance opportunities (Ahuja 2000; Chung et al. 2000). While the existing ties provide informational resources based on the current network structure (structural social capital), the quality of the relationship describes the relational social capital (Granovetter 1973; Nahapiet and Ghoshal 1998). Firms develop trust through repeated interactions, and therefore the risk of opportunistic behavior by the partners is reduced (Gulati 1999; Powell et al. 1996).

In contrast, the perspective of structural holes and the advantages of brokerage and access to more-diverse knowledge spurs the creation of ties between clusters (Burt, 1992). The question of network evolution (Zaheer and Soda 2009) and change (Ahuja et al. 2009; Rosenkopf and Padula 2008), rather than network reproduction, has recently received more scrutiny, in particular regarding the question how new entrants attach to existing networks. Zaheer and Soda (2009) have shown that the creation of structural holes spanned by project teams is driven by the project teams past status and centrality, as well as past structural holes spanned by them. Rosenkopf and Padula (2008) have studied the transformation of the network from two anglesthe creation of shortcuts across clusters and the attachment of new entrants. While the former is motivated by a search process of bridging structural holes between semidistant partners, both already in the established network, the latter reflects an even more distant search. The authors found that new entrants are more likely to enter into multiparty alliances, reflecting the more exploratory nature of the search and the fact that the newly created dense cluster of the multiparty alliance substitutes, by multiparty control, for the lack of trust and information about the partner. Ahuja et al. (2009) found that in asymmetric relationshipsfirms in an unfavorable network position partnering with a more central firmthe less well positioned firm is more likely to accept a minority equity stake in joint ventures. This allows the firm to gain more centrality in the network, while the more embedded firm gains more control in the new partnership.

These recent developments in network evolution not only increase our understanding of network transformation in addition to the well-established network reproduction, but have also begun to stimulate us to look at the partner relationship and its characteristics. In the case of Rosenkopf and Padula (2008), it was the number of partners studied; in the case of Ahuja et al. (2009), the equity stake of joint ventures. This new stream of research raises a more general question: How does the specific collaborative activity affect the relationship choice?

The focus on social capital in the explanation of network evolution has recently been challenged. Cowan and Jonard (2009) posited that the small-world characteristics of interfirm networks — the high clustering and short path length — can be explained by a simple rule of optimal resources between partners. The optimal level of overlap in resources actually reflects the confounding of opportunity and inducement to alliance formation (Ahuja 2000; Mowery et al. 1996). They simulated an alliance network based on the basic proposition of optimal resource overlap and showed that it created a network with small-world characteristics.

Dhanaraj and Parkhe (2006) introduced the concept of network orchestration in innovation networks based on the concept of hub firms that occupy central positions in the network. The definition of network orchestration as the set of deliberate, purposeful actions undertaken by the hub firm as it seeks to create value (expand the pie) and extract value (gain a larger slice of the pie) from the network (Dhanaraj and Parkhe 2006, page 659) can be seen as a more active notion or exploitation of social capital by the hub firm, which refers to the access to resources that a node has via its network. It assigns to the hub firm a dedicated role in facilitating network mechanisms such as trust and reputation to curb opportunistic behavior. Dhanaraj and Parkhe introduced three functions that hub firms performmanagement of knowledge mobility, innovation appropriability, and network stabilityto orchestrate the networks innovation output. Though network orchestration is mainly applied to one dominant firm as the hub firm (Batterink et al. 2010; Dhanaraj and Parkhe 2006; Ritala and Hurmelinna-Laukkanen 2009; Sabatier et al. 2010), the definition also applies to a group of hub firms, as in the case of an SDO.

2.2.1 Standard Developing Organizations

SDOs are ubiquitous in information and communication technologies. Their rules cover membership, intellectual property rights policies, organization and meeting structure, and contribution to innovations, including decision processes (Calderini and Giannaccari 2006; Chiao et al. 2007; Lemley 2002) and vary across SDOs in their details (Chiao et al. 2007). Membership is typically open to industry participants and is transparent via SDO rosters. Members, in particular technology providers, can gain enormous benefits if their proprietary technology is endorsed in the standard via long-term royalty payments, while technology users need to feed in their requirements (Bekkers and West 2009; Dokko and Rosenkopf 2010; Leiponen 2008; Rosenkopf et al. 2001). These benefits are the major motivation for organizations to maintain membership and active contribution. An important difference between SDOs and typical R&D consortia (Doz et al. 2000; Sakakibara 2002) and R&D alliances (Ahuja 2000; Gulati 1998) is that members do not jointly develop intellectual property rights, but members bring them to the SDO with the goal of getting them endorsed by the standard. Members are obliged to disclose standard-relevant intellectual property rights and grant licensing on fair and reasonable conditions (Calderini and Giannaccari 2006; Chiao et al. 2007). Hence, firms face little risk of unwanted knowledge leakage, as they want to have their knowledge spread and endorsed by the standard and benefit from the appropriability regime of the SDOs intellectual property rights policies.

SDOs typically consist of several subcommittees or technological modules that cover specific areas of expertise (Dokko and Rosenkopf 2010; Fleming and Waguespack 2007). The coordination in technological modules is accomplished via regular meetings where delegates, who act on behalf of their affiliated organization, present, discuss, and decide on technical proposals for the innovations under development (Dokko and Rosenkopf 2010; Leiponen 2008; Rosenkopf et al. 2001). The joint participation defines the meeting network within the SDO, where knowledge flows rather freely due to the appropriability regime. Innovations are supported by several member firms to avoid dominance by one firm and to guarantee sufficient resources and knowledge to develop the innovation (3GPP, 2010). The joint development of innovations in the SDO define the innovation network under study. The nodes of the network are the member firms; the ties are the support of the innovation, following the logic of two-mode networks (Wasserman and Faust 1994).

The definition of this interorganizational innovation network leads to three important differences compared to most interfirm networks in the literature: difference in number of partners, partner roles, and decision process with implications for the unit of analysis. First, as each innovation requires several supporters, the ties are not two-party or a dyadic relationship as in much interorganizational network research (Ahuja 2000; Ahuja et al. 2009; Baum and Wally 2003; Gulati 1999), but a multiparty connection. The multiparty ties lead to a rather dense network, as each innovation creates multiple ties rather than one. Second, in the multiparty affiliation there is a primus inter pares firm. This is the firm that takes some leadership for the innovation either by initiating the innovation, soliciting for further collaborators, or coordinating the innovation efforts. In contrast, in the dyadic perspective of other interorganizational networks, the dyad members are in most cases treated equally. Third, the decision of a member firm is whether to contribute to an innovation, rather than a partner selection as in alliance formation (Ahuja 2000; Ahuja et al. 2009; Chung et al. 2000; Rosenkopf and Padula 2008). The other contributing firms to the same innovation do not have the choice of rejecting a partner. Hence, the decision on the innovation is unilateral. The unit of analysis is therefore the firm-innovation dyad rather than the firm-firm dyad.

2.2.2 Technical Capital on the Firm Level: SDO Resources

In alliance formation, the decision process is bilateral, as both partners have to agree to collaborate. This bilateral decision process is normally reflected in the attractiveness of, and inducement to, a firm to form an alliance (Ahuja 2000; Rosenkopf and Padula 2008). The attractiveness reflects the willingness of the other side to agree on a collaboration with the focal firm, while the inducement defines the motivation of the focal firm. While the attractiveness of a focal firm, and hence its opportunity, increases with its endowments as technical or commercial capital (Ahuja 2000) or prestige (Podolny 1994), the inducement follows a reverse logic: Highly endowed firms are less motivated to form alliances, as they have no need to gain external knowledge or capabilities (Ahuja 2000). The interaction of these two leads to an inverse U-shape motivation of alliance formation. As the alliance formation is motivated by resource dependencies (Pfeffer and Salancik 1978), the motivation of the focal firm to seek external knowledge decreases with its endowments.

In the SDO environment, the major purpose of firms participation in the standard-developing process is to influence the standard and the technological trajectory in their favor. Technology suppliers gain benefits if their technology is endorsed by substantial long-term royalty payments and an increase of status and legitimacy (Leiponen 2008; Rosenkopf et al. 2001; Simcoe et al. 2009). Waguespack and Fleming (2009) showed that this also applies to small technology providers, whose probability of a liquidity event, either intellectual property rights or acquisition, increases with active collaboration. Technology users gain benefits by leading the technological trajectory favorable to their market requirements. The early influence on the standard is crucial for technology users, as by definition of a global standard, there is no adaptation to local requirements in late phases of the R&D process.

To gain these benefits, firms send delegates to the meetings of the SDO on a regular basis to gain experience and social capital in the SDO (Dokko and Rosenkopf 2010; Fleming and Waguespack 2007; Leiponen 2008). This leads to a stock of regular delegates who are the necessary resources to actively contribute to innovations via preparation, presentation, and negotiation of technical proposals at meetings. The stock of regular delegates also reflects the inducement to firms to actively contribute. As participation is associated with considerable costs, including salaries and travel costs for delegates in addition to fixed membership fees (Rosenkopf et al. 2001), firms make this investment only if they have the capabilities to contribute. The delegates reflect the firms capabilities that drive the benefits to contribute. In addition, firms want to amortize these costs by active contribution.

Though the membership in the SDO is also caused by a dependency, the need for compatibility and the interdependence of intellectual property rights (Bekkers and West 2009), the motivation to contribute to specific innovations is driven by the advantages that can be gained, where both opportunity and inducement follow the same logic. The opportunity of a firm increases with its endowments as resources in the form of delegates and knowledge. Similarly, knowledge is the major motivation for the firm to actively contribute to innovations to get its technology endorsed. Consequently, the probability of collaboration is steadily increasing with the firms endowments without any diminishing propensity to contribute.

Hypothesis 1. *The greater the stock of its SDO resources, the more likely the firm will contribute to an innovation.*

2.2.3 Technical Capital on the Firm-Innovation Dyad: Firm-Innovation Resource Match

The firm-innovation resource match is the match of the resources required to develop the innovation and the firms resources. In analogy to the partner selection process and match between partners, the match between the firm and innovation will play as important a role as the partner matching in the partner selection process. The match between nodes attributes as a driver of tie formation has been studied for tie formation of dyads between firms (Cowan and Jonard 2009; Garrette et al. 2009; Mitsuhashi and Greve 2009) and between entrepreneurs (Vissa 2011). On the basis of matching theory, Mitsuhashi and Greve (2009) discussed two processes in their study of alliance formation in the liner shipping industry: market complementarity and resource compatibility, where the former addresses market-related dissimilarities and the latter focuses on resource similarities. As they studied the tie formation for a firm-firm-dyad, the corresponding match was between the requirements of one partner and the complementary assets of the partner of choice. Because of the mutual decision process, the match needs to be reciprocal, that is, each partner needs to provide resources that the other lacks. Vissa (2011) applied matching theory to the tie formation of Indian Entrepreneurs and distinguished social similarity and task complementarity. While social similarity is based mainly on arguments of trust and ease of communication, task complementarity is motivated by access to required complementary resources. Garrette et al. (2009) studied the concept of match between a firm's resource endowments and product requirements and its influence on the propensity to form horizontal alliances. They found that a low fit leads to a product expansion more likely via alliances than within the firm, as the firm needs to seek the required resources outside its boundaries. The simulations by Cowan and Jonard (2009) of alliance tie formation based on technological overlap follows the similarity and dissimilarity between partners endowments, and they show that an optimal point of overlap that simultaneously provides compatibility and complementarity is sufficient to explain the formation of small-world networks. All these studies still examined the tie formation between one type of node, though Garrette et al. (2009) and Vissa (2011) took the activity of the actors and their match into consideration.

Innovations differ in the resources that are required to develop them. These differences can be due to the type of innovation and the search process. While incremental innovations require only local search in a given technological expertise, architectural innovations require broad knowledge of the system and understanding of the linkages between components (Henderson and Clark 1990). Modular innovations require in-depth knowledge of new technological principles in a certain area of expertise, while radical innovations with disruptive technologies require knowledge of both new principles and architectural knowledge (Henderson and Clark 1990). Another, however related, perspective is the depth and breadth of innovations. Depth refers to the degree of detailed knowledge required in a certain area, while breadth relates to the number of different areas covered by a certain innovation (Ahuja and Katila 2004; Wang and von Tunzelmann 2000). The depth and breadth of knowledge required to develop a certain innovation is the knowledge profile of this innovation. On the other hand, firms possess knowledge bases that differ in depth and breadth and are described by the knowledge profile of the firm.

Hypothesis 2. *The greater the firm-innovation resource match, the more likely the firm will contribute to an innovation.*

2.2.4 Social Capital and Network Orchestration

The driving mechanisms of endogenous network evolution, structural and relational embeddedness, allow alleviation of the risk of partner opportunism in the relationship. The embeddedness provides information about the partner and creates trust among partners (Ahuja et al. 2009; Gulati 1995a, 1999; Inkpen and Tsang 2005; Rosenkopf and Padula 2008). Although these endogenous mechanisms are well established and referred to as two well-proven rules (Rosenkopf and Padula 2008, 669), their underlying assumptions seem not to hold in the selection process of the SDO innovation network because of the intellectual property rights regime and the information flow in the meeting network. First, SDO members want to have their knowledge widely spread and accepted by the community. The intellectual property rights policies in SDOs along with the licensing provide a strong appropriability regime (Chiao et al. 2007; Lemley 2002). Firms can gain a rather large amount of information about partners via the meeting networkthey can observe the capabilities, either technological or market knowledge, and the behaviorproviding ex ante information about partners in collaborations. Furthermore, information about inappropriate behavior will disseminate quickly via the regular meetings, leading to a rather long shadow of the future. Though the work on a single innovation is limited in its duration, firm membership in the SDO is typically a long-term engagement in which firms want to be seen as good citizens. Therefore the meeting network provides an additional safeguard against opportunistic behavior. This line of argumentation indicates that social capital in the innovation network is not a key factor.

However, firms that have a central position in the innovation network are so-called hub firms, which can use their position for orchestration of the resources in the innovation network (Dhanaraj and Parkhe 2006). Although the management of knowledge mobility is facilitated via the meeting network, and the management of innovation appropriability via the intellectual property rights rules, the management of network stability is an important task for the hub firms in the innovation network. Though Dhanaraj and Parkhe introduced network orchestration as important activity to increase the innovation output, the management of the network stability is directly related to the tie formation with prevention of migration, attrition, isolation, and cliques and, hence, the building of the network (Ritala and Hurmelinna-Laukkanen 2009). The structural cohesion of the network, the minimum number of actors, who, if removed from a group, would disconnect the group (Moody and White 2003, 103), reflects these four causes of network instability.

Migration to another network and attrition are directly related to removal of nodes, while isolation refers to nodes that are not connected to the main part of the network. Cliques are densely connected subgroups with ties among each node, while nodes of a clique may have only sparse, bridging ties to nodes of other cliques. The removal of a bridging tie can lead to network fragmentation. Network cohesion is closely connected to the network resilience of scale-free networks (Albert et al. 2000), which are more robust to fragmentation by removal of a random node than are random networks. The reason is the degree of distribution whereby most nodes have only a small number of neighbors and their removal is unlikely to change the connectedness of the network. Another perspective of cohesive networks is how far a rather small group of highly connected nodes provides the cohesion and hence can influence the network (Moody 2004).

The network topology of several clusters loosely coupled to each other, a typical form of interorganizational alliances (e.g., Figure 1 on page 670 in Rosenkopf and Padula (2008), runs the risk of developing a technological system with limited support of the whole community. Network stability can be achieved by multiplex relationships or multiple projects (Dhanaraj and Parkhe 2006), which strengthens the connectivity of the network. The simultaneity of several innovations in the SDO provides the opportunity for hub firms to participate in multiple innovations. In addition, the affiliation of several firms with one innovation creates ties between multiple firms. A group of hub firms rather than a single dominant firm characterized by its central position in the network, acts as network orchestrators in the innovation network by managing network stability via tie formation.

Hypothesis 3. *The more central the position of a firm in the innovation network, the more likely the firm will decide to contribute to an innovation.*

2.3 Data and Methods

2.3.1 Sample and Data

I use the context of cellular telecommunications with 3GPP as the SDO. This choice is suitable for the following reasons. First, working procedures support the key setting of the study, that the primary decision process of firms is to support, that is, contribute to, innovations. Second, 3GPP has the advantage over its rival SDO — Third Generation Partnership Project 2 — in that it has a larger and more diverse membership base. Third, the development process is well documented on 3GPPs website (3GPP 2012), as well as in the management (Ansari and Garud 2009; Bekkers et al. 2002; Bekkers and West 2009; Leiponen 2008) and telecommunication-related literature (Haug 2002; Hillebrand 2002; Fuentelsaz et al. 2008). I use data from July 2001 to December of 2010. The following datasets of 3GPP are used to construct the dependent, explanatory, and control variables.

Work plan. The development of the standard occurs via so-called features or single innovations. Each innovation needs to have the support of at least four firms to be approved. All innovations are listed in the work plan with a unique identifier, the title, involved work groups (see next database item), supporters, start and finish date, and a rapporteur. The supporting firms are expected to contribute actively to the development of the innovation (3GPP 2012). Joint contribution to an innovation defines the tie in the innovation network. The work plan defines the sample frame of the innovation network. This sampling also defines the sample of member firms that contribute to the innovations as given by the list of supporters. It includes all firms that supported an innovation at least once. In total, 436 innovations and 217 firms are included in the sample. The sampling guarantees a clear boundary of the network under study, which is an advantage compared to other studies that define networks on the basis of, for example, news reports on alliance announcements. There is only a small risk of a missed innovation and consequently ties in the network.

Work structure. The work structure is the organizational structure of 3GPP with four technical specification groups whose work is split into three to five identification number working groups. These groups define the technological modules in 3GPP. The structure is rather stable over the period of the study with only a few changes, mainly mergers of groups. Meeting list. This lists all meetings with meeting identification, date, and location. Meetings are scheduled quarterly and typically take place for a whole week. In case of high work loads, working groups will have additional meetings.

Firm roster. The roster of all member firms consists of the name and country of the firm. For most member firms there is also a link to the firm's website. The roster is used to consolidate the member firms. Over the period of study, several firms mergedfor instance, Alcatel and Lucent merged in December 2006 to Alcatel-Lucentor changed their name. These changes are accounted for in both the meeting and innovation network.

Delegate roster. The list of all participation of each delegate includes the following information: the first and last name, ID number of the firm, firm affiliation, meeting ID, and meeting date. The delegate roster is the master list for participation in meetings. However, the delegates affiliated firm is based on the current (December 2010) affiliation. To correct for past affiliation before the meeting took place, participation lists were drawn from the single meeting reports and the affiliation information used from these lists.

2.3.2 Measurement: Dependent Variable

The unit of analysis is the firm-innovation dyad. The dependent variable is a dichotomous variable that takes the value of one if the firm decides to contribute to the innovation and zero otherwise. A firm contributes to an innovation if it is listed as a supporter of the innovation. This decision is normally made at the start of the innovation. This definition is based on the working procedures of 3GPP, which state that supporters are expected to contribute actively in the development of the innovation.

2.3.3 Measurement: Explanatory Variables

SDO resources. The major resources for the SDO collaboration are delegates in meetings. I use the number of participants in meetings at the given starting time of the innovation. I measure the starting date of an innovation monthly. However, the meetings of the different technological modules take place on varying dates. As the typical interval between meetings is three months, I measure the SDO resources quarterly to guarantee that all technological modules are taken into account. As some groups meet more than once in a given quarter, I choose the average number of participations. To test for a possible inverse U-shape, I also use the squared SDO resources. The number of delegates as an SDO resource has been used by several scholars (Leiponen 2008; Rosenkopf et al. 2001).

Resource match. This variable is the overlap of the binary profiles of the innovation and the firm, which measures the number of joint technological modules of the focal firm and innovation. The structure that defines both profiles is the technological modularity of the SDO. In the work plan, the work groups or technological modules involved in the development of the innovation are giventhese define the required resources. The profile of the firm is given by the spread of its SDO resources over the technological modules. For most innovations the required profile will be rather narrow and less broad than the resource profile of large system providers or network operators. Firm resources that are not relevant for a given innovation are not taken into account. For instance, if an innovation requires expertise from technological module A and E, while firm generalist has a profile of two delegates in each of the technological modules B, C, E, F, and G, the match between the innovation and firm generalist will be one, as there is overlap in only one work group. This measure was used by Cantner and Graf (2006) for a match of two partners in their resources. It is a measure of technological overlap, which follows a similar logic to measures based on patent data (Jaffe 1986), with the difference that the Manhattan metric instead of the Euclidean was used on vectors with binary entries. While in patent data the technological class defines the technological profile, in the SDO it is the technological module. I use binary firm profiles rather than the number of participations for two reasons: First, the dependent variable is dichotomous and measures the decision to contribute to the innovationthis can be accomplished by a match independent of the size; second, the binary profiles reduce the collinearity with the variable of SDO resources.

Network position (I). The two-mode innovation network is an affiliation network that consists of two types of nodes; firms and innovations and ties exist only between different types (Wasserman and Faust 1994). This reflects the two samples in the data, the firm sample and the innovation sample. In the one-mode firm projection, all firms contributing to an innovation are linked with each other for the duration of the innovation, defined as the period between start and finish date. The approach of projected two-mode networks was also used by Greve et al. (2010); Kogut et al. (2007) and Leiponen (2008). I assign weights to the ties according to the number of innovations the two connected firms have in common. Though many studies use degree centrality as a measure of network position because it captures the access to information well (Freeman 1978), it is not the most suitable for measuring orchestration via network stabilization and cohesion. I use the standardized betweenness centrality, which measures the fraction of shortest paths between nodes j and k that lead through the focal node i in a network of size N (Wasserman and Faust 1994). Betweenness centrality is a measure of the control of knowledge or information flow that a firm has over the network (Borgatti 2005; Freeman 1978), and brokers and gatekeepers are associated with high betweenness centrality (Rowley 1997). It is a global network measure of the firm's reach into the network and access to distant information (Gilsing et al. 2008; Siggelkow 2002), and a node with high betweenness centrality adds to the cohesion of the network, an important characteristic of network orchestration.

2.3.4 Measurement: Control Variables

Number of supporters. Innovations vary by the number of supporters they have. An innovation with a large number of supporters is more likely to be chosen by the focal firm. Number of technological modules. A higher number of involved technological modules allows more firms to contribute because of available resources.

Innovation type. While the innovation literature knows several types of innovation as incremental, architectural, modular, and radical innovation (Henderson and Clark 1990), 3GPP also has types of innovation that may differ in their attractiveness to contributors. In addition to a typical innovation, the default category, minor innovations, are bundled together to keep the number of innovations low. For the analysis, I have unbundled these innovations and categorize them as minor innovation. Other projects are not yet innovations, but studies to investigate the technological feasibility. And there are test innovations that provide testing functionality in the network for other innovations.

Release. Innovations are combined in so-called releases, packages of innovations that define new versions of the standard. The composition of releases regarding types of innovations can vary and hence impact the decision to contribute to a given innovation. Furthermore, the number of active innovations at any point of time is growing over the years. The difference in available innovations is captured by release, which is ordered along time.

Rapporteur value chain (vc) role. Members of 3GPP occupy different roles in the value chain. Instead of the seven categories used by (Leiponen 2008), I use only fournetwork operator, vendor (network equipment/cell phone supplier), component supplier, and others (e.g., research institutes, government bodies). Firms inclination to contribute to an innovation may depend on the value chain role of the rapporteur firm.

Tenure in SDO. The number of months the firm is active in the SDO, that is, the time since its first appearance in a meeting. To measure tenure, meeting participation is tracked back to the very first meetings in 1982. For meetings before 1998, only data for meetings on technical specification groups are available, which may lead to an underestimation of the tenure for smaller firms that joined before 1998.

Network position (M). The network position in the meeting network captures to a large degree the development of trust and availability of fine-grained information. To be consistent with the network position in the innovation network, I also use betweenness centrality. As the participation in meetings can be seen equally as a measure of technological capability and resources rather than social capital3. I measure betweenness centrality first on the level of the individual delegate and then use the geometric average on the firm level. Own value chain role. Firms may vary in their propensity to contribute to innovations, depending on their own value chain position. In particular, the motives for technology suppliers and network operators can vary largely.

Because of the unequal distribution of member firms, the variables are skewed. I transform the SDO resources by the logarithm on the base of 10, all other noncategorical explanatory and control variables by the third root. I choose the third root because it is applicable to variables with values of zero and the shape of the transformation is rather close to the logarithm for the intervals over which the data stretch. To reduce issues of multicollinearity, all variables are mean centered and scaled by the standard deviation.

2.3.5 Model Specification and Estimation

The analysis for a dichotomous dependent variable is logistic regression. To test for endogeneity of network position, I use a 2SLS approach with an instrumental variable. The instrumental variable needs to be correlated with the network position, however, not with the error term. I use the betweenness centrality of a randomly created network, where only firms whose resources match the required resources at the beginning of the innovation are considered. The risk set of the firm-innovation dyad is reduced from the theoretical 94, 612 firm-innovation dyads in two ways. First, not all firms are present in the observation period because of consolidation in the industry, new entrants in the SDO, or exits. Furthermore, though a firm may still be member of the SDO, it may not participate in a given quarter and hence can not make a decision to contribute to an innovation. I therefore include only firms that participate with at least one delegate at the time the decision is made. This reduces the number of observations to 53,444. Second, as firms can only contribute to an innovation in case of resource match, I consider only firm-innovation dyads with a resource match larger than zero at the starting time of the innovation, which reduces the sample to 20,563. As the repeated decisions by firms to contribute to innovations can cause dependence among observations, I use clustered standard errors that account for dependence within groups of firms. For network measures, I use the statistical program R (version 2.13.0) (R Development Core Team, 2010) with the igraph package (Csardi and Nepusz 2006) and the tnet package (Opsahl 2009). For the creation of random two-mode networks I use the

	1	2	3	4	5	6	7	8	9	10	11	12	13
1 Tie formation	1.00												
2 No. of supporters	0.19	1.00											
3 No. of techn. modules	-0.02	0.29	1.00										
4 Release	-0.01	0.28	0.20	1.00									
5 Innovation type	0.02	-0.04	-0.33	-0.03	1.00								
6 Rapporteur vc role	0.02	0.06	-0.02	-0.03	0.03	1.00							
7 Tenure	-0.15	0.12	0.12	0.25	-0.05	0.01	1.00						
8 Network position (M)	-0.08	0.04	0.06	0.04	-0.03	0.00	0.29	1.00					
9 Own vc role	-0.15	0.03	0.05	0.05	0.01	0.01	0.10	0.01	1.00				
10 SDO resources	0.30	-0.07	-0.15	-0.07	0.06	0.01	-0.48	-0.26	-0.27	1.00			
11 SDO res., sq	0.33	-0.07	-0.14	-0.06	0.05	0.01	-0.45	-0.26	-0.25	0.96	1.00		
12 Matching resources	0.15	0.26	0.61	0.22	-0.23	-0.02	-0.06	-0.03	-0.10	0.24	0.23	1.00	
13 Network position (I)	0.35	-0.07	-0.13	-0.08	0.04	-0.00	-0.45	-0.24	-0.40	0.77	0.80	0.20	1.00

Sample size N: 20563; Most correlations are significant due to the large sample size. Significant asterisks are omitted for sake of readability.

Table 2.1: Correlation matrix

	Mean Standard deviation	Minimum	Maximum	
Tie formation	0.17	0.38	0.00	1.00
Tenure	107.90	51.05	0.00	213.00
Network position (M)	0.00	0.00	0.00	0.03
No. of supporters	9.63	5.83	3.00	35.00
No. of technl. modules	2.21	1.63	1.00	10.00
SDO resources	29.62	33.10	0.33	183.00
SDO resources	1973.08	4226.31	0.11	33489.00
Matching Resources	0.34	0.22	0.01	1.00
Network Position (I)	0.01	0.02	0.00	0.18

Table 2.2: Basic statistics.

vegan package (Oksanen et al. 2011). The regression is performed with Stata 11, using the logit for the logistic regression and ivprobit for the 2SLS regression (StataCorp, 2009).

2.4 Results

Table 2.2 reports the summary statistics of the raw data. Table 2.1 reports the correlation coefficients based on the transformed and scaled variables.

Many of the correlations are significant because of the relatively large sample size. Problems of potential multicollinearity are tested via variance inflation factor. For all models and variables, the variance inflation factors are all less than five and raise no concern of multicollinearity (Gujarati 1995). Table 2.3 displays the coefficients for the hypothesis testing via logistic regression. The coefficient of the value chain role of the rapporteur is not reported, as it is not significant for any model and role. Model 1 reports the base model, which includes only the control variables. Models 2 to 4 include stepwise the independent variables; models 5 and 6 report results by substituting the network position in the innovation network with those from random networks. Following, the results are discussed on the basis of model 4.

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6

Constant	-1.42***	-2.64***	-2.74***	-2.37***	-1.95***	-2.04***
	(-5.76)	(-9.02)	(-9.53)	(-9.30)	(-6.73)	(-7.59)
No. of supporters	0.59***	0.65***	0.63***	0.65***	0.63***	0.64***
	(16.99)	(17.68)	(16.63)	(17.25)	(17.02)	(16.81)
No. of techn. modules	-0.18***	-0.12***	-0.42***	-0.39***	-0.41***	-0.40***
	(-6.28)	(-3.75)	(-7.37)	(-6.93)	(-7.20)	(-6.86)
Innovation type (minor)	-0.22*	-0.20	-0.22*	-0.21*	-0.21*	-0.21
	(-2.27)	(-1.93)	(-2.14)	(-1.97)	(-2.05)	(-1.94)
Innovation type (study)	0.03	0.04	0.06	0.05	0.04	0.06
	(0.34)	(0.47)	(0.71)	(0.60)	(0.48)	(0.63)
Innovation type (test)	0.16	0.07	0.10	0.11	0.13	0.12
	(1.17)	(0.45)	(0.67)	(0.75)	(0.86)	(0.83)
Release 6	-0.18	-0.18	-0.18	-0.18	-0.33	-0.46*
	(-1.05)	(-1.00)	(-1.00)	(-0.98)	(-1.88)	(-2.40)
Release 7	-0.13	-0.19	-0.18	-0.20	-0.29	-0.51*
	(-0.72)	(-0.96)	(-0.93)	(-0.95)	(-1.52)	(-2.39)
Release 8	-0.16	-0.32	-0.37*	-0.36	-0.43*	-0.67**
	(-0.84)	(-1.68)	(-1.97)	(-1.73)	(-2.15)	(-3.28)
Release 9	-0.02	-0.25	-0.32	-0.31	-0.36	-0.61**
	(-0.12)	(-1.21)	(-1.55)	(-1.38)	(-1.71)	(-2.82)
Release 10	-0.25	-0.52*	-0.62**	-0.58*	-0.62**	-0.88***
	(-1.07)	(-2.23)	(-2.75)	(-2.57)	(-2.76)	(-3.83)
Release 11	-0.23	-0.52*	-0.59**	-0.56**	-0.58**	-0.86***
	(-1.05)	(-2.34)	(-2.71)	(-2.67)	(-2.82)	(-4.11)
Rapporteur vc role	0.01	-0.01	-0.01	-0.01	-0.00	-0.00
(vendor)	(0.14)	(-0.13)	(-0.12)	(-0.12)	(-0.03)	(-0.05)
Rapporteur vc role	-0.05	-0.08	-0.07	-0.06	-0.06	-0.05
(component)	(-0.39)	(-0.64)	(-0.52)	(-0.42)	(-0.45)	(-0.40)
Rapporteur vc role	0.17	0.16	0.21	0.20	0.23	0.23
(other)	(1.58)	(1.39)	(1.83)	(1.67)	(1.91)	(1.93)
Tenure	-0.63***	-0.16**	-0.16**	-0.07	-0.15**	-0.07
	(-7.56)	(-2.70)	(-2.69)	(-1.53)	(-2.79)	(-1.53)
Network position (M)	-0.18***	-0.02	-0.03	0.00	-0.03	-0.02
	(-3.50)	(-0.59)	(-0.72)	(0.06)	(-0.88)	(-0.52)
Own vc role	0.25	-0.56**	-0.52*	-0.16	-0.32*	-0.20
(vendor)	(1.11)	(-2.63)	(-2.51)	(-1.16)	(-2.21)	(-1.49)
Own vc role	-1.02***	-0.75***	-0.71***	-0.36**	-0.52***	-0.33**
(component)	(-4.24)	(-4.57)	(-4.48)	(-2.92)	(-3.49)	(-2.69)
Own vc role	-1.94***	-1.37***	-1.30***	-0.76**	-1.12***	-0.72**
(other)	(-6.10)	(-3.61)	(-3.48)	(-3.08)	(-3.30)	(-2.72)
SDO resources		-0.17	-0.37*	-0.31*	0.05	-0.27
		(-0.98)	(-2.23)	(-2.26)	(0.28)	(-1.86)
SDO res., sq		0.85***	0.91***	0.52***	0.40**	0.50***
		(5.85)	(6.48)	(4.49)	(2.74)	(3.89)
Matching resources			0.33***	0.30***	0.32***	0.30***

			(6.93)	(6.33)	(6.77)	(6.31)
Network position (I)				0.63***		
				(8.91)		
Random position 1					0.36***	
					(4.25)	
Random position 2						0.62***
						(8.78)
Observations	20563	20563	20563	20563	20563	20563
Log likelihood	-8146.08	-7566.20	-7519.05	-7381.43	-7412.06	-7372.48

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 2.3: Logistic regression for tie formation of the firm-innovations dyad

The results partially support Hypothesis 1, which predicts the increase of the probability to contribute to an innovation with the increase of SDO resources of the firm. The coefficient is negative and significant for the linear term ($\beta = -0.31, p = 0.05$) and positive for the quadratic term and significant ($\beta = 0.52, p < 0.001$). The negative linear term leads to a u-shape rather than an inverse u-shape in alliance formation.

The results support Hypothesis 2, which predicts the increase of the probability of contributing to an innovation with the match of the firm's resources and the required resources to conduct the innovation. The coefficient for the matched resources is positive and highly significant ($\beta = 0.30$ and $p < 0.001$).

Hypothesis 3 suggests that the probability of contributing to an innovation increases with the central position in the innovation network. The results support the hypothesis with a positive coefficient and high significance ($\beta = 0.63$ and $p < 0.001$). Because of the concern of endogeneity, I performed a two-stage probit model. This test is not reported, as the null model of no endogeneity cannot be rejected (p = 0.78). In the absence of endogeneity, the logit model is more efficient. The validity of the instrument is supported.

To answer the question of the relative importance of technical versus social capital, I test for SDO resources as the driver for network position via number of involved innovations. As the number of involved innovations is the result of repeated tie formation over a period of time, I use cumulated SDO resources. I chose the period on the basis of the mean and median duration of an innovation of 16.2 and 15 months, respectively. An alternative period of 12 months shows very similar results (not reported). The regressions have a reduced number of variables as innovation-specific variables are not any longer predictors due to the accumulation.

Table 2.4: Mediation of SDO resources by number of ties and network position (I)

	Mediation: direct path	Mediation: No.of innovations	Mediation heightConstant
0.12	0.13	0.03	
	(1.26)	(1.60)	(0.62)
Tenure	-0.05	-0.03	-0.02
	(-1.58)	(-1.06)	(-1.65)
Network position (M)	-0.02	-0.01	-0.01
	(-1.26)	(-0.74)	(-1.25)
Own vc role (vendor)	-0.48***	-0.36***	-0.24***
	(-3.85)	(-3.43)	(-3.52)
Own vc role (component)	-0.46***	-0.41***	-0.18**
	(-4.35)	(-4.55)	(-2.99)
Own vc role (others)	-0.68**	-0.67***	-0.22
	(-3.12)	(-4.00)	(-1.95)
Cumulated SDO resouces	0.87***	0.87***	0.28***
	(19.51)	(21.89)	(5.94)
Cum. SDO resouces, sq.	0.22***	0.16***	0.11***
	(12.15)	(9.72)	(7.37)
No. of innovations			0.68***
			(19.11)
Observations	20563	20563	20563
Adjusted R^2	0.734	0.749	0.849

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The left column shows the regression of the network position on the cumulated SDO resources with positive coefficients for the linear and square term and both highly significant ($\beta = 0.87$ and $\beta = 0.22, p < 0.001$). The middle column shows that the number of innovations are positively and significantly associated with the cumulated

SDO resources as the main model suggests. The right columns shows the mediation of the resources by the number of ties in the formation of the network position. This suggests that the network position itself is largely determined by the technical capital in form of SDO resources as cumulated tie formations. It can be seen as the memory of previous tie formations with innovations that are still actively under development.

Another test in how far the network position contributes to the tie formation is the comparative analysis of the actual network position and random network positions (Gulati 1995b). Two two-mode random networks are constructed: first, for newly formed ties between firms and innovations, the degree of firms, that is, the number of their innovations, was kept the same as in the actual network. Second, the degree of innovations also, that is, the number of firms involved in them, was kept. Results from substituting the resulting network position in the one-mode projections of these random networks are reported in models 5 and 6 in table 3. While model 5 has a smaller coefficient for network position (I) ($\beta = 0.36$) and has less predictive power with a log likelihood of -7412 versus -7391 ($p < 0.001$) compared to model 4, model 6 shows nearly the same coefficient ($\beta = 0.62$) and has a significantly (p = 0.0014) higher predictive power than model 4 with a smaller likelihood ratio. I conclude that the network position in the innovation network mediates the SDO resources via the number of past ties in the innovation network. It can be interpreted as the manifest result of previous tie formations that are largely driven by the SDO resources, hence the technical capital.

The coefficient of the number of supporters is, as expected, positive and significant, while the number of technological modules is negative. The latter can be explained by a high participation of both small and large firms in innovations with only one technological module. Minor innovations are less likely to attract supporters, though the significance is only on a level of 0.05. With the exceptions of Release 11 and Release

10 none of the releases show significant influence. Both tenure and network position in the meeting network are non-significant in the full model. Component providers and other organizations such as research institutes are less likely to form ties compared to network operators, whereas system and handsets vendors do not show a significant difference in the full model. As the vendor group is normally rather broad in its expertise this may be an effect of suitable available innovations to contribute to. The role of the rapporteur organization is not significant for any of the categories.

In the appendix of this chapter, I report robustness analysis regarding sampling procedures, dependence of observations and measurement.

2.5 Discussion

This study investigates the formation of interorganizational ties in multiparty relationships, where the major selection process is not a partner, but innovation selection, leading to a shift of the focus from the firm-firm dyad to the firm-innovation dyad. I choose the context of SDOs and joint innovations, where the decision process in the SDO supports the selection of an innovation rather than a partner. First, a firms technical capital in the form of SDO resources leads to a higher probability of contributing to innovations without diminishing returns. While there is consistently a positive square term, the results for the linear term are mixed and shows negative results for the full model as well as for some releases (release-specific models are shown in the appendix of this chapter). Robustness tests suggest that there is a size effect and that the organizations with very high resources drive this relationship. Further research is required to understand, whether the effect is due to relatively more resources in TSGs, indicating some type of orchestration, lack of suitable innovations for smaller firms or other reasons. This u-shape is in contrast to the formation of alliances where the inducement to form new relationships shows an inverse U-shape due to limited benefits for highly endowed firms. These results demonstrate the different underlying motives between the two types of relationships. As a consequence, the past SDO resources largely drive the number of supported innovations of a firm and hence its network position in the innovation network. They are congruent with the propositions by Cowan and Jonard (2009) that optimal technical overlap of partners can explain small-world characteristics in alliance networks. The findings of the SDO process may also apply to affiliation networks, where the benefits of affiliations can be complementary to the endowments and facilitate their full usage.

Second, the study confirms the importance of the match between the firm's resources and those required for the innovation. This emphasizes the quality of the relationship as a major driver in the tie formation. It confirms that the recent efforts of researchers to look at the attributes of the relationship (Ahuja et al. 2009; Rosenkopf and Padula 2008; Rothaermel and Boeker 2008) should be further pursued with more scrutiny on the match between the actor and the activity. Previous literature looks at ownership characteristics or the size of the multiparty relationship, which are rather results than causes of the actual activity. This study is able to examine the actual relevant characteristics, the technological profile.

Third, the network position in the innovation network is significant and plays a major role in the tie formation. However, accounting for the number of innovations a firm is contributing to, that are largely driven by accumulated SDO resources, the network position is a result of technical capital. As a consequence firms can establish themselves as coordinating hub firms in the innovation network by continuous contributions to innovations.

There are implications of the findings regarding SDO policies, in particular the relationship of technical and social capital and network orchestration, and tie formation in the actor-activity dyad. First, they answer an important question asked by policy

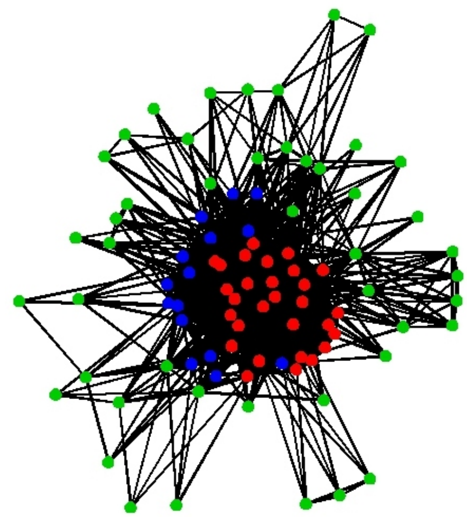

Figure 2.1: Example of blockmodel result for the innovation network. The red nodes are hubs, blue nodes are contributors and green nodes are peripheral firms.

makers for SDOs: How open are SDOs regarding contributions from all players? While a process largely driven by social network position would pose a disadvantage for non- or low-embedded firms, the results show that SDO resources and their match with the innovation requirement drive the network position. This implies that firms that are willing to invest in SDO participation and the required resources are well equipped to contribute to innovations and develop into hub firms orchestrating the innovation process. This was demonstrated by several firms through the period of investigation. The first years cover the early development of the third generation of the standard with newly entered firms such as Huawei and ZTE from China, which developed from peripheral firms into those with a very central position. Verizon, from the US, showed a similar evolution after its entry at the beginning of the fourth generation. For each of these examples the emerging central position in the innovation network lagged the increase of SDO resources. Though building SDO resources takes time, it is a deliberate action a firm can take without being held back by others.

The results and examples above underscore the openness of the innovation process in 3GPP. The network position in the innovation network is a result of past tie formation. The firms take a role in the innovation network, either as hubs or peripheral nodes. Blockmodelling as shown in figure 2.1 based on structural equivalence reveals three persistent roles: hubs (red), contributors (blue) and peripheral (green) firms. Both contributor and hub firms take central positions, however, with the distinction that contributors are connected only among themselves and to hub firms, but rarely to peripheral firms. It is the hub firms that integrate the peripheral firms and lead to a cohesive innovation network with one large component. The connection of hub and peripheral firms leads to a disassortative network structure, where highly connected firms have ties with rarely connected ones, a rather rare phenomenon in social networks (Newman 2002; Rivera et al. 2010). As was shown in the models with network positions in randomly created networks, the conservation of degree distributions of firms and innovations was necessary to reproduce the network position. This reflects the dependence of tie formation in one-mode projections, as ties are built between all firms affiliated with a given innovation and the number of supporters defines the size of fully connected cliques. It suggests that the degree heterogeneity of innovations is crucial in shaping the innovation network and its cohesion.

Second, the focus on a different selection process, the activity rather than the partner, and consequently, activity and actor-activity attributes, brings a rather new perspective to tie formation theory. I expect that this perspective is relevant beyond the SDO context for interfirm networks with more focus on the characteristics of the activity in the relationship and, hence, relationship attributes. Furthermore, the activity or affiliation selection process is most likely applicable to other affiliation and multiparty networks such as open source developments (Grewal et al. 2006). Although the match between firms' resources and those required by the innovation is rather obvious in the firms studied for innovations, it can also apply to other interorganizational networks in the restriction of potential partners. A firm will consider only partners whose profiles match the planned activity.

While the argument above is mainly rooted in resource arguments and the context of SDOs, it can also be viewed from a network theoretical perspective and triadic closure in a three-mode network. Triadic closure in one-mode networks induces partners of partners to form a tie and build a triangle of three connected nodes (Coleman, 1988). It can be measured by the clustering coefficient, which gives the fraction of triangles in a node's neighborhood compared to the maximum possible number of triangles (Watts Strogatz, 1998). By definition, closure is not possible in two-mode networks, as ties can exist only between nodes of different modes, for example, between firms and innovations, but not between firms. By the same argument, the clustering coefficient as defined above has no meaning in two-mode networks. However, Latapy et al. (2008) extended the definition of the clustering coefficient to two-mode networks based on overlapping neighborhoods (for details refer to appendix A). I apply the same logic to the three-mode network under analysis: A focal firm's neighborhood in the two-mode meeting network comprises the technological modules to which it is connected via participations in the meeting, equivalent to the technical profile of the firm. Similarly, the neighborhood of a focal innovation in the innovation-module network comprises the technological modules required to develop this innovation, equivalent to its technical profile. The overlap of these neighborhoods is therefore identical to the resource match. From this perspective, the confirmation of Hypothesis 2 can be interpreted as an extension of triadic closure to three-mode networks: The resource match or, equivalently, the overlap of neighborhoods in terms of the technological modules (the third type of node) of two types of nodes, the firm and innovation, leads to an increased propensity to form a tie between these two nodes. With the integration of the technological modules into the framework of a three-mode network, the technical capital in the form of the resource match becomes part of network embeddednessnot social, but technological embeddeness.

This study has its limitations. First, its context of only one SDO. This is the first study, to my knowledge, investigating tie formation in the innovation network of SDOs. The process depends on the motives of firms, and these can change with rules in the SDO, for instance, appropriation and voting rules (Chiao et al. 2007). This concern applies also to general interfirm networks, where partner and activity selection may be confounded. This study focuses solely on the decision process on the activity, ignoring partner selection effects. In many interfirm relationships, both partner and activity selection will happen simultaneously.

Hence, this work should be seen as a first step in the study of two-mode tie formation, where tie and node heterogeneity has to be accounted for. Though network position is important and is interpreted as network orchestration by a group of firms, the orchestration process itself is not uncovered, nor the interplay between the hub firms among themselves and contributor and peripheral firms. The mixed results for the linear term of SDO resources and the found size effect indicates that there is a difference between small and very large firms measured in their SDO resources. This may be due to orchestration efforts by large firms in TSGs, leadership positions of meetings or rapporteur roles or smaller firms participate more in small technical enhancements that are not covered in the innovation network. The insignificance of the closeness centrality shows that it is not the distance to other firms, but the quality of the position that matters. Innovations are assumed to be exogenous, but they are suggested by SDO member firms. The proposal of new innovations can be an important part of network orchestration. The dichotomous dependent variable does not measure the degree of contribution. There may be firms such as the rapporteur firm that steer the whole innovation, while other firms contribute only marginally. A firm can contribute along a broad range of expertise, or only a small piece in its limited area of expertise. Accounting for the heterogeneity of the contribution will change both the dependent variable and the two-mode innovation network. The identification of specific orchestration processes, interaction between firms in the orchestration process, as well as quantification of contributions of firms to innovations, is subject to future research.

2.6 Appendix: Robustness tests

To examine the sensitivity of the results to sampling procedures, independence of observations of innovations and measurement, I perform several robustness tests.

2.6.1 Alternative Samples

I use alternative samples for three reasons: First, I want to test the impact of reducing the sample to organizations that have matching resources. Second, due to the heterogeneity regarding the SDO resources I exclude either the smallest or the largest organizations within the sample. Third, as innovations are enhanced in subsequent releases innovations are not completely independent. I split the data into release-specific subset and test these separately. The first alternative sample includes firms that participate in meetings at the time of the decision; however, they lack the match of required resources. This leads to a sample size of 53,444. The results are shown in table 2.5. Next, I exclude firms with fewer than five SDO resources, leading to a sample of size 16,431 with the results shown in table 2.6. Similarly, firms with more than 80 SDO resources are excluded, giving a sample size of 18,490 with the results shown in table 2.7. An important assumption of regression is the independence of observations. While I account for repeated choices by firms with clustered error terms, the assumption of independence may be violated by related innovations, for which a new functionality is further developed in following releases. Firms that contributed to the very first innovation may also contribute to the extensions. As extensions of existing functionality occur along subsequent releases, innovations in one release should be void of this dependence. I perform model tests on release-specific subsets with sample rather small sizes from 2,078 to 4,501.

The test with all present organizations confirms all three hypothesis. The linear term of SDO resources is not significant. The matching coefficient is much larger compared to the SDO resources and network position in contrast to the restricted sample. It shows that the ability to exclude organizations that cannot make the choice to contribute leads to different conclusions regarding the size of the effect. The inclusion of organizations without match would lead to an overestimation of the coefficient of matching resources.

Table 2.5: Robustness test: include all present organizations

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Constant	-2.88***	-3.48***	-3.86***	-3.79***	-3.51***	-3.52***
	(-10.01)	(-15.53)	(-17.62)	(-17.94)	(-15.80)	(-16.97)
No. of supporters	0.51***	0.60***	0.55***	0.57***	0.56***	0.56***
	(18.96)	(19.55)	(17.16)	(17.68)	(17.50)	(17.34)
No. of modules	0.01	0.01	-0.37***	-0.36***	-0.36***	-0.36***
	(0.42)	(0.44)	(-10.68)	(-10.27)	(-10.51)	(-10.34)
Inn. type (minor)	0.04	0.02	-0.15	-0.14	-0.14	-0.14
	(0.38)	(0.22)	(-1.43)	(-1.30)	(-1.34)	(-1.27)
Inn. type (study)	0.03	0.06	0.03	0.02	0.01	0.02
	(0.48)	(0.74)	(0.33)	(0.24)	(0.12)	(0.27)
Inn. type (test)	0.00	-0.11	0.16	0.16	0.17	0.16
	(0.03)	(-0.64)	(1.13)	(1.13)	(1.25)	(1.14)
Tenure	-0.98***	-0.18**	-0.17**	-0.09	-0.16**	-0.08
	(-7.19)	(-2.80)	(-2.75)	(-1.70)	(-2.94)	(-1.69)
Network position (M)	-0.24***	-0.01	-0.02	0.00	-0.03	-0.02
	(-3.35)	(-0.14)	(-0.55)	(0.14)	(-0.81)	(-0.44)
Own vc role (vendor)	0.26	-0.72**	-0.55**	-0.22	-0.37*	-0.23
	(0.87)	(-3.20)	(-2.74)	(-1.47)	(-2.52)	(-1.72)
Own vc role (comp)	-1.39***	-0.94***	-0.80***	-0.48***	-0.63***	-0.44**
	(-4.55)	(-5.39)	(-4.99)	(-3.39)	(-4.00)	(-3.09)
Own vc role (other)	-2.12***	-1.49***	-1.28***	-0.80***	-1.11***	-0.73**
	(-6.95)	(-4.16)	(-3.73)	(-3.54)	(-3.61)	(-3.10)
SDO resources		0.57**	-0.22	-0.17	0.14	-0.14
		(3.05)	(-1.40)	(-1.21)	(0.80)	(-0.93)
SDO res., sq		0.64***	0.81***	0.43***	0.35*	0.40**
		(4.27)	(6.18)	(3.44)	(2.32)	(2.95)
Matching resources			1.02***	0.98***	1.00***	0.98***
			(16.99)	(16.41)	(17.07)	(16.28)
Network position (I)				0.52***		
				(8.27)		
Random position 1					0.25***	
					(4.41)	
Random position 2						0.52***
						(8.32)
Observations	53444	53444	53444	53444	53444	53444
Log likelihood	-11360.94	-9577.60	-9096.04	-8948.47	-8977.01	-8925.36

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 2.6: Robustness test: exclude small firms

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Constant	-1.22***	-3.40***	-3.70***	-3.30***	-2.01***	-2.91***
	(-4.74)	(-5.08)	(-5.63)	(-6.85)	(-3.45)	(-5.48)
No. of supporters	0.62***	0.68***	0.66***	0.68***	0.66***	0.67***
	(16.78)	(17.61)	(16.40)	(17.09)	(16.69)	(16.68)
No. of techn. modules	-0.15***	-0.11***	-0.44***	-0.41***	-0.43***	-0.41***
	(-4.95)	(-3.35)	(-7.43)	(-6.86)	(-7.17)	(-6.75)
Innovation type (minor)	-0.18	-0.14	-0.17	-0.15	-0.16	-0.15
	(-1.77)	(-1.27)	(-1.53)	(-1.38)	(-1.44)	(-1.33)
Innovation type (study)	0.02	0.04	0.06	0.05	0.04	0.06
	(0.22)	(0.48)	(0.69)	(0.58)	(0.42)	(0.59)
Innovation type (test)	0.19	0.08	0.12	0.12	0.15	0.13
	(1.33)	(0.48)	(0.72)	(0.76)	(0.96)	(0.86)
Tenure	-0.49***	-0.13*	-0.13*	-0.04	-0.11*	-0.04
	(-6.20)	(-2.17)	(-2.25)	(-0.94)	(-2.01)	(-0.82)
Network position (M)	-0.16**	-0.04	-0.05	-0.00	-0.04	-0.02
	(-2.77)	(-0.94)	(-1.09)	(-0.14)	(-0.88)	(-0.75)
Own vc role (vendor)	0.27	-0.64**	-0.60**	-0.24	-0.36*	-0.27
	(1.17)	(-2.73)	(-2.64)	(-1.56)	(-2.20)	(-1.92)
Own vc role (component)	-1.00***	-0.80***	-0.76***	-0.38**	-0.53**	-0.34*
	(-3.79)	(-4.46)	(-4.34)	(-2.87)	(-3.15)	(-2.56)
Own vc role (other)	-2.17***	-1.60***	-1.52***	-0.93***	-1.29***	-0.87**
	(-6.40)	(-3.86)	(-3.74)	(-3.60)	(-3.36)	(-3.02)
SDO resources (H1)		-0.52	-0.78*	-0.80**	-0.04	-0.75**
		(-1.42)	(-2.15)	(-3.03)	(-0.13)	(-2.61)
SDO res., sq (H1)		1.20***	1.35***	0.99***	0.47	0.96***
		(3.77)	(4.33)	(4.52)	(1.66)	(3.82)
Matching resources (H2)			0.38***	0.34***	0.36***	0.34***
			(6.81)	(6.09)	(6.48)	(6.04)
Network position (I) (H3)				0.62***		
				(8.67)		
Random position 1					0.38***	
					(4.18)	
Random position 2						0.63***
						(8.78)
Observations	16633	16633	16633	16633	16633	16633
Log likelihood	-7306.64	-6844.81	-6799.69	-6663.92	-6698.29	-6651.71

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 2.7: Robustness test: exclude large firms

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Constant	-1.37***	-2.13***	-2.19***	-1.83***	-1.71***	-1.54***
	(-4.85)	(-6.09)	(-6.33)	(-6.39)	(-6.18)	(-5.34)
No. of supporters	0.59***	0.62***	0.60***	0.62***	0.61***	0.62***
	(15.93)	(16.73)	(15.92)	(16.35)	(15.89)	(15.93)
No. of techn. modules	-0.19***	-0.14***	-0.42***	-0.38***	-0.39***	-0.39***
	(-5.47)	(-3.81)	(-6.86)	(-6.31)	(-6.46)	(-6.24)
Innovation type (minor)	-0.22	-0.23	-0.25*	-0.23	-0.23	-0.23
	(-1.95)	(-1.90)	(-2.12)	(-1.89)	(-1.91)	(-1.86)
Innovation type (study)	0.10	0.10	0.12	0.12	0.12	0.13
	(1.33)	(1.18)	(1.43)	(1.42)	(1.38)	(1.53)
Innovation type (test)	0.22	0.14	0.17	0.20	0.21	0.19
	(1.52)	(0.90)	(1.11)	(1.37)	(1.45)	(1.33)
Tenure	-0.55***	-0.18**	-0.18**	-0.09	-0.14**	-0.07
	(-7.55)	(-2.67)	(-2.69)	(-1.68)	(-2.60)	(-1.48)
Network position (M)	-0.16***	-0.04	-0.04	-0.01	-0.04	-0.03
	(-3.50)	(-0.87)	(-1.02)	(-0.16)	(-0.89)	(-0.77)
Own vc role (vendor)	-0.26	-0.59**	-0.55**	-0.16	-0.27*	-0.19
	(-1.36)	(-3.10)	(-2.95)	(-1.31)	(-2.19)	(-1.70)
Own vc role (component)	-1.07***	-0.78***	-0.75***	-0.37**	-0.45**	-0.32**
	(-4.84)	(-4.91)	(-4.80)	(-3.15)	(-3.18)	(-2.75)
Own vc role (other)	-1.91***	-1.40***	-1.34***	-0.77***	-1.01**	-0.70**
	(-6.10)	(-3.87)	(-3.76)	(-3.37)	(-3.18)	(-2.86)
SDO resources (H1)		0.06	-0.10	-0.03	0.13	-0.02
		(0.27)	(-0.49)	(-0.22)	(0.77)	(-0.16)
SDO res., sq (H1)		0.60**	0.63**	0.21	0.25	0.22
		(2.71)	(2.95)	(1.39)	(1.47)	(1.50)
Matching resources (H2)			0.32***	0.28***	0.29***	0.29***
			(6.47)	(5.64)	(6.05)	(5.66)
Network position (I) (H3)				0.61***		
				(9.82)		
Random position 1					0.36***	
					(7.10)	
Random position 2						0.60***
						(9.90)
Observations	18785	18785	18785	18785	18785	18785
Log likelihood	-6704.96	-6433.56	-6391.29	-6260.98	-6270.26	-6247.81

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 2.8: Robustness test: Release-6 only

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Constant	-1.45***	-2.82***	-2.85***	-2.17***	-2.13***	-2.42***
	(-5.70)	(-5.95)	(-6.05)	(-4.62)	(-3.46)	(-5.48)
No. of supporters	0.47***	0.52***	0.53***	0.54***	0.53***	0.53***
	(8.44)	(8.27)	(8.37)	(8.55)	(8.31)	(8.33)
No. of techn. modules	-0.17*	-0.16*	-0.34**	-0.33*	-0.33**	-0.32*
	(-2.56)	(-2.22)	(-2.63)	(-2.56)	(-2.59)	(-2.48)
Innovation type (minor)	0.04	-0.02	0.04	0.06	0.04	0.02
	(0.28)	(-0.11)	(0.23)	(0.35)	(0.27)	(0.13)
Innovation type (study)	-0.21	-0.21	-0.16	-0.15	-0.19	-0.15
	(-0.78)	(-0.74)	(-0.55)	(-0.53)	(-0.62)	(-0.53)
Tenure	-0.40	-0.01	-0.01	0.05	-0.00	0.03
	(-1.95)	(-0.05)	(-0.03)	(0.30)	(-0.01)	(0.18)
Network position (M)	-0.07	-0.00	-0.00	0.02	-0.01	-0.00
	(-0.62)	(-0.02)	(-0.03)	(0.17)	(-0.08)	(-0.01)
Own vc role (vendor)	0.35	-0.35	-0.33	0.03	-0.23	-0.14
	(1.13)	(-1.19)	(-1.14)	(0.11)	(-0.91)	(-0.62)
Own vc role (component)	-1.08***	-0.69**	-0.66**	-0.40	-0.61**	-0.44
	(-4.07)	(-2.89)	(-2.72)	(-1.70)	(-2.65)	(-1.95)
Own vc role (other)	-2.06*	-1.41	-1.42	-1.10	-1.36	-1.18
	(-2.57)	(-1.95)	(-1.94)	(-1.52)	(-1.84)	(-1.65)
SDO resources (H1)		-0.25	-0.30	-0.03	0.07	-0.13
		(-0.78)	(-0.96)	(-0.10)	(0.19)	(-0.45)
SDO res., sq (H1)		0.82***	0.82***	0.29	0.37	0.47*
		(3.61)	(3.61)	(1.17)	(1.08)	(2.08)
Matching resources (H2)			0.19*	0.20*	0.19*	0.18*
			(2.20)	(2.22)	(2.14)	(2.08)
Network position (I (H3)				0.51***		
				(3.52)		
Random position 1					0.28	
					(1.81)	
Random position 2						0.41**
						(3.29)
Observations	2078	2078	2078	2078	2078	2078
Log likelihood	-874.09	-822.63	-820.19	-811.66	-814.02	-809.59

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 2.9: Robustness test: Release-7 only

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Constant	-1.49***	-3.31***	-3.35***	-2.75***	-2.06***	-2.64***
	(-5.14)	(-6.27)	(-6.33)	(-5.62)	(-4.25)	(-5.59)
No. of supporters	0.50***	0.54***	0.54***	0.58***	0.57***	0.58***
	(9.02)	(9.28)	(9.23)	(9.93)	(9.72)	(9.54)
No. of techn. modules	-0.08	-0.05	-0.18**	-0.15*	-0.17*	-0.16*
	(-1.63)	(-0.85)	(-2.58)	(-2.05)	(-2.40)	(-2.16)
Innovation type (minor)	-0.15	-0.17	-0.15	-0.14	-0.13	-0.14
	(-1.13)	(-1.14)	(-1.05)	(-0.95)	(-0.87)	(-0.95)
Innovation type (study)	0.14	0.14	0.16	0.16	0.15	0.17
	(1.23)	(1.22)	(1.32)	(1.31)	(1.17)	(1.36)
Innovation type (test)	0.18	0.01	0.02	0.10	0.14	0.11
	(0.82)	(0.03)	(0.11)	(0.48)	(0.66)	(0.54)
Tenure	-0.50***	-0.07	-0.08	0.01	-0.06	0.01
	(-3.36)	(-0.74)	(-0.82)	(0.14)	(-0.68)	(0.11)
Network position (M)	-0.21	-0.08	-0.08	-0.03	-0.10	-0.07
	(-1.78)	(-0.74)	(-0.83)	(-0.34)	(-0.95)	(-0.80)
Own vc role vendor	0.18	-0.56	-0.55	-0.09	-0.14	-0.05
	(0.57)	(-1.84)	(-1.83)	(-0.36)	(-0.62)	(-0.22)
Own vc role (component)	-1.13***	-0.81**	-0.80**	-0.39	-0.49*	-0.27
	(-3.70)	(-3.26)	(-3.24)	(-1.82)	(-2.05)	(-1.35)
Own vc role (other)	-2.10***	-1.57***	-1.55***	-0.88*	-1.23**	-0.67
	(-4.91)	(-3.35)	(-3.36)	(-2.57)	(-3.02)	(-1.70)
SDO resources (H1)		-0.48	-0.53	-0.40	0.17	-0.35
		(-1.49)	(-1.64)	(-1.27)	(0.47)	(-1.14)
SDO res., sq (H1)		1.06***	1.07***	0.52*	0.20	0.43
		(3.92)	(3.96)	(2.12)	(0.68)	(1.70)
Matching resources (H2)			0.16***	0.13**	0.14**	0.13**
			(3.62)	(2.97)	(3.14)	(2.83)
Network position (I) (H3)				0.78***		
				(7.10)		
Random position 1					0.50***	
					(5.61)	
Random position 2						0.81***
						(8.35)
Observations	4501	4501	4501	4501	4501	4501
Log likelihood	-1893.06	-1788.61	-1784.86	-1728.90	-1736.24	-1730.05

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 2.10: Robustness test: Release-8 only

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Constant	-1.63***	-3.09***	-3.25***	-3.01***	-2.21***	-2.74***
	(-7.81)	(-7.06)	(-7.56)	(-7.71)	(-5.04)	(-7.20)
No. of supporters	0.51***	0.60***	0.59***	0.61***	0.60***	0.63***
	(8.82)	(9.99)	(9.43)	(9.65)	(9.44)	(9.47)
No. of techn. modules	-0.20**	-0.15*	-0.64***	-0.59***	-0.60***	-0.58***
	(-3.07)	(-2.25)	(-5.50)	(-5.16)	(-5.26)	(-5.07)
Innovation type (minor)	-0.36	-0.29	-0.25	-0.22	-0.23	-0.21
	(-1.94)	(-1.48)	(-1.33)	(-1.14)	(-1.16)	(-1.08)
Innovation type (test)	0.25	0.18	0.29	0.30	0.35	0.33
	(1.18)	(0.77)	(1.25)	(1.29)	(1.52)	(1.40)
Tenure	-0.39**	-0.06	-0.06	0.05	-0.02	0.07
	(-3.13)	(-0.57)	(-0.62)	(0.50)	(-0.24)	(0.71)
Network position (M)	-0.22*	-0.07	-0.06	-0.02	-0.07	-0.04
	(-2.26)	(-0.82)	(-0.62)	(-0.26)	(-0.78)	(-0.54)
Own vc role (vendor)	0.26	-0.64*	-0.54	-0.21	-0.26	-0.14
	(0.94)	(-2.08)	(-1.83)	(-0.78)	(-1.16)	(-0.69)
Own vc role (compoent)	-0.90**	-0.71**	-0.63**	-0.30	-0.35	-0.15
	(-3.00)	(-3.02)	(-2.84)	(-1.42)	(-1.61)	(-0.81)
Own vc role (other)	-1.28**	-0.82	-0.71	-0.30	-0.46	-0.10
	(-3.20)	(-1.76)	(-1.82)	(-1.07)	(-1.31)	(-0.36)
SDO resources (H1)		-0.27	-0.52*	-0.53*	0.08	-0.42
		(-1.01)	(-2.03)	(-2.35)	(0.29)	(-1.78)
SDO res., sq (H1)		0.90***	0.91***	0.61**	0.19	0.39
		(3.76)	(3.91)	(2.82)	(0.76)	(1.90)
Matching resources (H2)			0.55***	0.50***	0.52***	0.49***
			(5.86)	(5.27)	(5.58)	(5.33)
Network position (I) (H3)				0.59***		
				(5.34)		
Random position 1					0.48***	
					(4.72)	
Random position 2						0.80***
						(8.03)
Observations	3857	3857	3857	3857	3857	3857
Log likelihood	-1465.50	-1381.05	-1353.32	-1331.52	-1318.47	-1315.58

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 2.11: Robustness test: Release-9 only

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Constant	-1.70***	-3.27***	-3.43***	-3.22***	-2.81***	-3.03***
	(-8.99)	(-9.23)	(-9.67)	(-9.80)	(-8.04)	(-9.52)
No. of supporters	0.59***	0.71***	0.70***	0.71***	0.71***	0.72***
	(5.50)	(5.79)	(5.68)	(5.78)	(5.74)	(5.79)
No. of techn. modules	-0.29***	-0.17*	-0.44**	-0.40**	-0.42**	-0.39**
	(-4.30)	(-2.26)	(-3.16)	(-2.89)	(-3.08)	(-2.78)
Innovation type (minor)	-0.21	-0.17	-0.28	-0.26	-0.27	-0.26
	(-1.51)	(-1.05)	(-1.75)	(-1.61)	(-1.69)	(-1.56)
Innovation type (test)	-0.65	-0.59	-0.63	-0.61	-0.65	-0.61
	(-1.52)	(-1.27)	(-1.40)	(-1.34)	(-1.45)	(-1.33)
Tenure	-0.94***	-0.35*	-0.35**	-0.23	-0.29*	-0.20
	(-6.32)	(-2.56)	(-2.62)	(-1.82)	(-2.35)	(-1.62)
Network position (M)	-0.13	0.10	0.09	0.12	0.10	0.10
	(-1.19)	(1.22)	(1.15)	(1.40)	(1.28)	(1.28)
Own vc role (vendor)	0.31	-0.80***	-0.74***	-0.52**	-0.62***	-0.39*
	(1.16)	(-3.56)	(-3.48)	(-2.85)	(-3.36)	(-2.06)
Own vc role (component)	-1.21**	-1.02***	-0.98***	-0.71***	-0.82***	-0.63***
	(-3.28)	(-4.69)	(-4.49)	(-3.88)	(-3.88)	(-3.29)
Own vc role (other)	-3.31***	-2.62***	-2.57**	-2.11**	-2.41**	-2.03**
	(-4.37)	(-3.31)	(-3.25)	(-2.94)	(-3.08)	(-2.83)
SDO resources (H1)		-0.30	-0.57	-0.55*	-0.18	-0.44
		(-1.03)	(-1.94)	(-2.02)	(-0.57)	(-1.52)
SDO res., sq (H1)		1.07***	1.15***	0.89***	0.70***	0.72***
		(5.35)	(5.87)	(4.95)	(3.42)	(3.85)
Matching resources (H2)			0.27*	0.22*	0.24*	0.22*
			(2.44)	(2.00)	(2.23)	(1.96)
Network position (I) (H3)				0.48***		
				(4.04)		
Random position 1					0.33***	
					(3.42)	
Random position 2						0.62***
						(5.43)
Observations	2960	2960	2960	2960	2960	2960
Log likelihood	-1062.09	-957.28	-953.72	-946.35	-943.02	-941.63

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 2.12: Robustness test: Release-10 only

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Constant	-1.68***	-2.69***	-2.89***	-2.65***	-2.39***	-2.59***
	(-7.82)	(-6.54)	(-7.37)	(-8.10)	(-5.63)	(-7.96)
No. of supporters	0.65***	0.73***	0.69***	0.73***	0.70***	0.73***
	(10.38)	(10.98)	(10.13)	(10.48)	(10.27)	(10.31)
No. of techn. modules	-0.10	-0.02	-0.28*	-0.22	-0.27*	-0.23
	(-1.76)	(-0.39)	(-2.33)	(-1.79)	(-2.18)	(-1.87)
Innovation type (minor)	-0.03	-0.11	-0.09	-0.08	-0.05	-0.05
	(-0.07)	(-0.23)	(-0.18)	(-0.17)	(-0.10)	(-0.10)
Innovation type (type)	0.01	0.17	0.26	0.20	0.18	0.17
	(0.08)	(0.92)	(1.46)	(1.03)	(0.88)	(0.82)
Tenure	-0.73***	-0.18	-0.18	-0.03	-0.14	0.00
	(-6.88)	(-1.75)	(-1.76)	(-0.32)	(-1.47)	(0.04)
Network position (M)	-0.21*	0.02	-0.00	0.03	-0.01	0.02
	(-1.98)	(0.20)	(-0.05)	(0.31)	(-0.06)	(0.23)
Own vc role (vendor)	0.16	-0.56	-0.52	-0.19	-0.39	-0.16
	(0.54)	(-1.80)	(-1.68)	(-0.83)	(-1.49)	(-0.68)
Own vc role (component)	-1.03***	-0.81**	-0.76**	-0.38	-0.60*	-0.31
	(-3.43)	(-2.98)	(-2.78)	(-1.59)	(-2.21)	(-1.20)
Own vc role (other)	-2.04***	-1.50***	-1.40***	-0.68*	-1.17**	-0.56
	(-5.28)	(-3.76)	(-3.30)	(-2.27)	(-2.84)	(-1.80)
SDO resources (H1)		0.28	-0.00	-0.01	0.29	0.06
		(0.81)	(-0.01)	(-0.03)	(0.82)	(0.21)
SDO res., sq (H1)		0.60*	0.69**	0.35	0.32	0.29
		(2.23)	(2.73)	(1.58)	(1.07)	(1.22)
Matching resources (H2)			0.32**	0.26*	0.30**	0.26*
			(3.06)	(2.41)	(2.84)	(2.43)
Network position (I) (H3)				0.70***		
				(6.07)		
Random position 1					0.30*	
					(2.01)	
Random position 2						0.75***
						(5.31)
Observations	4418	4418	4418	4418	4418	4418
Log likelihood	-1657.37	-1509.09	-1500.63	-1466.98	-1486.50	-1464.98

t statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The exclusion of the smallest firms leads to a rather large negative, significant coefficient of the linear term of hypothesis 1 ($\beta = -0.80, p < 0.01$), while the exclusion of the largest firms shows no significant results for hypothesis 1 after the matching resources are included. This suggests that the dependence on SDO resources is driven by the organizations with the highest SDO resources.

The release specific tests show mixed results regarding hypothesis 1. Release-6 and Release-10 show no significance for both coefficients, while Release-7 has a positive significant square term supporting the hypothesis and Release-8 and Release-9 have a significant negative linear term and positive square term. For all release-specific models the random network position 2 has a similar or larger coefficient and with the exception of Release-7 also a lower Log likelihood.

2.6.2 Measurements

I use alternative measures and test the model by replacing the measure of network centrality by four alternative measurements. Network position has a large variety of possible operationalizations via network centrality or roles in the network. As the projected one-mode network is a weighted network with a highly skewed distribution of weights, I use betweenness for weighted networks as an alternative measure with an α of one (Opsahl et al. 2010). In appendix A I provide introduce the adaptation of centrality measures for weighted networks. As a second alternative centrality measure, I use a closeness measure. Closeness is defined as the inverse of the average length of the shortest paths to the other nodes in the network. Third, I use the normalized betweenness centrality in the two-mode network (Borgatti and Everett 1997). Finally, I use the role in the network as resulting by blockmodelling based on structural equivalence (White et al. 1976) with three roles persistent over time: peripheral nodes and outer and inner core nodes. The inner core nodes differ from the outer core nodes by their relatively good connection to the peripheral nodes, while the outer core firms are mainly connected among themselves or with the inner core firms. The results are shown in table 2.13.

Table 2.13: Robustness test: alternative match measures

	Model 1	Model 2	Model 3	Model 4	Model 5
Constant	-2.37***	-2.12***	-2.72***	-2.05***	-2.06***
	(-9.30)	(-7.43)	(-9.41)	(-6.79)	(-8.81)
No. of supporters	0.65***	0.64***	0.63***	0.63***	0.65***
	(17.25)	(16.85)	(16.67)	(16.73)	(17.14)
No. of techn. modules	-0.39***	-0.42***	-0.42***	-0.38***	-0.38***
	(-6.93)	(-7.44)	(-7.41)	(-6.73)	(-6.76)
Innovation type (minor)	-0.21*	-0.22*	-0.22*	-0.20	-0.20
	(-1.97)	(-2.07)	(-2.13)	(-1.86)	(-1.91)
Innovation type (study)	0.05	0.06	0.06	0.07	0.06
	(0.60)	(0.67)	(0.71)	(0.75)	(0.69)
Innovation type(test)	0.11	0.09	0.08	-0.00	0.13
	(0.75)	(0.56)	(0.53)	(-0.02)	(0.87)
Tenure	-0.07	-0.17**	-0.15**	-0.10	-0.07
	(-1.53)	(-2.96)	(-2.59)	(-1.87)	(-1.63)
Network position (M)	0.00	-0.04	-0.03	0.00	-0.00
	(0.06)	(-0.91)	(-0.69)	(0.02)	(-0.12)
Own vc role (vendor)	-0.16	-0.44**	-0.52*	-0.36	-0.15
	(-1.16)	(-2.62)	(-2.49)	(-1.88)	(-1.43)
Own vc role (component)	-0.36**	-0.66***	-0.71***	-0.55***	-0.27*
	(-2.92)	(-4.51)	(-4.44)	(-3.71)	(-2.52)
Own vc role (other)	-0.76**	-1.27***	-1.27***	-0.96**	-0.68**
	(-3.08)	(-3.68)	(-3.40)	(-3.01)	(-2.76)
SDO resources (H1)	-0.31*	-0.03	-0.43**	-0.48**	-0.15
	(-2.26)	(-0.20)	(-2.68)	(-3.20)	(-1.12)
SDO res., sq (H1)	0.52***	0.54***	0.94***	0.81***	0.32**
	(4.49)	(3.50)	(6.88)	(5.97)	(3.15)
Matching resources (H2)	0.30***	0.33***	0.33***	0.30***	0.29***
	(6.33)	(7.01)	(6.97)	(6.44)	(6.26)
Betweenness 1-mode (H3)	0.63***				
	(8.91)				
Weighted betweenness		0.23***			
		(4.55)			
Closeness			0.09		
			(1.94)		
Role (outer core)				-0.37***	
				(-4.30)	
Role (periphery)				-1.00***	
				(-7.38)	
Betweenneess 2-mode					0.74***
					(14.07)
Observations	20563	20563	20563	20563	20563
Log likelihood	-7381.43	-7456.59	-7516.11	-7448.00	-7322.53

t statistics in parentheses

$^{*}\ p < 0.05$, $^{**}\ p < 0.01$, $^{***}\ p < 0.001$

The linear term of the SDO resources shows sensitivity on the measure of position, while the square term is robust. Hypothesis 3 is supported for all alternative measures with the exception of closeness centrality. The inner core firms with their connections to the peripheral firms capture rather well the concept of hub firms that orchestrate the peripheral firms. The firms with a role in the outer core ($\beta = -0.37$) and with a peripheral role ($\beta = -1.00$) are less likely to form ties compared to those in the inner core.

Chapter 3

Order without Hierarchy — the Innovation Ecology of a Standard Developing Organization

3.1 Introduction

The locus of innovation for open complex systems — systems with a large number of components, interacting among each other (Simon 1962) — is not any longer a single firm or a small group of firms, but the whole community or ecology of complex innovation (Dougherty and Dunne 2011).

Standard developing organizations (SDOs), voluntary inter-organizational organizations with the goal to develop a joint technological compatibility standard, are an example of such an ecology of complex innovation. The contribution of organizations to innovations is the major mechanism to influence the standard (Leiponen 2008) and results in the innovation network within the SDO. The SDO environment facilitates knowledge mobility among its members via joint meetings and an approbiability regime in form of intellectual property rights rules (Chiao et al. 2007; Lemley 2002) — two pillars in the orchestration of innovation networks (Dhanaraj and Parkhe 2006). While it is established that SDOs are soecioeconomic systems for technological evolution and innovation (Tushman and Rosenkopf 1992), it is an open question, whether order emerges in this ecology of equal partners without a formal hierarchy. Further questions are, which form this order may take, how it emerges and whether it leads to a stable system. This chapter answers these question of emerging order by applying approaches of mutualistic systems or networks to the ecology of complex innovation in a SDO.

Ecological mutualistic systems are interaction networks between two different types of species where both sides gain an advantage. Examples are pollinator-plant networks, where pollinating insects, while indulging themselves on the plants' nectar, are pollinating these and seed-dispersing networks, where birds eat the plants' fruits and spread their seeds. These mutualistic systems can be described as two-mode or bipartite networks (Jordano 1987; Wasserman and Faust 1994), where animals as pollination insects belong to one type of nodes and the nectar or fruit spending plants to the other type. Two-mode networks are characterized by ties only between the two different types of nodes (Appendix 1 provides an overview of current state-of-the-art analysis of bipartite networks). The research of mutualistic systems in ecology as complex networks has seen an exponential growth in studies in the last ten years (Ings et al. 2009).

A central research question is the existence of order in the structure of these networks and the underlying formation processes as well as consequences, in particular the stability of the networks. Bascompte et al. (2003) found that most mutualistic systems are nested, i.e. nodes with few links (specialists) are mainly linked to nodes that interact with those with many links (generalists). An important characteristic of nested systems is a group of nodes densely connected among each other as well as highly connected nodes are connected to sparsely connected ones (Ulrich et al. 2009). The analogy of mutualistic system to social systems was already drawn in a report on the stability of financial systems (May et al. 2008) and the collaboration of designers and manufacturers in the New York garment industry (Saavedra et al. 2009, 2011). I draw on the analogy of the innovation ecology in SDOs to ecological mutualistic systems and use the developed methods in ecology as a framework of analysis to study the emergence of order in 3GPP's innovation network.

I conceptualize the innovation network in the SDO as a two-mode network, where organizations are one type of nodes and the innovations are the other type. The interaction or tie in the organization-innovation dyad is the decision of the organization to contribute to the innovation. I argue that this interaction provides mutual benefit to both partners of the dyad as organizations gain advantages in form of long-term royalty payments by implementing their proprietary technology into the standard and increase their legitimacy (Rosenkopf et al. 2001; Waguespack and Fleming 2009), while innovations only get into existence via the contribution of organizations. An innovation has several organizations contributing to it and organizations can support many innovations. In the analogy of pollinating networks the organizations are the pollinating insects, while the innovations are the plants providing royalty and legitimacy. An important departure of this study from the approach by Saavedra et al. (2009, 2011) is the organization-innovation interaction rather than an organization-organization interaction. This emphasizes that both, organizations and innovations, are crucial elements of the ecology of complex innovations.

I address the question of emerging order in following steps: First, I show that the innovation network is an ordered system via comparison of the key structural properties with appropriate benchmark or null model networks. Second, I establish that the match of organizations' resources and those required for the development of innovations is the underlying process that reproduces to a large degree the structure of the empirical network. Third, I examine the stability of the system against removal of nodes as well as the temporal stability on system level, while considerable changes are occurring on node level. I use data from 3GPP from July 2001 to December 2011 with 217 organizations and 436 innovations through the observation period, the same set of innovations and organizations as in chapter 2.

This study makes three contributions. First, it pushes the concept of ecologies of complex innovations (Dougherty and Dunne 2011) one step further by applying ecological methods to an innovation ecology. These allow to analyze the emerging order, the underlying process as well as the stability of the order. Second, it applies a newly developed extension of nestedness to individual nodes that allows to study the individual contribution of nodes to the order of the system and their dynamics. Third, the organization-innovation interaction emphasizes that both, organizations and innovations, or more general — actors and their activity — are crucial elements of the ecology of complex innovations and the emergence and maintenance of order. The emerging nestedness of the network can serve as a principle of order in a variety of social systems without an a priori order.

The chapter proceeds the following. After a review of the literature of mutualistic systems, overview of data and methods, I analyze the structure of the innovation network by comparing the structure of the innovation network with those of appropriate random and simulated networks. I end with a discussion of the findings.

3.2 Ecological Mutualistic Systems

In this section I provide an overview over mutualistic systems in ecology[1] , including a definition, major structural properties (degree distribution, nestedness and modularity), underlying processes (neutrality theory versus forbidden links) and stability of the system and how these approaches help to address the questions of emerging structure in the innovation ecology of an SDO. For each subsection I provide a summary of the current research of mutualistic systems and the implication for the SDO's innovation network.

[1] Bascompte and Jordano (2007), Ings et al. (2009), Vazquez et al. (2009) provided excellent recent reviews on mutualistic systems, while Montoya et al. (2006) discussed the differences between ecological and social networks.

3.2.1 Definition, basic parameters and research approach

Mutualistic systems are complex systems that are defined by mutually beneficial interactions of species that belong to different types of species as animals and plants (Vazquez et al. 2009). Examples of mutualistic systems are plant-pollinator systems, where insects are pollinating plants while they are accessing their nectar, and seed dispersal systems, where birds eat the fruits of plants and disperse their seeds. Mutualistic systems play an important role for the earth's biodiversity and are the dominant mechanisms for plants' reproduction (Bascompte and Jordano 2007). Jordano (1987) introduced in his analysis of patterns of mutualistic systems their conceptualization as two-mode networks. Building on the advances of complex networks as small worlds (Watts and Strogatz 1998) and scale-free networks (Barabasi and Albert 1999) the research of mutualistic systems as two-mode networks has seen an exponential growth in the last decade (Ings et al. 2009).

As shown in figure 3.1 key elements of this research is the understanding of the network structure, its underlying processes and consequences, in particular the stability of the systems under species extinction. Supported is the research by appropriate null models for networks and the definition of structural measures. The basic parameters that describe mutualistic systems are the number of nodes of both types (the *species richness*) and the density (called *connectance*). Mutualistic networks are rather small networks with a couple of dozens to a few hundred nodes for each type. There are typically more animals than plants in the system. The density is the number of ties in the network divided by the number of possible ties, the product of the number of animals and number of plants. It is with values between 0.02 and 0.3 low to moderately low (Olesen and Jordano 2002) and decreases with the size of the network as ties typically scale with the species number, while the potential ties scale with the square of the species number. In the innovation network the two types of nodes are organizations

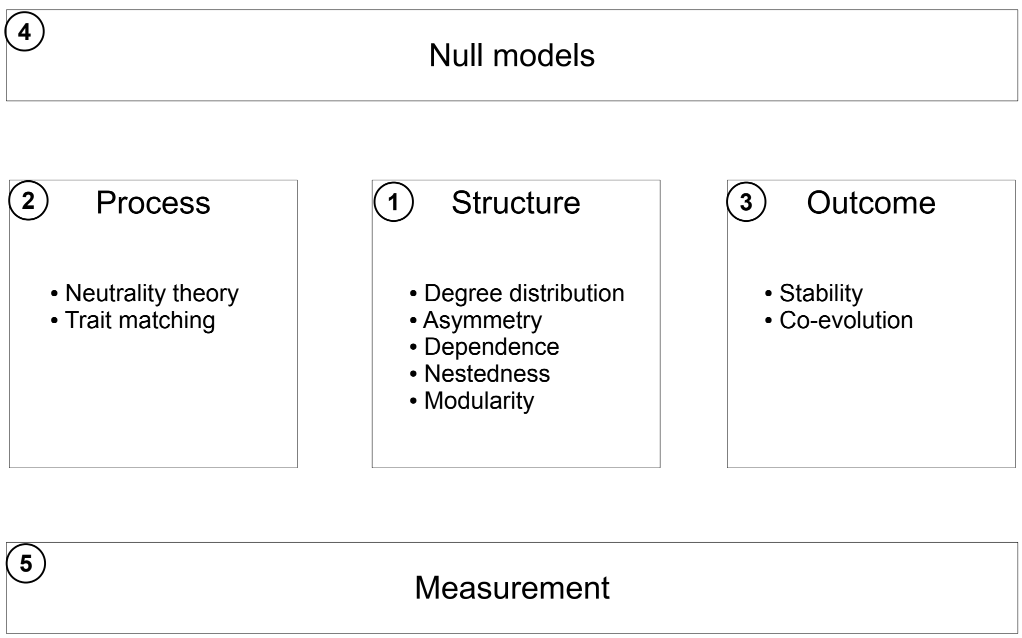

Figure 3.1: Overview of the key topics and supporting methods in the analysis of mutualistic systems.

and innovations with a mutualistic interaction and the framework of figure 3.1 is applied to this bipartite network.

The research approach of the literature of mutualistic networks (and in general of studies of complex network in natural sciences) seldom articulates explicit hypothesis, but compares empirical data with null models that contain implicitly the hypothesis. For the research questions of this study this translates into the following procedure:

Question 1: Does order emerge in this ecology of equal partners without a formal hierarchy? The question translates into the comparison of the structural attributes of the innovation network with those of appropriate null model networks. The degree distribution is probably the most studied structural property and a significant difference of the empirical networks to null model or random networks is an indicator of some order in the network.

Question 2: Which form may this order take? The question regarding the type of order is addressed by comparing two candidate forms of order, nestedness and modularity, of the empirical networks with those of random networks. In case the empirical networks show a stronger structural property than null models they are considered to have this order, e.g. an empirical network with a significantly higher degree of nestedness than a random network is considered to have a nested order.

Question 3: How does this order emerge? This question addresses the underlying process. Several alternative processes of tie formation can be derived from theory and these are translated into network simulations. Again, the comparison of the empirical network attributes with those of simulated networks provide an answer whether a process fits the empirical data and whether it has a stronger predictive power than random networks.

Question 4: Does the order lead to a stable system? This question is broken down in two questions: The robustness of the network under removal of nodes. The removal of nodes can take various forms, the robustness of the network is measured and compared with a scenario of random removal. The second perspective is the stability over time and dynamics in the network attributes and relates to a comparison of networks over time.

Question 1 and 2 refer to the structure in figure 3.1, question 3 to the process and question 4 to the consequences. Random networks and their appropriate choice play a crucial role as they are the basis for the rejection of the null hypothesis that the empirical network is not different to the chosen type of random network. Equally important are the definition and measurement of network attributes.

3.2.2 Structural properties

The major structural properties entail the degree distribution for each type of node, nestedness and modularity (or compartmentalization or community structure) (Bascompte and Jordano 2007; Vazquez et al. 2009). Both, nestedness and modularity, constitute order in the system.

Degree distribution

The *degree* is the number of nodes a focal node is connected to via a tie. In two-mode networks these connected nodes belong to the other type of node and there are separate degree distributions for both types of nodes. With the the seminal study of Barabasi and Albert (1999) and subsequent work it was shown that many complex networks in different fields are scale-free, where the degree distribution follows a power law without a characteristic degree or scale for the system. The degree distributions for mutualistic systems are right-skewed as in other complex networks, however they do not show a pure power law distribution in most cases, but a truncated power-law (Jordano et al.

2003; Medan et al. 2007)

$$p(k) \propto k^{\gamma} \cdot e^{-k/k_c}, \tag{3.1}$$

where $p(k)$ is the probability to have the degree k. The first term on the right-hand side in equation 3.1 is the power law term, where the exponent γ is the slope of the power law, a straight line in a double logarithmic chart. The second term is the truncation term that leads to a steeper decline after the cutoff point k_c. While the truncation is also found in rather small social networks (Kogut et al. 2007), where the network size is a limiting factor to a *the rich-gets-richer* or *Matthew effect*, the key distinction to social networks is the exponent γ of the power law distribution. Jordano et al. (2003) found much smaller coefficients with a value of about one (on average 1.23 for animals and 0.84 for plants for pollination networks and 1.12 and 0.82 respectively for seed-dispersion networks) compared to values between 2 and 3 for social networks. The lower coefficient results in a less steep decline of the degree distribution of mutualistic systems compared to social systems.

Degree asymmetry, a characteristic of mutualistic systems, refers to the negative correlation of the degree with the degree of nearest neighbors (directly connected nodes), i.e. highly connected species (called *generalists*) are connected to sparsely connected species (called *specialists*). In the language of social networks such a behavior is attributed as disassortative. Most social networks are assortative with a positive correlation of the focal node's degree and its neighbors (Rivera et al. 2010). However, it must be noted that in two-mode networks the ties are between nodes of different types.

Nestedness

Nestedness is the outstanding characteristics of mutualistic systems (Bascompte et al. 2003)[2] . While nestedness within one type or category means that a nested unit is

[2] Ulrich et al. (2009) reviewed the literature of nestedness in ecology research.

completely contained in the next larger unit and both are contained in the next larger unit as in the example of Russian dolls or hierarchical organizations, nestedness in mutualistic systems is across the two types of species. In a completely nested system specialists, nodes with few links, interact with proper subsets of interaction partners of generalists (highly connected nodes). For instance bees that visit only a few flower species will visit flowers that are also frequented by insects that interact with many flowers. For the innovation network under study nestedness implies that organizations that contribute only to few innovations will choose innovations that are also supported by those organizations that work on many innovations. A consequence of a nested network is a core of highly connected nodes and a dissassortative structure, where generalists are connected to specialists and hence leading to a cohesive system.

Figure 3.2 demonstrates nestedness (or its absence) for three different networks. All three networks are sorted with rows and columns along their degrees, i.e. for rows the high degree nodes are at the top and the low degree nodes at the bottom, for the column nodes high degree elements are at the left and low degree nodes at the right. In networks ordered in such a manner nested networks are characterized by the concentration of ties in the upper left part of the network. In the completely nested network in figure 3.2a the upper left part is completely connected, while the right bottom part of the network lacks ties. In contrast the random network (figure 3.2b) does not reveal any specific pattern. The observed example of a pollinator network (figure 3.2c) exhibits the tendency of connections in the upper left side, but has also deviations from the idealistic purely nested structure.

Nestedness is an order of the network resulting in the cohesion of the network with an integration of the densely connected group of generalists with specialists. It can be an alternative model to the network orchestration by a single hub or lead firm (Langlois and Robertson 1992) that substitutes the typical hub and spoke structure

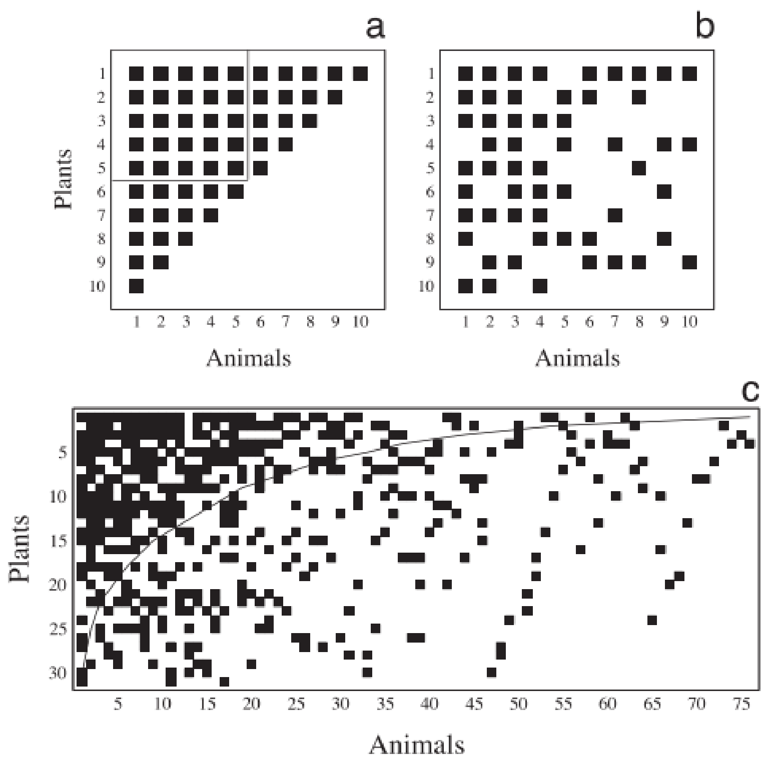

Figure 3.2: Examples of networks with differing degree of nestedness: a completely nested network (a), a random network (b) and an empirical mutualistic network (c). Adopted from Bascompte et al. (2003).

with the strong dependence on the technology sponsor in a one-mode perspective to the ordered system of a heterogeneous ecology of organizations and innovations in a two-mode perspective. This network in the one-mode projection (refer to appendix A) will resemble the decentralized network as described by Langlois and Robertson (1992). The group of generalists together with the integrative, cohesive character can lead to a rather high stability of the network (see below), which is beneficial to the value creation and innovativeness of the system (Dhanaraj and Parkhe 2006; Madhavan et al. 1998).

Modularity

The concept of *modularity* has a long tradition in social sciences starting with the influential paper by Simon (1962) on nearly decomposable systems. The key concept of modularity — a high level of connections or ties within modules and few between modules — allows the containment of most dependence and interaction within modules and hence reduces the complexity, while the few inter-modular ties provide the integration of modules into a system. The dense interactions within modules is based on a common function within the modules. In social networks cohesive subgroups or communities are a major source of influence on individuals and their behavior and integration into organizations.

The identification of modules or communities and the goodness of fit of the result are crucial elements in social network analysis (Frank 1995). Traditional methods are based on clustering techniques, in particular hierarchical clustering based on a similarity measure (Wasserman and Faust 1994). For instance, block modeling defines roles based on similarity of structural equivalence, which measures in how far two nodes are connected to the same neighbors (White et al. 1976). Recently developed algorithms often focus on the maximization of the modularity measure Q (Fortunato 2010). The modularity measure Q (Newman 2004) is the difference between the fraction of the ties within

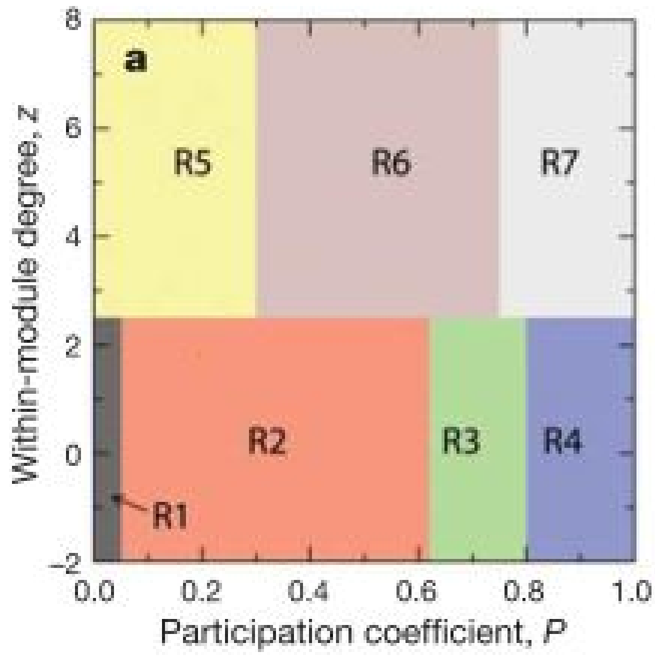

Figure 3.3: Definition of roles based on modularity in the within-module degree (z score) and among-module connectivity (participation) plane. Adopted from Guimer and Amaral (2005).

modules of the empirical network and the fraction of within module ties expected from equally distributed ties given the community structure. The modularity maximizing algorithms have the advantage over hierarchical clustering, that they directly rely on dense connections within communities and are independent of any similarity measure and arbitrary cutoff of the hierarchical dendrogram.

Guimer and Amaral (2005) introduced heuristic definitions of seven distinct roles in a network based on their standard scores of within-module degree and among-module connectivity (or participation) — where "weak, but not neglible" among-module connectivity on system level was the crucial characteristics of Simon's nearly decomposable system.

Figure 3.3 shows the definition of roles in the within-module degree and among-module connectivity plane. The major distinction of these roles is between hubs, nodes with a within-module degree beyond 2.5 standard deviations and non-hub nodes below this threshold. Both, hubs and non-hubs, are further divided based on their among-module connectivity. Non-hubs are divided into four roles with increasing among-module connectivity: ultra-peripheral (R1) and peripheral (R2) nodes, both have low scores in both dimensions, non-hub connectors (R3) and kinless non-hub connectors (R4) with medium to high among-module connectivity. Hubs are further divided into three roles: provincial hubs (R5), connector hubs (R6) and kinless hubs (R7). The bulk of nodes in the studied networks are ultra-peripheral and peripheral nodes, while kinless nodes, those whose ties are equally distributed among modules, are rather rare. Though hub and non-hub connectors are only a small percentage of all nodes (about five to 15 percent), they are crucial in integrating the modules into a nearly decomposable system.

While modularity is a common phenomena in different types of networks, e.g. social networks as alliance networks (Rosenkopf and Padula 2008), metabolic networks (Guimer and Amaral 2005), technical networks as the global network network and the internet (Guimer et al. 2007) and in prey-predator foodwebs, this property is not very distinct for mutualistic networks and is even seen as conflicting to purely nested systems (Vazquez et al. 2009). However, Olesen et al. (2007) have shown that larger mutualistic networks with more than 150 species show modularity. About 15 percent of the species play as either hub or connector a crucial role for the stability of the overall system. Olesen et al. (2007) suggested, that the more dense interactions within modules may lead to coevolution of traits for these species.

In SDOs technological modularity is the key organizing principle, where the modularity of the technological system is mirrored in its working and meeting structure.

For instance the two major parts of the network, the core and radio part, have distinct TSGs, which are further divided into WGs. The question, whether the modularity of the meeting network translates into modularity of the innovation network is of particular importance. A composition of the innovation network into strong functional modules with sparse connections between them bears the risk of fragmentation into rather separated modules or communities. The standard may evolve into different directions and different subgroups only supporting certain developments, while ignoring others. A heterogeneous population of organizations — from the perspective of the value chain position as well as geographic dispersion — can lead to diverging demands. In particular the case of the TD-SCDMA technology within the standard, that is often seen as a Chinese home-grown technology (Fan 2006), may result in a TD-SCDMA community, focusing on TD-SCDMA technology with organizations mainly working on TD-SCDMA development.

3.2.3 Null models

The pure values of a network's structural properties alone do not yet reveal, whether they are noteworthy or just a random result. They require the comparison with an appropriate null model or random network — a technique that became popular with the work on small worlds by Watts and Strogatz (1998). The choice of an appropriate null model is not an easy task and is still under discussion (Gotelli and Entsminger 2001; Gotelli and Ulrich 2012; Ulrich et al. 2009). For two-mode networks several null models are used with different constraints. The least constraint networks are random networks that preserve the density and roughly the node number and are based on an equal probability of tie formation for each cell in the incidence matrix[3] (fixed

[3] The incidence matrix is a network representation in matrix form, where one type of nodes defines the rows and the other type the columns and a tie between two modes is indicated with a non-zero element in the matrix. Figure 3.2 shows examples of incidence matrices.

density or FD). An additional constraint is the preservation of the degree distribution of either rows (fixed row or FR) or columns (fixed column or FC). The most severe constraint is to keep the degree distribution of both types simultaneously (fixed row fixed column or FRFC). In addition Bascompte et al. (2003) used a null model where the probability of a tie is the average of its rows and column ties or occupancies (probable row column or prc). This is one of the most often used null model in the literature as it has a a reasonable level of constraints. Recently Blthgen et al. (2008) suggested null models where the degree distribution for the null model is drawn from an underlying distribution as the lognormal distribution rather than the empirical degree distribution (lognormal null model).

3.2.4 Process

As the structure of networks can have profound impact on their their stability and vulnerability (Albert and Barabasi 2002; Bastolla et al. 2009; Burgos et al. 2007), the question of the processes leading to these properties becomes crucial in order to steer the system to a sustainable structure.

For mutualistic systems two theories prevail for tie formation: The *neutrality* and the *forbidden links* hypothesis. The basic assumption of the neutrality theory is that the probability of interaction between animals and plants is uniformly distributed and hence the greater abundance of a species leads to more interactions. While the abundance of species can explain part of the structural properties, they are not sufficient to reconstruct the observed patterns (Krishna et al. 2008; Vzquez et al. 2009). In contrast the forbidden link theory assumes that some interactions are impossible or forbidden by the matching of phenomenological traits or trait complementarity of the species. For instance insects may not be able to reach into the corolla of a flower to get to the nectar or small birds are not able to carry rather larger fruits (Stang et al. 2006). A fruitful way forward in disentangling the processes leading to a nested structure are simulations, where random networks are created with a tie formation probability either based on the neutrality or forbidden link assumption or a mix of both (Krishna et al. 2008; Rezende et al. 2007; Santamara and Rodrguez-Girons 2007). The simulations can be seen as a specific type of random networks, where the theoretical assumptions provide additional constraints to the preservation of the network's density. In the simulation studies typically between one hundred and one thousand networks are simulated and the average of their structural properties are compared to those of empirical networks.

A well-established patterns in the tie formation in inter-organizational networks is importance of social capital in form of past as well as existing ties between two potential partners. However, the tie formation in two-mode networks between organizations and activities is a novel perspective. In chapter 2 I suggest that the amount of SDO resources as well as resource match are the key driving forces, while social capital is a mediator of the resource perspective. The neutrality theory maps to the SDO resource process, while the forbidden links hypothesis refers to the matched resources. While the study in chapter 2 has single organization-innovation dyads as unit of analysis, the focus in this study is on the structural properties of the network and nodes.

3.2.5 Stability

The stability of networks can be studied under two perspectives: The stability under loss of nodes (robustness) and the stability over time (dynamics).

Robustness

The interest in scale-free and broad-scale networks lies in addition to their ubiquity in their stability against the random loss of nodes and vulnerability towards targeted attacks (Albert and Barabasi 2002). As the vast majority of nodes in a scale-free network has a small degree the removal of a random node will most likely bear little consequences for the structure of the system. In contrast, the attack of the system by deliberate removal of the node with the highest degree can lead to the break-up of the system into non-connected parts. For technical system this question is relevant for infrastructure networks, while for ecological systems the stability under loss of nodes is most pressing with continuing extinction of species due to human influence. Recent studies have found that mutualistic systems are rather resilient to the removal of nodes (Burgos et al. 2007; Memmott et al. 2004). In contrast to one-mode technical networks, these previous studies simulate the removal for both types of nodes separately, with three different scenarios: random removal, removal with increasing degree, i.e. the least-connected node first and the most highly last and *attack* scenario with the highly connected nodes first with a decreasing degree order. The underlying assumption of the order of removal is that it reflects the probability of removal. The random removal serves as a null model to which the order removals are compared (Memmott et al. 2004). For each scenario nodes of one type are removed one by one and the remaining number of nodes of the other species is calculated, where a node of the other type is considered as extinct or removed from the network when it has not any longer remaining ties. Figure 3.4 depicts typical scenarios of loss of nodes, where the x axes represents the fraction of removed nodes of the species under removal and the y axes the fraction of surviving nodes of the other node type.

The reaction of the network to node removal in the chart of fraction of removed versus fraction of surviving nodes is called *attack tolerance line* (ATC). The network is resilient under the null model, the random removal, where with removal of 80 percent of the pollinators still 80 percent of the plants survive in the system, i.e. have at least still one tie. The reason for the robustness is the right-skewed degree distribution of the pollinators, which leads to mainly random draws of low-degree nodes. The removal of

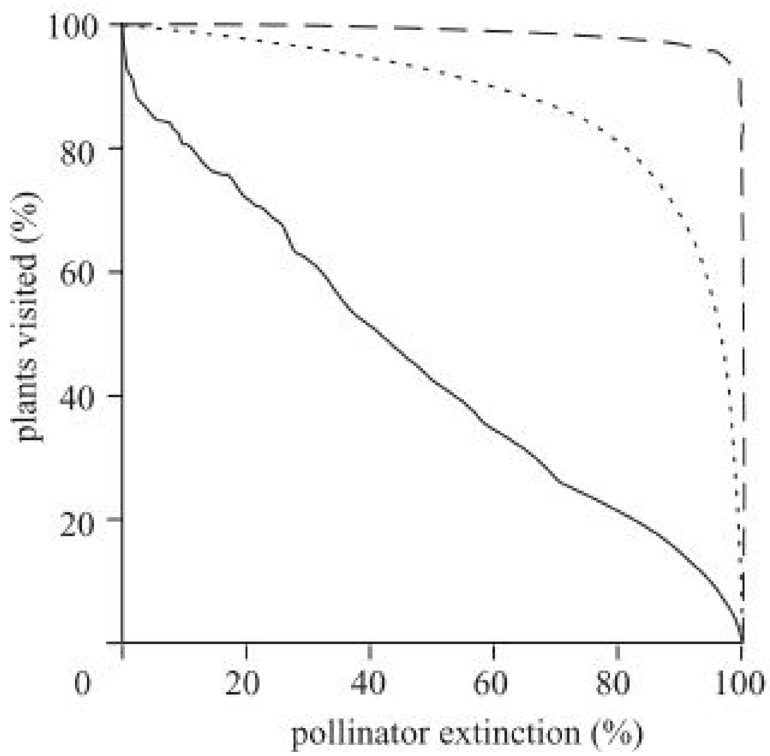

Figure 3.4: Example of attack tolerance curves (ATC) under certain scenarios of node removal for an empirical mutualistic network: The dotted line represents the null model of random elimination, the solid line the removal with highest degree first (attack scenario) and the dashed line the removal of nodes with lowest degree first. Adopted from Memmott et al. (2004), figure 1b).

the least connected node first is, as expected, even mode resilient. The more surprising result is the still relative high robustness under attack (high degree nodes first), which follows a linear decline rather than a steep decline after the removal of the high-degree nodes. Memmott et al. (2004) attributed this relative robustness to high redundancy of ties and the nestedness of the network with lack of modules.

Burgos et al. (2007) introduced the *robustness* measure, the area under the ATC in figure 3.4, with values from zero to one. Values approaching one indicate a high robustness with a very slow decline of surviving species as in the case of least-degree nodes removal first. Values close to zero signal a fast extinction with the removal of a few high-degree nodes and hence low robustness. A linear extinction as shown in figure 3.4 has values close to 0.5, with the lower half of the square filled.

For SDOs the loss of nodes needs a more nuanced perspective. While organization become "extinct" by going out of business or change their identity via mergers and acquisitions, their resources often survive, in particular for large firms whose loss can have substantial impact. An example is Nortel, a long-term strong contributor to the SDO under study, whose assets, business parts and patents, were acquired by other industry players, including members of the SDO (Nortel 2010; Sloan 2011). However, an "extinction" scenario can occur, when organizations decide to withdraw their active participation in the SDO and join a rival SDO. In case innovations become extinct, i.e. their development is stopped, most of the contributing organizations may reallocate their resources to other innovations (this may be less viable for small, very specialized organizations, however these are not crucial for the structure of the network) rather than become extinct themselves, i.e. stop participating in the innovation network. From this perspective the analysis of node loss serves more as a test of the cohesiveness of the system and the redundancy of ties, rather than a true robustness test.

In contrast to the the framework of orchestration of innovation networks, where the maintenance of dynamic network stability, the third pillar of network orchestration, is facilitated by the hub firm via social processes as reputation and shadow of the future as well as via multiple relationships as multiple joint projects (Dhanaraj and Parkhe 2006), in the mutualistic network approach the network stability is solely facilitated by the network structure — and ultimately by the underlying process.

Dynamics

The alternative perspective is the temporal perspective, which looks at two different levels: the structure of the network and its stability over time and the changes on node level. Only few studies analyzed the temporal evolution of mutualistic networks over years due to the difficulty of data collection. Of the few studies that exist most cover only a short period of two to four years (Alarcn et al. 2008; Olesen et al. 2008). The most comprehensive study by Olesen et al. (2011) stretches over twelve years, which confirmed the rather stable structure over time on the network level. The species number of plants as well as the network density were constant, while the number of animal species increased slightly in the long-term trend, though there were fluctuations on a yearly base. In contrast to the stable network level, there was a considerable amount of changes on the species level.

For the SDO the temporal stability or evolution provides insight in the vitality of the network in form of ongoing innovation activities and attraction of new organizations to the system. Fluctuations within the period may be due to different phases of the technological evolution as e.g. transitions from one generation to the next. While the network as a whole may be found rather stable as in the ecological systems, the stability or its dynamics on the node level addresses the question of openness of the SDO innovation network. In case a new generation of the standard induces new inflow of organizations, can these newcomers assume prominent roles as e.g. hub or connectors in the network?

3.2.6 Ecological and social networks

Though mutualistic systems are in most cases different to social systems (Burgos et al. 2008; Montoya et al. 2006), recent research has successfully applied ecological methods to social systems (May et al. 2008; Saavedra et al. 2009, 2011). Saavedra et al. (2009) used simulations to reproduce the degree distribution, nestedness and modularity of ecological and social mutualistic systems. Their empirical context for the social networks are collaborative contracts as ties between contractors (designers), one set of nodes, and manufacturers, the other set of nodes, in the New York garment industry[4] . These networks show similar properties than the ecological mutualistic systems. Saavedra et al. (2009) were able to reconstruct seventy percent of the structural properties of both, ecological and social, networks by their simulations with only three basic input parameters (the size of each type of nodes, designers and manufacturers, and the number of ties between them). They used two processes for their simulation: specialization and interaction. The specialization rule determines with how many partners a manufacturer will interact and it is defined by a uniformly distributed reward trait that its service provides. This rule does only apply to manufacturers. The interaction rule is based on trait complementarity, where the traits of contractors are also uniformly contributed.

Similar to Saavedra et al. (2009, 2011) I apply the methods of mutualistic ecological systems to a social collaborative innovation network. A key difference to the networks of the garment industry is that the nodes are organizations and innovations, rather than two organizations. The network can be seen as mutualistic, as organizations benefit by contribution to innovations and innovations come only into existence by the

[4] This is the same context used by Uzzi (1996) in his ethnography of the NY garment industry and the impact of network embeddedness of economic performance.

contribution of organizations. The benefits of organizations depend on their role in the system: technology providers as component and equipment providers gain long-term royalty payments in case their proprietary technology is endorsed into the standard (Rosenkopf et al. 2001) as well as legitimacy (Fleming and Waguespack 2007). For technology users, the network operators, active contribution is the only way to get their specific needs implemented into the standard and hence support their strategy.

3.3 Data and Methods

3.3.1 The Data

I use data from 3GPP, a SDO for cellular telecommunications (3GPP 2012). The standard development work is conducted by member organizations of 3GPP, which are either firms in the cellular telecommunication ecosystem, research institutes, universities or national ministries. The majority of the members are firms in the industry and its value chain with component suppliers as semiconductor firms, test equipment or software firms, equipment and cellphone vendors and network operators (Leiponen 2008). The members are from about thirty countries from three major regions: Western Europe, North America and East Asia. The standard evolves via a stream of heterogeneous innovations, where bundles of innovations define so-called releases of the standard. I use date from July 2001 to December 2010. During this period 241 organizations were active and 489 innovations were jointly developed in six different releases (Release-5 to Release-10). This period covers most of the third generation of the standard and its evolution into the fourth generation (Release-8 and onwards). The begin of the observation period in July 2001 is due to incomplete coverage of innovation regarding the supporting organizations prior to it .

The network under study is the innovation network within 3GPP, a binary two-mode network between organizations and innovations. The network is constructed in the following way: 3GPP provides a so-called work-plan, a list of all its innovations. For each innovation following information is provided: the begin and end date, the involved technological meetings/modules, and the supporting organizations. Normally organizations decide at the begin of an innovation to support it and continue this support until the innovation is completed. The support of an innovation requires according the working rules of 3GPP an active contribution of the organization to the innovation (3GPP 2012). A tie between an organization and an innovation exists in case the firm is one of the supporting organizations and it persists from the begin to the end date of the innovation. As the work plan only provides the information of support or not support, the ties are binary and take the values of one in case a firm supports, i.e. contributes, to an innovation and zero otherwise. The innovation networks are constructed on a monthly basis.

In addition to the innovation network the technological profiles of the innovations and organizations are constructed. Based on the roster of 3GPP, which lists for each meeting the working group (technological module), the participating individuals and their affiliated organizations and the date, for each organization its technological profile is created on a quarterly base: It is defined by the number of individual participants affiliated with this organization for each working group. It is defined on a quarterly base as meetings take place typically every quarter. In case of high work load meetings are every six weeks — in these cases the average over the two meetings is calculated. Similarly the profile of the innovations is constructed based on involved working groups in its development. In contrast to the profiles of organizations this profile is binary as only the presence or absence of a working group is available. The profile for innovations is constant over its lifetime.

In the analogy of ecological networks I conceptualize organizations as pollinators and innovations as plants[5] . The profiles define the match between organizations and innovations similar to matching traits in ecological systems. The argument is that organizations can only contribute to an innovation if they possess some of the capabilities that are required to develop it. The sum over the organizational profile for a given quarter defines the total number of the organization's SDO resources at this time — it is the analogy to abundance of animals of ecological systems. In this analogy the innovations all share the same abundance of one.

3.3.2 Methods

The basic properties of the network and structural analysis uses well established network measures for two-mode networks (Borgatti and Everett 1997; Dormann et al. 2008; Vazquez et al. 2009). A short summary of the measures is provided in table 3.1.

Measure	Definition
Number of organizations N_O	Number of rows in the incidence matrix
Number of innovations N_I	Number of columns of the incidence matrix
Number of ties or links L	Number of filled elements in the incidence matrix
Density of the network	Number of ties / Number of possible ties ($\frac{L}{N_O \cdot N_I}$)
Degree	Number of directly connected nodes to focal node (row or column margin of the incidence matrix)

Table 3.1: Measures used in the structural analysis of the innovation network.

In the following I describe in more detail the modularity detection and role definition as well as the simulation of the networks.

Nestedness

Nestedness can be measured in several ways. I use the so-called *NODF* measure, based on paired overlap and decreasing fill (Almeida-Neto et al. 2008), as it is closest to the

[5] This is mainly a metaphorical interpretation and does not impact the analysis, which is symmetric regarding the two types of nodes.

concept of nestedness and has been widely adopted since its introduction. It measures the percentage of overlap of ties for pairs of rows and columns (nested overlap). The network wide nestedness is the average over all pairs, where the degree of one row (columns) is less than the degree of the other. The NODF measure lies between 0 and 100, where 0 marks no nestedness and 100 complete nestedness. The NODF measure also provides nestedness measures for the columns and rows separately. I extend the nestedness measure to the individual node level based on the concept of two-mode clustering (refer to appendix B for details).

Modularity

The modularity Q of the network is difference between the fraction of the ties within modules of the empirical network and the fraction of within module ties expected from equally distributed ties given the community structure.

$$Q = \sum_{i=1}^{M}(e_{ii} - a_i^2) \quad \text{with} \quad e_{ii} = \sum_{ij} \frac{a_{ij}}{L}\delta(i,j) \quad \text{and} \quad a_i = \frac{k_i}{L} \tag{3.2}$$

where M is the number of modules, L the number of ties, a_{ij} the elements of the adjacency matrix, which are one in the case of a tie between nodes i and j and zero otherwise, k_i the degree of node i and $\delta(i,j)$ the Kronecker symbol, which is one in case i equals j and is zero otherwise. The modularity Q ranges from -0.5 to 1, were values larger than zero indicate stronger modularity compared to randomly distributed ties across modules. Values of 0.4 to 0.7 signal strong modularity and values larger than that are rare in real networks. While previous studies (Guimer and Amaral 2005; Olesen et al. 2007; Saavedra et al. 2009) uses a simulated annealing algorithm for the maximization of the modularity, I use a function in the *biparitite* package that applies the Newman-Girvan mechanism.

Based on the identified modules the within-degree score and among-module connectivity (or participation) are defined (Guimer and Amaral 2005; Olesen et al. 2007).

The within-degree score takes the following form:

$$z_i = \frac{\kappa_i - \bar{\kappa}_{si}}{\sigma_{\kappa(si)}} \tag{3.3}$$

where κ_i is the number of nodes to which the focal node i is connected to within its own module s_i, $\bar{\kappa}_{si}$ is the average within-degree in module s_i and $\sigma_{\kappa_{si}}$ is the standard deviation of the within-degree distribution for module s_i. The among-module connectivity c_i or participation is given as:

$$c_i = 1 - \sum_{s=1}^{N_m} \left(\frac{\kappa_{si}}{k_i} \right)^2 \tag{3.4}$$

where N_m is the number of detected modules, $\kappa(si)$ the number of connected nodes in module s and k_i the total degree of node i. The among-module connectivity is a measure of diversity across modules and is identical to the Blau index (Blau 1977).

Based on the thresholds given by Guimer and Amaral (2005) I define accordingly the roles. Nodes with a z score above 2.5 are hubs, while nodes below this threshold are non-hubs. Furthermore the thresholds of among-modular connectivity for the distinction of non-hubs into four roles is at 0.05, 0.62 and 0.8, while hub nodes are divided in three roles with the thresholds of 0.3 and 0.75. These are heuristic values based on the networks with an average of 15 modules and a maximum of 19. Furthermore, the model was developed for one-mode networks with only one degree distribution, while in two-mode networks each type has its own degree distribution, which can differ in their heterogeneity and hence one node type may be more prone to have high z score values.

Simulations

The procedure of simulations I am following is similar to the steps for a simulation model of trait complementarity (Rezende et al. 2007), with the technological modules or working groups are identified as traits.

Step 1. I define the technological profiles of organizations and innovations as described in section 3.3.1. The organization's profile is drawn at the time where the innovation starts, as this is the time when the decision on support and hence contribution to an innnovation is made. The innovation profile is constant over time.

Step 2. The match of traits is the technological overlap between organization i and innovation j for a given cell ij of the incidence matrix. For the first two models I use the Manhattan metric with the sum of overlap between the two profiles in each working group, standardized by the number of working groups the innovation is assigned to (Cantner and Graf 2006). The first model, *binary match*, calculates the technological overlap of both profiles, where the profile of the organization is dichotomized, i.e. for each technological module it can take either zero (no resources) or one. The rationale is that organizations can contribute, independent of the size of their resources. The second model, *valued match*, keeps the information how many resources an organization has for each technological module. The third model, *Jaffe*, uses the Jaffe overlap or mean-centered correlation between the two technological profiles, the most often used metric for technological overlap (Jaffe 1986). The fourth model, *SDO resources*, solely measures the total number of resources of an organization — it applies equally to all innovations.

Step 3. The simulation of tie formation based on the probabilities as defined by the second step. The probability is proportional to the matching between the two profiles. In order to preserve the density of the empirical networks these propabilities are normalized such, that their sum is identical to the density of the empirical network. In case of the abundance or resource hypothesis the first and second step can be skipped and the probability in step three will be defined by the SDO resources of the organization, rather than the match (Krishna et al. 2008).

Step 4. For each of the simulations the structural analysis is performed and compared with the empirical values and those of appropriate random networks.

3.4 Results

First I provide the basic statistics — number of nodes of both types and density — of the empirical network over time and compare them with those of ecological mutualistic networks. Then I analyze the structure based on degree distribution for organizations and innovations, the nestedness and modularity and finally the stability of the networks, including robustness and dynamics. For each step I compare the empirical result with those of random and simulated networks.

I use the statistical package R, version 14.1, to perform the analysis. The package *igraph* (Csardi and Nepusz 2006) is used for neighborhoods in the individual nestedness measure, the package *bipartite* (Dormann et al. 2008) is used for the degree distribution analysis, creation of the modules, the lognormal random networks and the robustness analysis, the package *vegan* (Oksanen et al. 2011) is used to calculate random networks as well as the nestnedness measure (NODF). I developed additional code for the individual nestedness measure (NOCI), identification of roles and simulation of networks as well as for the prc random network and the network simulations.

3.4.1 Basic statistics

First, I present a picture of the innovation network at the beginning of the observation period, in July 2001, in figure 3.5 as an incidence matrix.

The nodes in the network are ordered along their degree, with the high degree nodes on the top and to the left. The network picture reveals some degree of nestedness with the tendency to be filled in the top left corner and empty in the right bottom part of the matrix.

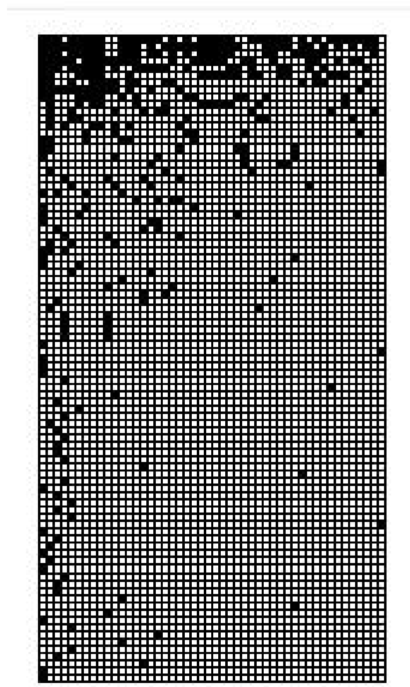

Figure 3.5: Two-mode innovation network at the beginning of the observation period in July 2001 as incidence matrix with the organizations in the rows and innovations in the columns. A filled matrix element indicates the presence of a tie.

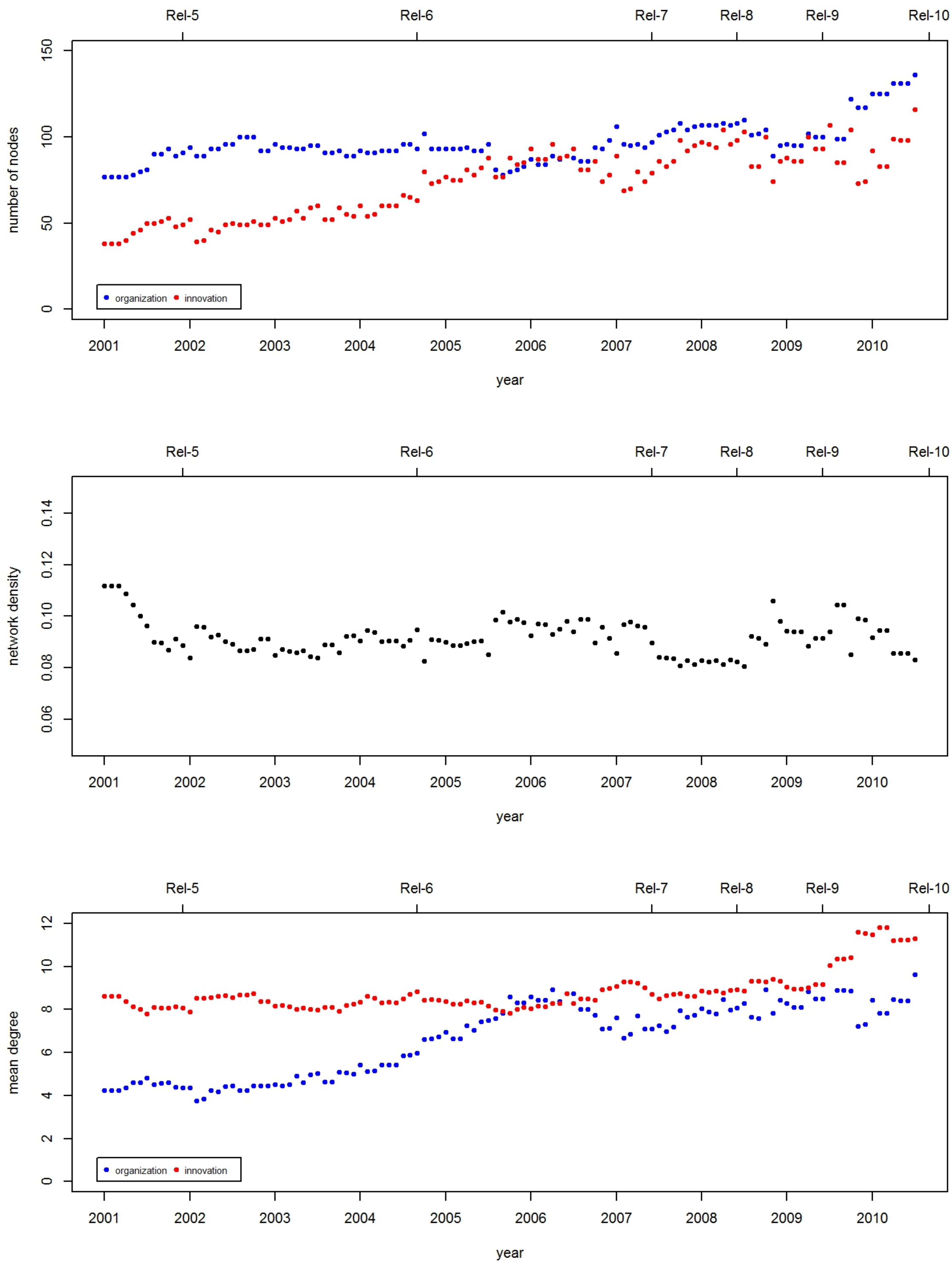

Figure 3.6: Basic networks statistics for the innovation network: Number of firms and innovations (top), the network density (middle) and the average degree of organizations and innovations (bottom).

Figure 3.6 shows the basic statistics of the network over the period under analysis. The number of organizations was for most of the third generation development slightly less than 100 and increased since 2008 with the development of the fourth generation to about 130 end of December 2010. The number of innovations increased during the third generation period until 2007 from 40 to about 90 and fluctuates since then around this value. These values are comparable to those of large ecological mutualistic systems. For the majority of the months the number of organizations is larger than that of innovations, however the ratio between 0.5 and 1 is smaller than those for pollination networks (values of about four) and closer to those of seed dispersal networks with values of 1.2 to 1.6 (Vazquez et al. 2009). The density of the network is rather stable on a level between eight and ten percent for most of the time. This value is comparable to typical density values of mutualistic networks, which range between 2 and 30 percent (Olesen and Jordano 2002) and has values of eight to ten percent for networks with a comparable size. The average degree for organizations increases from four to eight until 2007 and stays on this level until end of 2010. This behavior reflects the number of available innovations. The average degree for innovations is for many years stable on a level of about eight and increases since the begin of 2009 to twelve until the end of 2010. These values are well above the required minimum of four supporting organizations by the rules of the SDO. The average degrees are larger than those of mutualistic system as reported in Jordano et al. (2003), however those reported networks are considerable smaller.

While this comparison with ecological systems is not crucial for the application of the methods from ecology (for instance the networks from the NY garment industry are much larger than the ecological systems), it demonstrates that they have similar basic parameters (number of nodes and number of links) and hence are easily comparable. This is of importance so far as for instance the emergence of the giant component depends on the density of the network. The more interesting comparisons are those of the degree distribution and the asymmetry as these are the characteristics where social and ecological networks normally show departing behavior (Montoya et al. 2006).

3.4.2 Degree distribution

As the degree distribution depends on the network size, I use the standardized degree to make the results comparable over all months, following the approach by Saavedra et al. (2009). The standardized degree is the degree divided by the average degree of the node type (L/N_i, where L is the number of ties and N_i is the number of nodes of the types under consideration).

Figure 3.7a shows the standardized cumulative degree distribution for organizations in a double logarithmic diagram and fits of the exponential, power law and truncated power law distribution. The empirical distribution with data points for the whole periods shows a rather narrow distribution, which indicates a stable distribution of the standardized degree over the observation period of nearly ten years. This is in particular remarkable as the average degree for organizations has doubled in the first half of the observation period (refer to figure 3.6) and it shows that the degree distribution scales with the average degree. The distribution is best described by a truncated power law (blue line) with a slope of 0.57 and a cutoff at about six of the standardized degree, i.e. the sixfold of the average degree. The distribution is rather flat, reflecting the low average exponent of the truncated power law. The average coefficient of the (non-standardized) degree distribution over all months is 0.64 with a standard deviation of 0.14. This exponent is much closer to those of ecological mutualistic systems (1.23 and 1.12 for animals in pollinator and seed dispersal networks and 0.84 and 0.82 for plants) and far below the values between two and three typically reported for social networks (Albert and Barabasi 2002) and the theoretical value of three for a preferential

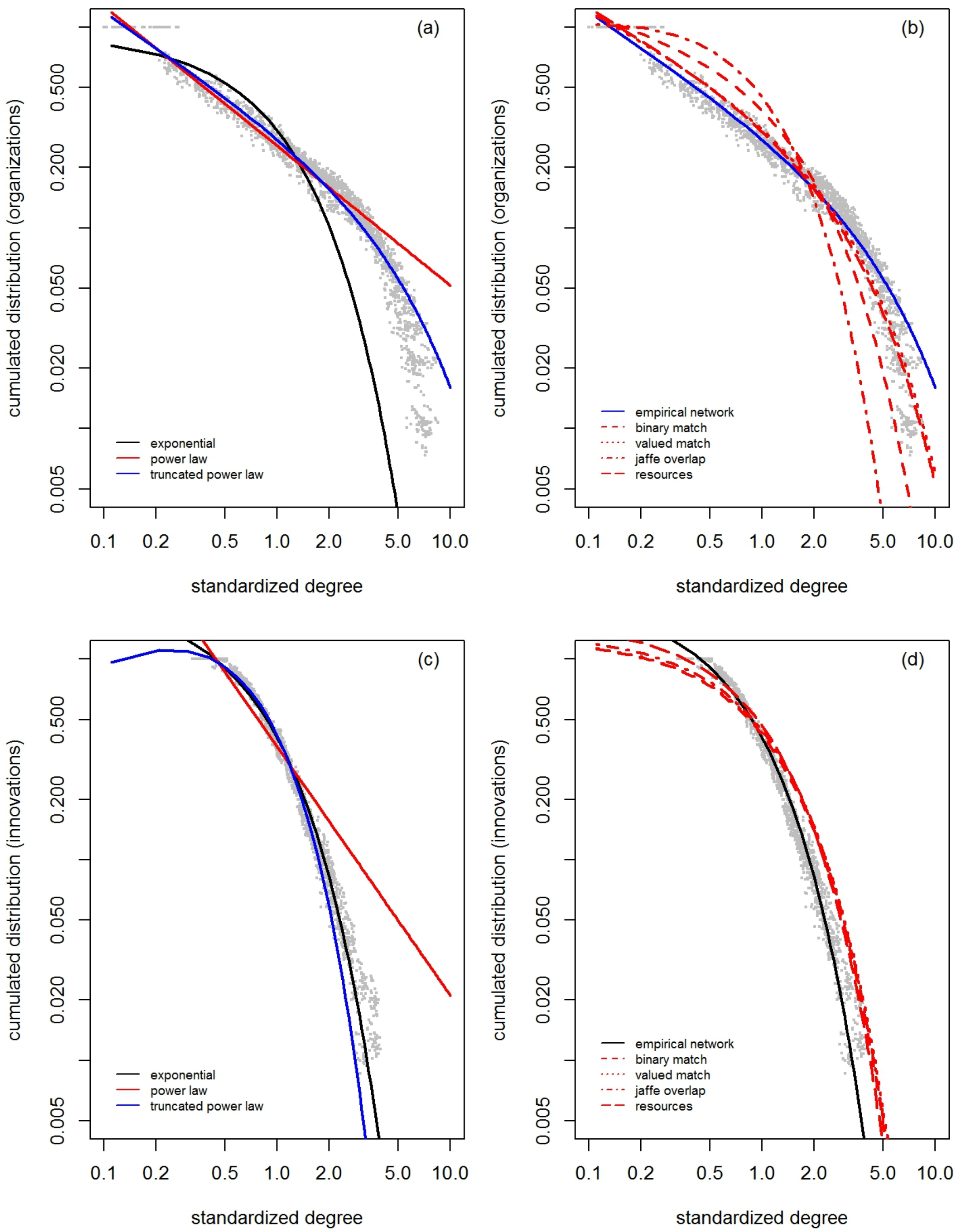

Figure 3.7: The cumulative distribution of the standardized degree for all months in the observations period and fit of exponential, power law and truncated power law for organizations (a) and innovations (c) and the comparison with fits to simulated networks based on four different processes for organizations (b) and innovations (d).

attachment process (Barabasi and Albert 1999).

In the following I compare the degree distributions of the empirical network with those of the degree distributions of simulated networks. For each simulation 100 networks were simulated and the degree distributions show the average degree over the simulated networks. Figure 3.7b compares the fitted truncated power law (blue line) of the empirical networks with fits of a truncated power law to simulated networks based on four different processes (red lines). Neither the fitted curves to simulations based on a binary match (dashed line) or Jaffe overlap (dashed-dotted line) can reproduce the empirical distribution. Both the simulations based on valued match (dotted line) and the amount of resources (long dashed line) provide qualitatively good fits with the truncated power law (blue line). Both are remarkably similar and only differ marginally in the range beyond the cutoff point. While they overestimate the distribution for smaller values of the standardized degree, they are closer to the empirical values for large standardized degrees.

Figure 3.7c and 3.7d show the analog figures for the degree distribution of innovations. This distribution is even more narrow and hence more stable than that of organizations. In contrast to organizations, this distribution is best described by an exponential distribution with a steep decline for standardized degrees beyond 0.5, which indicates that innovations have a rather well defined degree around the average standardized degree, however degrees up to four times of the average standardized degree occur. All simulated networks show a very similar distribution, which generally reproduce the empirical distribution rather well, however they are slightly shifted to the right, hence showing more innovations with larger degrees compared to the empirical distribution.

As the simulations based on binary match and Jaffe overlap fail to reproduce the

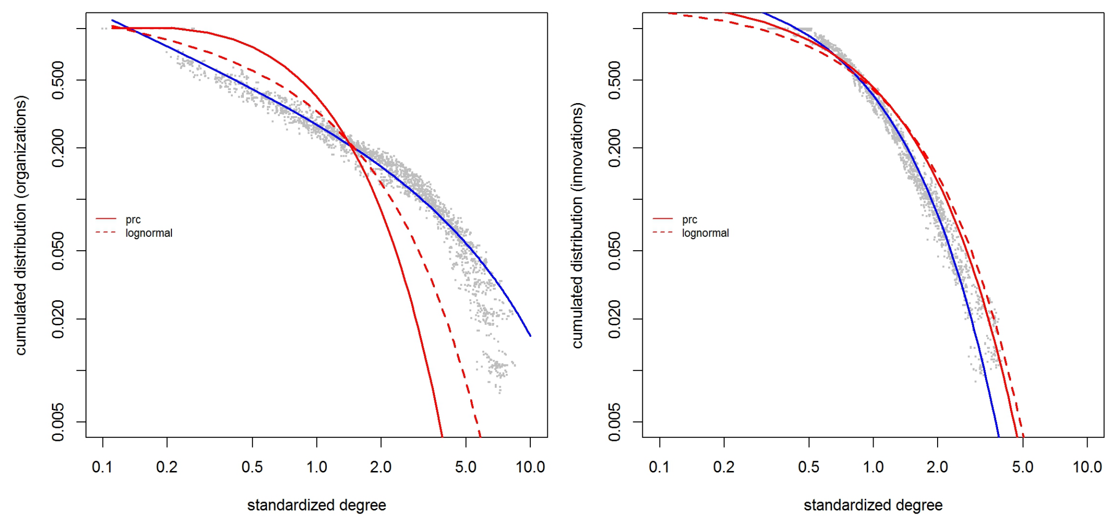

Figure 3.8: The cumulative distribution of the standardized degree for all months in the observations period for organizations (a) and innovations (b) and the comparison with fits to two random networks (prc and lognormal).

degree distribution[6] , I focus in the following on the simulations based on valued match and amount of resources together with the random network of probability-row-column (prc) and random networks based on an underlying lognormal distribution.

For sake of completeness I compare in figure 3.8 the empirical degree distribution with those of two types of random networks (prc and lognormal). For organizations (left side) both random networks provide a poor description of the empirical degree distribution and fall short compared to the simulations of valued match and resources. For the degree distribution of innovations, however, both are rather close to those of the empirical network, similar to the simulations. I conclude that the two-mode network has a structure different from appropriate null models.

Figure 3.9 shows the correlation of the degree of nodes with the degree of their nearest neighbors for organizations and innovations separately. The negative correlation for most of the periods demonstrates that the system is dissassortative, where nodes

[6] They also demonstrate weak predictive power for nestedness.

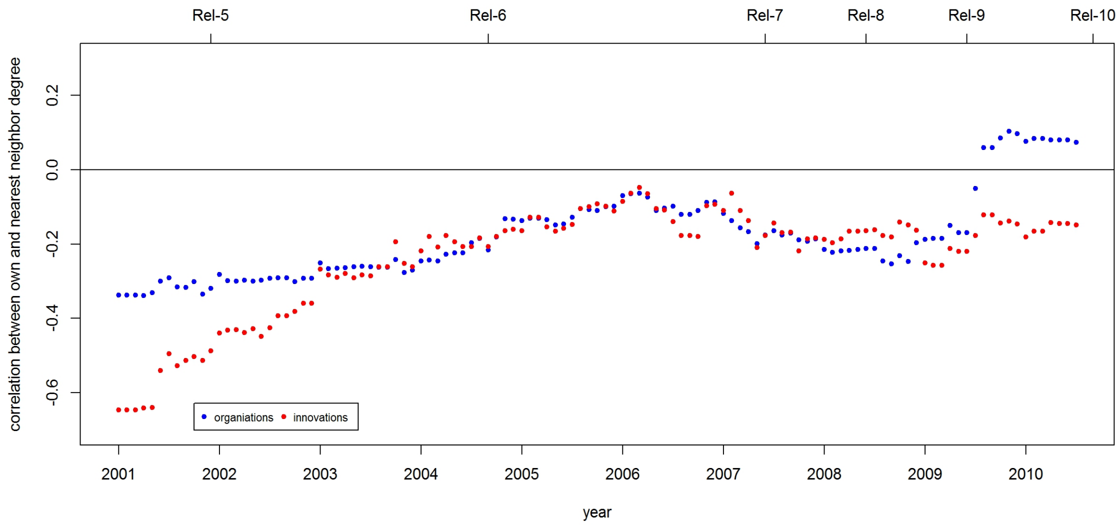

Figure 3.9: Correlation between node and nearest neighbor degree.

with high degree are connected to many nodes with a low degree leading to a cohesive system.

3.4.3 Nestedness

Figure 3.10 shows the nestedness of the monthly innovation networks and the comparison with two random and two simulated networks. First, the nestedness of the empirical network fluctuates around the level of 25, with the highest values of about 30 at the beginning of the observation period and the lowest value of about 21 in the year 2003. The amount of the fluctuation becomes smaller and the cycles shorter with increasing time.

The nestedness of the prc random networks (figure 3.10a) is with a level of 15 significantly smaller than that of the empirical network[7] . It shows similar fluctuations than the empirical network, however less pronounced. The nestedness of lognormal

[7] For each random and simulated network type I performed a t-test for each month comparing the empirical nestedness value with those of the random/simulated networks resulting in significantly different values

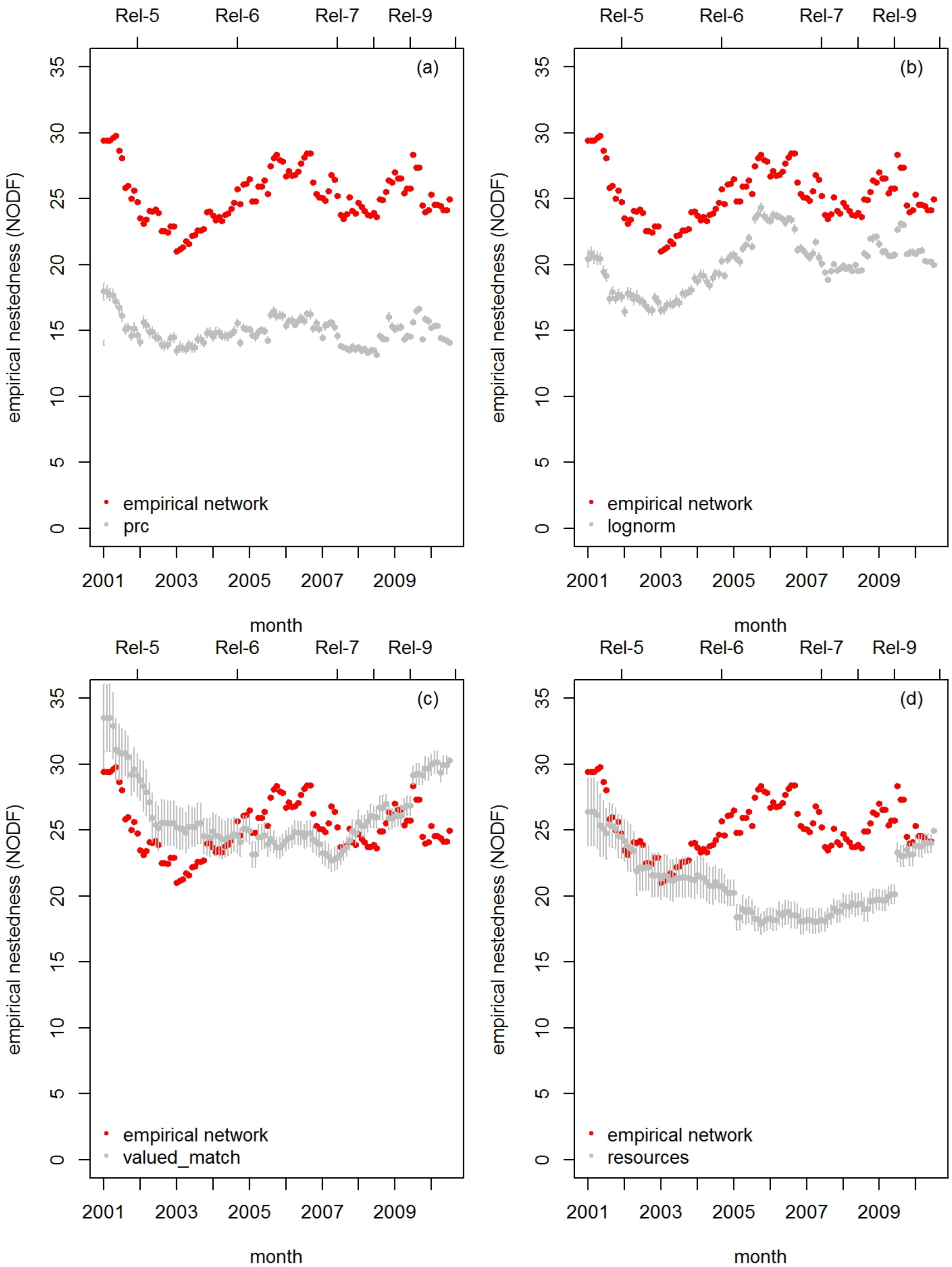

Figure 3.10: Nestedness of monthly two-mode innovation networks (red dots) and nestedness of random and simulated networks (grey dots including error bars of one standard deviation) ((a) prc, (b) lognormal, (c) valued match and (d) amount of resources.

random networks (figure 3.10b) is still smaller than the empirical network, however it is on a level of about 20 and it reproduces well the fluctuations of the empirical network. Both random networks have rather small error bars.

While both random networks are less nested for the whole observation period, the two simulation networks show a different behavior. The valued match simulation (figure 3.10c) is at the beginning and end of the observation period more nested than the empirical network, while it is less nested from 2004 to 2007, largely during the development of Release-7. The simulation based on the amount of resources reproduces well the empirical nestedness in the beginning and end, when the valued match is too high, and is far too small in the years from 2004 to 2007. These results suggest, that there was a shift in the underlying formation process, with the dominance of the resource based process at the beginning and the end and the valued match process in the period in between.

In order to gain a better understanding where the simulations deviate form the empirical network I look next at the nestedness of individual nodes based on the new measure "nested overlap based on clustering for individual nodes" (NOCI) developed in appendix B. The sum over all individual nestedness values of one type of nodes — either organizations or innovations — is equivalent to the NODF measure.

Figure 3.11 shows the individual nestedness for organizations and innovations for December 2004 (a to d) and December 2010 (e to h) for both simulation networks on a logarithmic scale for the individual nestedness. The x coordinates are node identifications ordered along decreasing individual nestedness. December 2004 was a month where the valued match simulation provides a good fit with the empirical value, while simulations based on resources are a good fit in December 2010. First, the distribution of individual nestedness of organizations show similar patterns across different time

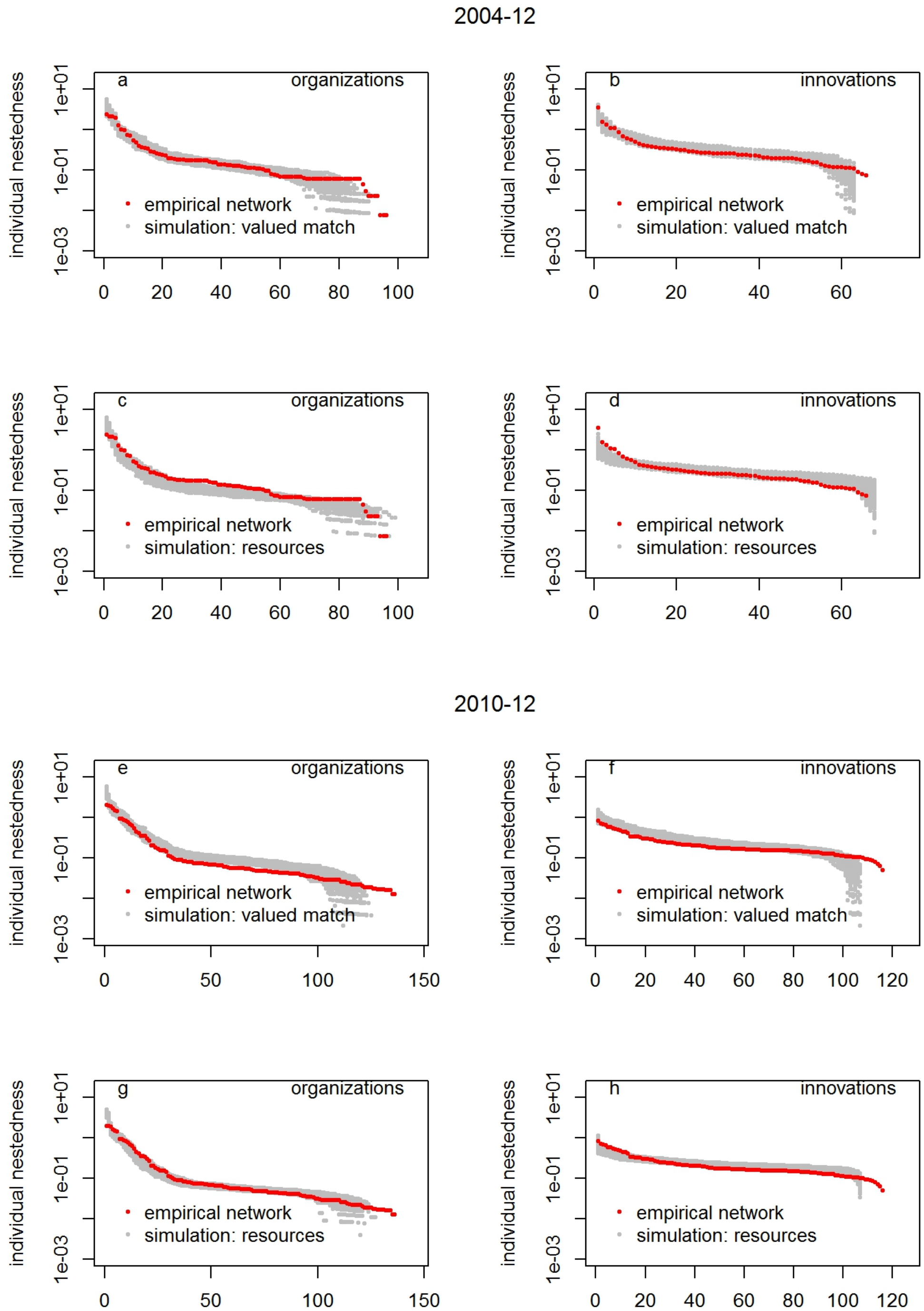

Figure 3.11: Comparison of individual nestedness for organizations (left column) and innovations (right column) for both types of simulations. The x coordinates are node identifications ordered with decreasing individual nestedness, i.e. the first node has always the highest individual nestedness and the last node the least.

periods. There is a group of about 20 organizations with rather large values of nestedness and a smooth decrease within this group of an order of magnitude. There is a large group of firms with low values, close to the median and a slow decay in the individual nestedness[8] . The distribution for innovations is similar, however with a less pronounced group of strong contributors and a very slow decrease for the low value group.

Second, the distributions of the simulated individual nestedness are rather narrow and coincide in general well with the empirical values for both types of simulations. They show a stronger decline for very low values of individual nestedness. For December 2004 the simulation based on valued match (a and b) provide excellent agreement with the empirical results with only deviations for the lowest individual nestedness. The simulation based on resources (c and d) generally underestimates slightly the individual nestedness for organizations and in particular underestimates the strong contributors of innovations. For December 2010 both simulation types underestimate the tail of low individual nestedness, which is most likely due to an underpresentation of ties with very low probability in the simulation with only 100 simulated networks. The simulation based on resources provides a good fit, while the simulation based on valued match still reproduces well the group of highly nested organizations.

3.4.4 Modularity

Figure 3.12 illustrates the results of the nestedness analysis for December 2010 and is based on figure 1 in Olesen et al. (2007). The top left depicts the incidence matrix with ordered rows and columns along decreasing degree. It is characterized by the rather dense fill in the upper left corner and empty space in the right bottom area as it is typical for a nested structure. However, it also shows several deviations from

[8] Nodes with no contribution to nestedness are dropped due to the logarithmic scale.

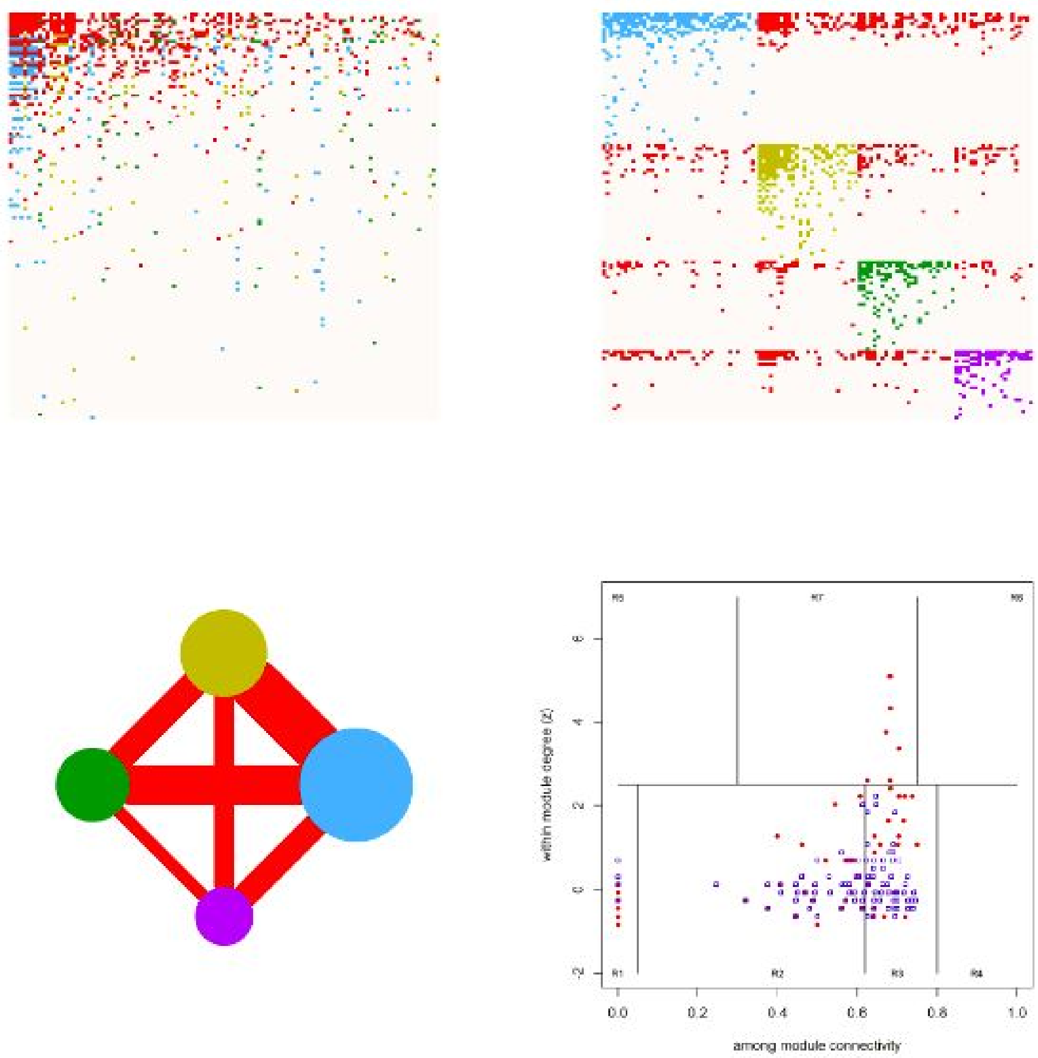

Figure 3.12: Example of the modularity of the innovation network for December 2010 with the incidence matrix of the network ordered along decreasing degree (top left), ordered along modules and within modules along degree (top right), the simplified network with modules as network nodes and ties between modules (bottom left) and the roles of the nodes (bottom right).

this structure resulting in a moderate nestedness for the network as discussed in the previous section. The colors of elements symbolizes either the module to which both nodes belong or is red in case of an inter-modular connection. The very top left corner is dominated by inter-modular connections.

The top right depicts the incidence matrix ordered along modules, with the modules ordered along their size. There are in total four modules with moderately decreasing size. The density of ties within modules is larger than in the areas across modules. The modules appear to show some nestedness within themselves, however not very distinct. The high-degree nodes of each modules are those with many inter-modular connections — in particular organizations demonstrate this behavior with connections of the across all modules for the top-degree nodes, illustrated as red horizontal ribbons on the top of each module.

The bottom left in figure 3.12 visualizes the network in a simplified way with the modules as nodes and ties are only shown between modules. The size of the modules reflects the number of single nodes they contain and the thickness of the ties the actual number of links. The modules are rather densely connected among each other with many ties between module one and the other three modules. The bottom right identifies roles of nodes based on within-module degree and among-module connectivity (Guimer and Amaral 2005; Olesen et al. 2007). Only four of the seven by Guimer and Amaral defined roles are populated. The bulk of nodes is in the ultraperipheral role (R1) — the large number of nodes is hidden by coinciding values of participation (among-module connectivity) and within-module degree. There are also rather big populations in the peripheral role (R2) with small within-module degree and low to moderate participation as well as the connector role (R3) with higher values of participation compared to the periphery. Organizations (red dots) and innovations (blue squares) populate the periphery and serve as connectors. The last role, hub nodes (R6),

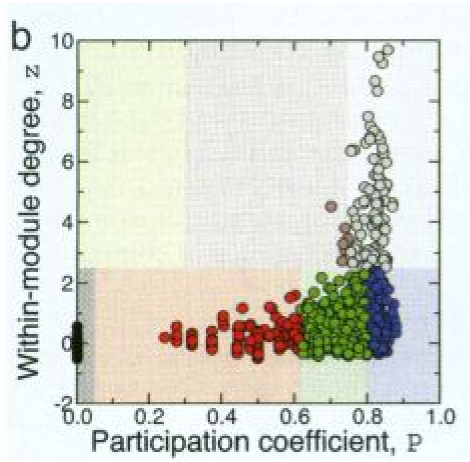

Figure 3.13: The distribution of roles of a random network with most hubs being kinless hubs and appearance of kinless non-hubs. Adopted from figure 4b in Guimer et al. (2005).

have a high within-module degree and high among-module connectivity. In December 2010 only organizations serve as hubs, while in other periods innovations may play the role as hub, however are underrepresented compared to organizations. This is due to their rather narrow degree distribution, which makes within-module degrees above 2.5 standard deviations above the mean unlikely.

The number of modules with four is much less than those found in the networks studied by Guimer and Amaral (2005) with average of 15 modules. In a network with only four modules the threshold for kinless nodes needs to be reconsidered. For completely equally distributed ties among all four modules, the characteristic of kinless nodes, equation 3.4 leads to value of 0.8, just at the threshold. This suggests that for a smaller number of modules the threshold has to be shifted to the left. With a redefinition of thresholds the empirical distribution of roles resembles that of a random network as shown (figure 3.13). Both, the empirical network as well as the random network shown in figure 3.13 are characterized by mainly kinless hubs and the absence of provincial hubs.

Figure 3.12 is a snapshot at the end of the observation period, however the nearly

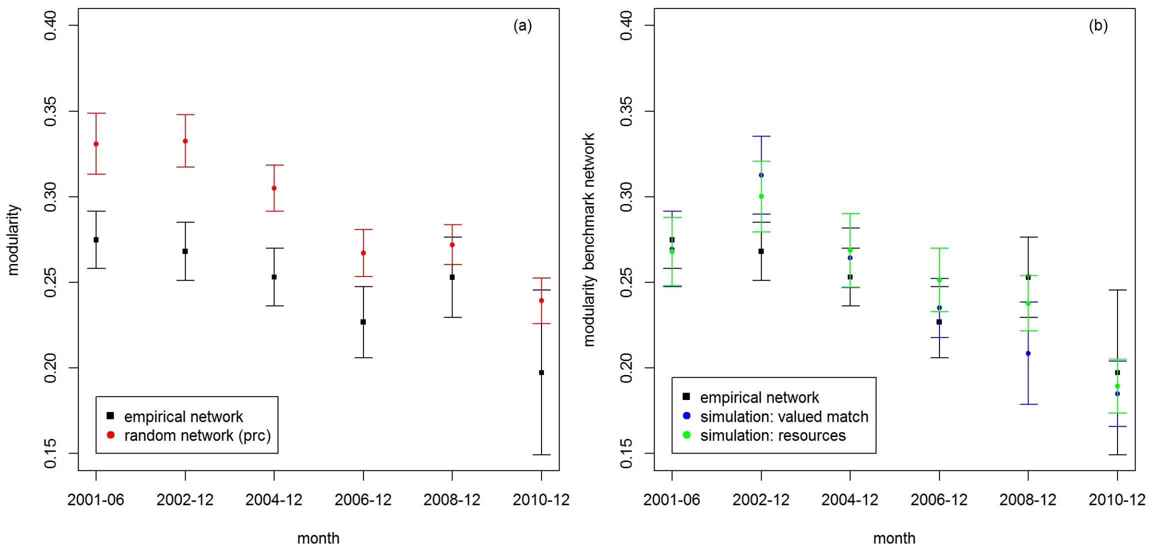

Figure 3.14: The comparison of the modularity of the innovation network (black square) for six different months with the modularity of a random network prc (red points) and two simulation networks, valued match (blue points) and resource-based (green points).

absence of provincial hubs and hubs close to among-module connectivity of 0.8 is a common feature for most monthly observations of the empirical network. This findings raises the question about the strength of the system's modularity.

Figure 3.14 compares the modularity of the empirical network with those of the prc random network (figure 3.14a) and the valued match and resource based simulation (figure 3.14b) for six months over the observations period[9] . As the module detection is a non-deterministic algorithm, resulting in different modules for each run, I apply the modularity detection 100 times for each of the six empirical networks to test for the sensitivity in module detection. The reported modularity values are the mean values of the 100 different detected modularity structures with an error bar of one standard deviation. The values of the empirical network (black squares) around 0.27 is positive and hence shows higher within modular connections compared to a random distribution of ties among the number of modules. However, the values are rather small and fairly

[9] The analysis is restricted to six different months stretching over the observation period as the modularity analysis is very computing time intensive.

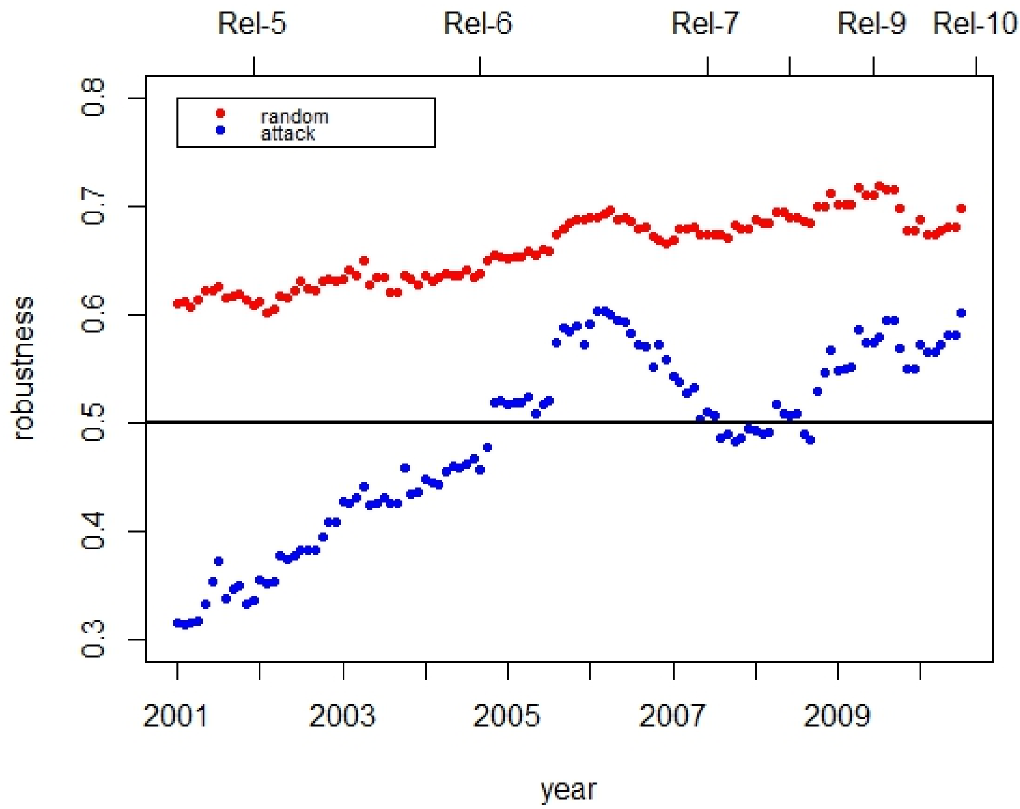

Figure 3.15: The robustness of the networks under removal of innovations with random removal (red points) and attack (blue points highest degree) over the period of observation.

below the range above 0.4, which is perceived as strong modularity. The rather weak modularity is also confirmed by a higher modularity of the random network prc (red data points) for four months and equal modularity (within a range of one standard deviation below and above the mean) for two months. The simulation networks based on valued match and resources reproduce the empirical values within error bars of one standard deviation.

3.4.5 Stability

Robustness

Figure 3.15 shows the robustness of the innovation network over time, both for random removal of innovations and attack with removal of the innovations with highest degree. i.e. large number of supporters, first. The random removal has through the whole period a rather high values between 0.6 and 0.7. The robustness under attack scenarios is in the first years rather low and reaches the threshold of 0.5, which reflects a linear removal of nodes, and is since then above o close to this threshold, showing a high robustness of the network since then. Furthermore the attack scenario is not a realistic scenario in the elimination of innovations. Innovations with a high number of supporters have higher chances to make good progress in their development. It is the low support of innovations and their lack of progress which leads occasionally to the stop of innovations. The figure for removal of organizations is not shown. It is very stable for both attack and random removal with robustness values very close to 0.5 for both scenarios.

Dynamics

The structural properties of the innovation network, basic parameters, degree distribution, nestedness and modularity were already presented for the full period in the previous sections. Overall, the ”global” parameters of the network are relatively stable despite the increase of the number of innovations until 2009 and the number of organizations since 2009, hence changing network size. This stability is remarkable in the density of the network (figure 3.6) and the standardized degree distribution for both organizations and innovations (figure 3.7). The nestedness shows fluctuations around a level of 25 (figure 3.10) and the modularity is rather stable on a level of about 0.25, though there is a stronger decrease in the last observation month (figure 3.14).

The stability on the global network level is summarized in table 3.2, which lists the

	intercept	slope
Number of organizations	82.21***	2.47E-01***
Number of innovations	42.77***	5.22E-01***
Density	0.09***	-3.19E-05†
Nestedness	24.91***	4.36E-03
Modularity	0.29***	-5.68E-04*

*** :< 0.001, ** :< 0.01, * :< 0.05, † :< 0.1

Table 3.2: Results of OLS regression of structural parameters over months

intercept and slope coefficients from OLS regressions for the structural properties over time. The positive and significant slope for the number of organizations and innovations confirms the growth of the network over time. The slope for the density and nestedness is not significant, confirming the stability despite the network growth, while the slope for modularity is negative on a low level and significant on a level of 0.05.

The stability of the innovation network over nearly ten years, though with fluctuations, raises the question of stability on the individual node level. I use the individual nestedness to study the stability of nodes contribution to the nestedness of the network. The individual nestedness is in particular suitable, as nestedness is the key property of network order, which also influences the robustness of the network. The nestedness distribution is rather heterogenous (figure 3.11), where nodes with high individual nestedness are those of most interest.

While innovations change from release to release organizations can and do persist over the observation period and are the focus of figure 3.16. It depicts the percentage that the individual nestedness contributes to the network's nestedness of the six organizations with highest nestedness in July 2001 (Ericsson, Nokia, Siemens, Motorola, Vodafone and Nortel) and in December 2010 (Huawei, Ericsson, Alcatel-Lucent, China Mobile, NSN, ZTE). Ericsson (figure 3.16a) is the only organization that is in the top six in the first and last observation month and kept its top position. Nokia (figure 3.16b) has steadily lost individual nestedness, however if its 50 percent joint venture

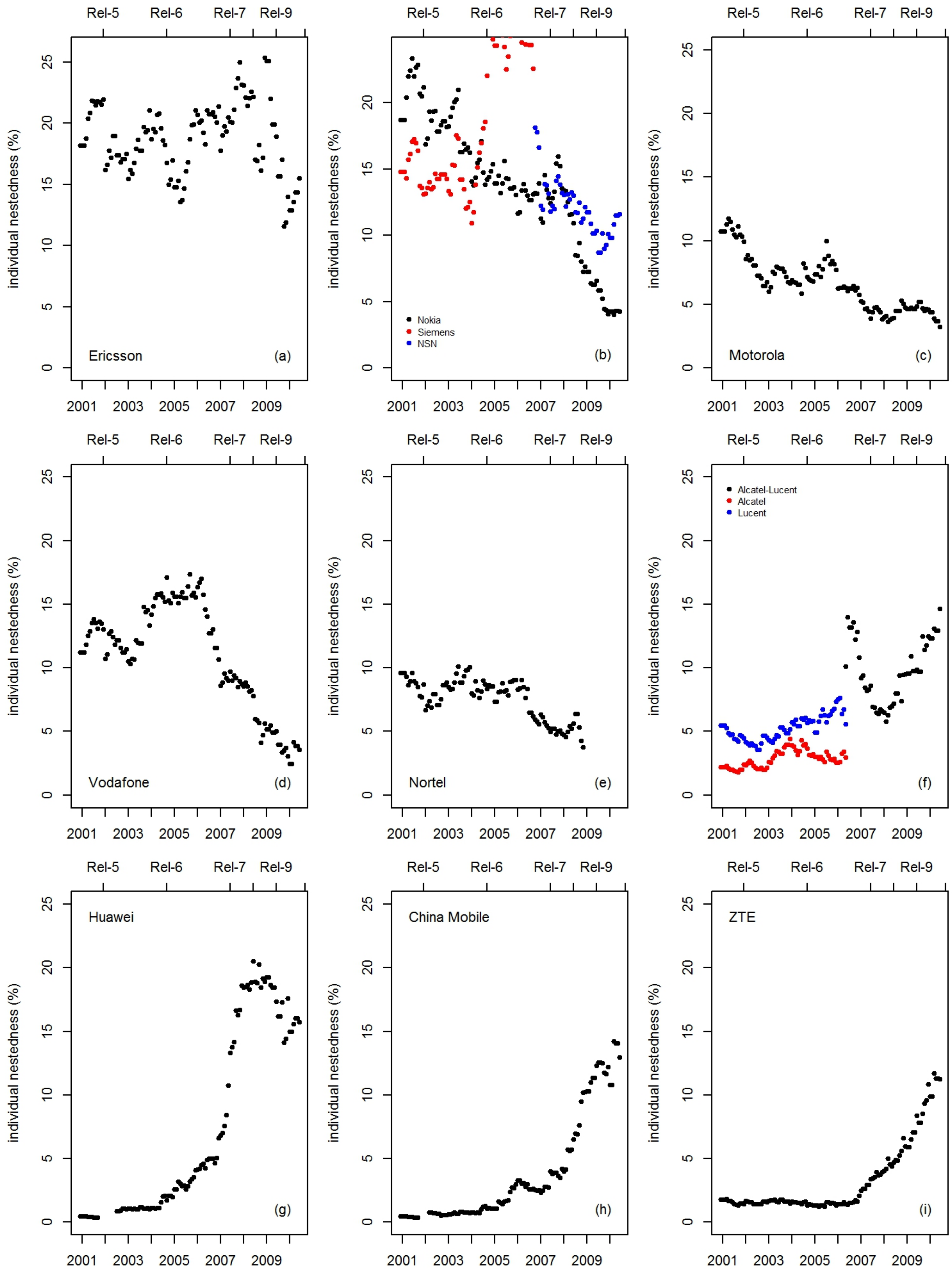

Figure 3.16: The evolution of individual nestedness for selected organizations.

with Siemens, Nokia-Siemens Networks (NSN), is taken into account, it still has a major contribution to the nestedness of the network, while Siemens does not any longer contribute in 3GPP with the formation of the joint venture. Motorola (figure 3.16c) started from a already considerably lower level and decreased its nestedness to about half of its level in July 2001. Vodafone (figure 3.16d), one of the world's largest network operator is loosing nestedness since Release-7, when work on the fourth generation started. Nortel (figure 3.16e) is an example of a firm that indeed got out of business after a steady decrease in its individual nestedness. Alcatel-Lucent (figure 3.16f), a merger between Alcatel and Lucent, entered the top six by combining two high, but not top, nested organizations.

The next three examples are all three from China, two equipment manufacturers (Huawei and ZTE) and one network operator (China Mobile), with marginal to low nestedness in July 1001 after they joined 3GPP end of the 1990s and were in December 2010 within the top six after an enormous catch-up. Huawei (figure 3.16g) had in December 2010 the largest individual nestedness after a very steep increase in the year 2008. China Mobile (figure 3.16h), the now world's largest network operator, as well as ZTE show strong increases of individual nestedness from 2007 onward, the period were the development of the fourth generation started.

This example of these former and/or current top nested organizations demonstrates high dynamics below the rather stable "surface" of the network properties. These are the most extreme examples, where the catch-up of the three Chinese organizations alone leads to the rearrangement of more than 40 percent of the nestedness within four years.

3.5 Discussion

I have developed a model of the innovation ecology in a SDO, a community of organizations without formal hierarchy that jointly develop and evolve a technological standard via a stream of innovations. While this parsimonious model is a simplification of the real world, it offers insights into the complexity of the innovation system, which I put in a broader perspective. First, the conceptualization of the innovation ecology as a mutualistic system explains the emergence of order, second I discuss in how far the framework can be transferred to other contexts. Lastly, I discuss limitations and directions of future research.

3.5.1 The innovation ecology as mutualistic system

I conceptualize the innovation ecology in a SDO as a mutualistic system and develop a model of the emergence of order in this system by applying methods of ecology. The development of this model consists of two steps: In step one, I extend the ecology beyond the participating organizations by including the innovations, in which the organizations are jointly involved and contribute to, as equally important elements. This allows the conceptualizing of the innovation ecology as two-mode network with organizations and innovations as network nodes and mutualistic ties or interactions between them. when an organization contributes to an innovation. In step two, I apply methods of ecological mutualistic network analysis to study the structure of the innovation network and answer crucial questions regarding the emergence of order in this innovation ecology as the form of the order, the underlying process creating the order and the stability of the order.

First, the emerging order takes the form of nestedness, where specialists, organizations supporting only a few innovations, mainly contribute to innovations supported by generalists and analogous for innovations. Nestedness leads to a dense core where generalists are connected among each other and also to a dissassortive behavior where low and high degree nodes are connected, an uncommon characteristic in social networks. The large heterogeneity in the degree distribution of organizations reflects their role in the value chain, where high degree organizations are mainly equipment vendors or network operators with a large end user base. Component providers have a technical more limited scope and hence less opportunities to participate in innovations. Though innovations have a more narrow degree distribution, they show a considerable variation around the mean of about eight, double of the required number of supporters. This reflects a heterogeneity of the innovations and suggests that various types of innovations are simultaneously present. (the question of the evolution of the technological system is addressed in the chapter 4 and 5). The lack of modularity appears to be favorable for the innovation ecology as it avoids fragmentation of the ecology in diverse interest groups. In contrast to innovation ecologies with a technology sponsor as hub a group of nodes, rather than a single member, is highly nested and creates the cohesion of the system. The lack of distinct, rather isolated, compartments or modules underlines that the ecology is more than an assembly of organizations specializing in and contributing to only certain areas of innovation.

Second, the emergence of the structural properties can be well explained by a parsimonious process, the valued match of resources. The valued match process is actually a hybrid between match and resource or abundance as it measures the amount of available resources in each technical area required for the development of the innovation and is actually a n-fold combination of abundance processes, where n is the number of areas of expertise required for the innovation.

Third, the innovation network has a remarkable stable structure over the nearly ten years of its analysis with a stable density, standardized degree distribution, nestedness and modularity despite its growth. Though the nestedness shows fluctuations and some cyclic behavior, it is rather stable on network level over the ten years. However, on the level of individual nodes the picture changes completely with a high variability over time with decline and even elimination in the network or gain of nestedness by either mergers and acquisitions or catch-up from marginal players to top contributors. The catch-up demonstrates the rather openness of the ecology, where an investment in SDO resources is followed by an increase in nestedness, reflecting the underlying tie formation process.

In summary, the innovation ecology in the SDO possesses a nested structure based on a resource-based process, where the stability of the ecology on network level is accompanied by dramatic changes on the individual node level. The emerging order is not that of a hierarchy of nearly decomposable subsystems, where elements of lower order are nested in the elements of the higher order, but elements or nodes of the system are nested across different types of nodes. The nestedness of the system is an example of emergence, "the arising of novel and coherent structures, patterns, and properties during the process of self-organization in complex systems" (Goldstein 1999, page 49) where the interaction of two types of nodes leads to the novel property of the system.

3.5.2 Applicability of the model to other contexts

The successful transfer of the model of mutualistic ecological systems to the innovation ecology in 3GPP raises the question whether a next, less distant, transfer to other social actor-activity systems appears fruitful. In order to answer this question it is worth to summarize the implicit and explicit assumptions of the model.

First, there is a set of actors, a set of potential activities or problems to be solved and capabilities required for the activities possessed by the actors. Though this appears trivial, in case of an emerging industry it may not be clear, who are the actors, what are the problems that need to be solved and what are the required capabilities. The distinction between actor and activity also implies that the decision is made by the actor, while the activity is subject to the decision. Second, the tie between the actor and activity is mutualistic and provides benefits for both. Third, a process of fit or match between actor and activity drives the decision process. This implies transparency on the activities for a given competence field at a given point of time and full eligibility for all actors to participate. This in particular assumes that there are no additional ties between actors or activities that influence the decision of the actors, i.e. the decisions of the actors are independent. Fourth, the process of matched resources assumes an appropriabilty regime that provides benefits based on the contributions to the activities. It also assumes that these contributions are measurable and transparent. Fifth, it assumes broad-scale capability profiles with a spectrum of actors ranging from many specialists to few generalists.

Though this is a stringent list of assumptions, which will seldom, if at all, be met in reality, it is more about whether these assumptions are met to a large degree. In the example of 3GPP the formation of 3GPP facilitates the first assumption and its mission of standard development the second and broad-scale profiles satisfy the fifth assumption. While 3GPP also provides transparency and eligibility, the condition of no further influencing ties among actors is not fully met, however I argue that these ties are less important than those of interest. Similarly for the fourth assumption, while there is an IPR regime that supports appropriability, there are other mechanisms as market success, where the SDO participation is only one of many elements.

An example to which the model may apply are consulting firms. They have a given order, however are less hierarchical than large traditional firms. The boundary of the consulting firm defines the actors, consultants, project leaders and partner, the activities in form of consulting projects, and competencies as industry expertise or practices. The tie provides benefits for both sides as actors need to be involved in projects and projects need actors. There may not be full transparency and full choice, and yet staffing will be largely based on the fit between the task and the capabilities and potential friendship or competitive relations may not dominate the decisions in a professional environment.

The assumption of broad-scale capabilities is imperfectly given with three types of roles with increasing generalist capabilities from consultants over project leaders to partners. On project side this assumption is given with different types of projects with small size projects dominating. While the emerging structure of membership in customer projects is not the official structure in a consulting firm it may have important consequences for the knowledge flow and cohesion within the firm.

In the case of changing, converging and new industries due to technological change or new challenges as sustainability the most important step is the formation of an organizational frame that defines the actors, activities and capabilities. While for established industries and problems existing industry associations can perform this task, these may not exist for new or changing industries or compete for the lead. The case of cellular telecommunications was a changing industry with transition from analog to digital technology and the standardization started with a loose association of European operators, and a crucial step was the formation of the European Telecommunications Standardisation Institute (ETSI) by the European Commission (EC), the predecessor of 3GPP for the second generation development.

The establishment of a home for the innovation ecology can be seen as the very first task of public policy. A current example of converging industries is the ongoing development of *smart grids*, the future, more efficient electrical grid. In Europe the development of smart grids is embedded in the EC's long-term roadmap and strategy. Five focus areas were identified: standard development, consumer data protection, a regulatory framework for incentives, an open retail market, and innovation support (EC 2011). The activities of the European Union include the bridging of industries. "The Commission will continue bringing together the energy and ICT communities within an expert group to assess the network and information security and resilience of Smart Grids as well as to support related international cooperation." (EC 2011, page 9). In the US smart grids are part of federal policy, which includes the creation of a grid modernization commission and the development of standards by the National Institute of Standards and Technology (Wikipedia 2012).

A case of a new cross-disciplinary technology that impact multiple industries is nanotechnology. It is mainly defined via the size of the objects it deals with in the range of nanometers, one to 100 billionth of a meter, the size of atoms and molecules, including technical and biological structures as microchips, neurones and genes, rather than being a scientific discipline in itself (Bozeman et al. 2007). Nanotechnology is seen as a new general purpose technology that may drive the next wave of Schumpeterian innovation (Mangematin and Walsh 2012). Allarakhia and Walsh (2012) saw in their analysis of several nanotechnology consortia on national, regional and global level an apparent government role in several consortia, including the involvement of the European Union and its research programs, the National Science Foundation in US and national governments as catalysts. Based on drivers as knowledge and technology complexity the consortia objectives vary among knowledge sharing, technology development, product development support and stakeholder linkage. Stakeholders can be universities and research institutes, government agencies and firms. The cross-disciplinary, pan-industrial nature of nanotechnology provides a particular challenge in providing a home for activities. It may need a system of orchestrating ecosystems, where each addresses a certain function, a similar approach as the EC has chosen with the focal areas for smart grids.

3.5.3 Limitations and directions for future reserach

While this study looks promising in the endeavor of understanding ecologies of complex innovation, it is a very first step with a number of limitations.

One limitation is the dichotomy of the innovation network as it does not allow to distinguish between organizations that contribute only marginally and those that are the power horses in the development of an innovation. The same applies to innovations, which range from incremental extensions to existing functionality to radical innovations in the transition from the third to the fourth generation and required contributions will largely vary. Furthermore, innovations are assumed to be exogenous, while they come into existence via proposals by organizations and hence there is a dependence between the two types of nodes. I also ignore direct relationships between organizations and innovations, while in reality customer-supplier or competitive relationship exist, collaborative ties via alliances or embeddedness in local environments. Also innovations are related, in particular over time, where a new service as location based service is enhanced over time creating a sequence of innovations over time. While the research context of SDO with rules to facilitate knowledge mobility and IPR appropriability is ideal to focus on structure and stability, it is also a limitation. First, the study covers only one SDO and may not be representative for other SDOs, second, more critical, the specific environment does not allow to transfer these results to other inter-organizational ecologies.

In addition, the nature of this study with the transfer of a research approach and agenda from one discipline to another is rather broad. The findings of this study point to directions of future research. Within 3GPP's context the study of SDO resources as combinations of valued match, the refinement of measures matched profiles and the understanding, whether the lack of full agreement of simulations and empirical data is based on measurement or the process are potential future directions.

In a more general framework the understanding of the sensitivity of the resulting network structure on the technological profiles is important. How important is the specialist-generalist distribution of capabilities to achieve the resulting structure? Is there a key difference between one generalist and ten generalists — for actors and for activities? The answers to these questions may answer the question of key differences between sponsor-orchestrated networks and SDOs. They may also provide insights on the importance of the simultaneity of narrow and broad innovations in the emergence of order.

The assumption of independent choice of activities by actors is often not met in reality. The study of two simultaneous processes, capability match and additional attracting or repulsing forces will make the model applicable in a broader context.

3.6 Appendix

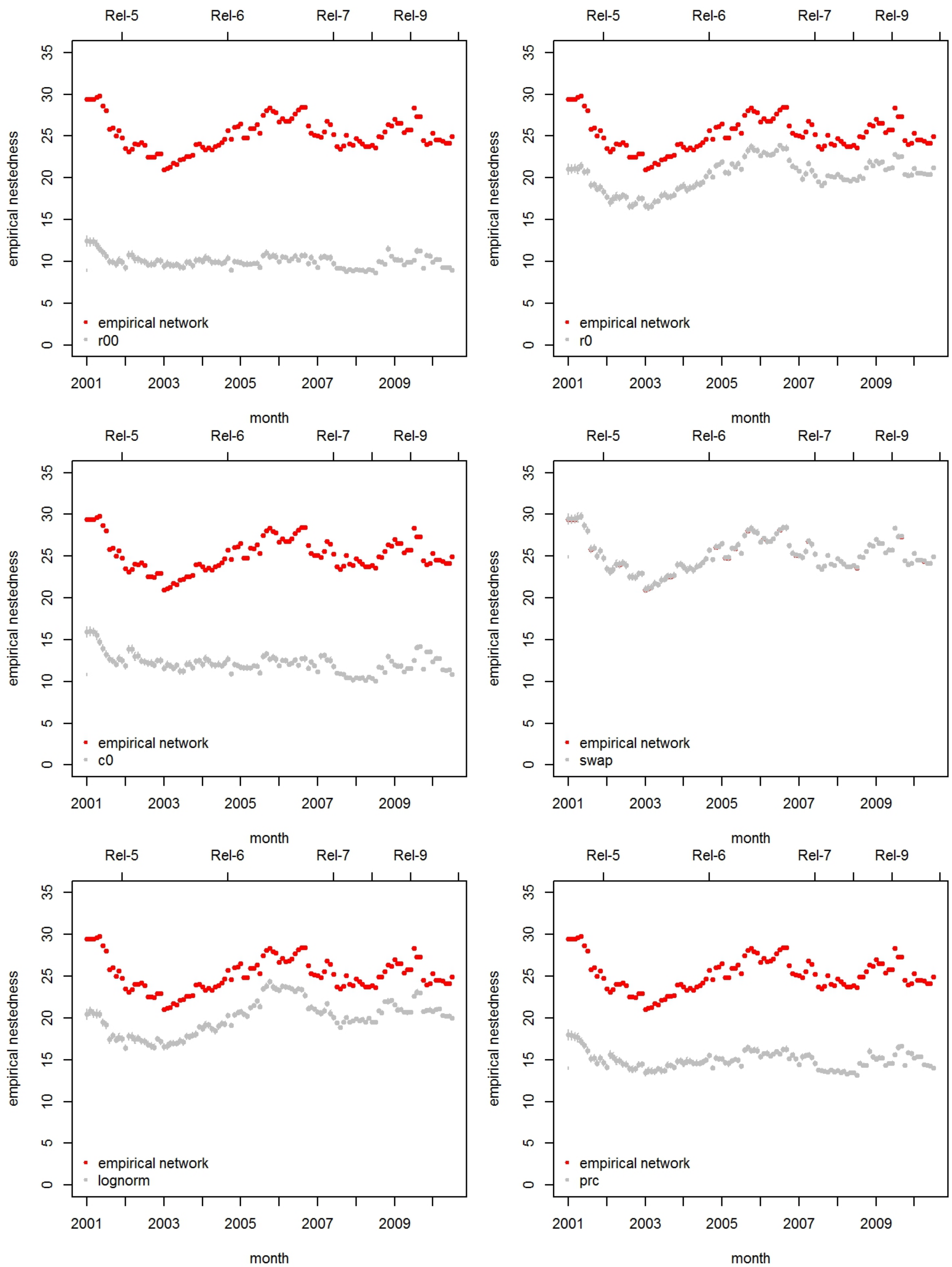

Figure 3.17: Nestedness of innovation networks and six different types of random networks.

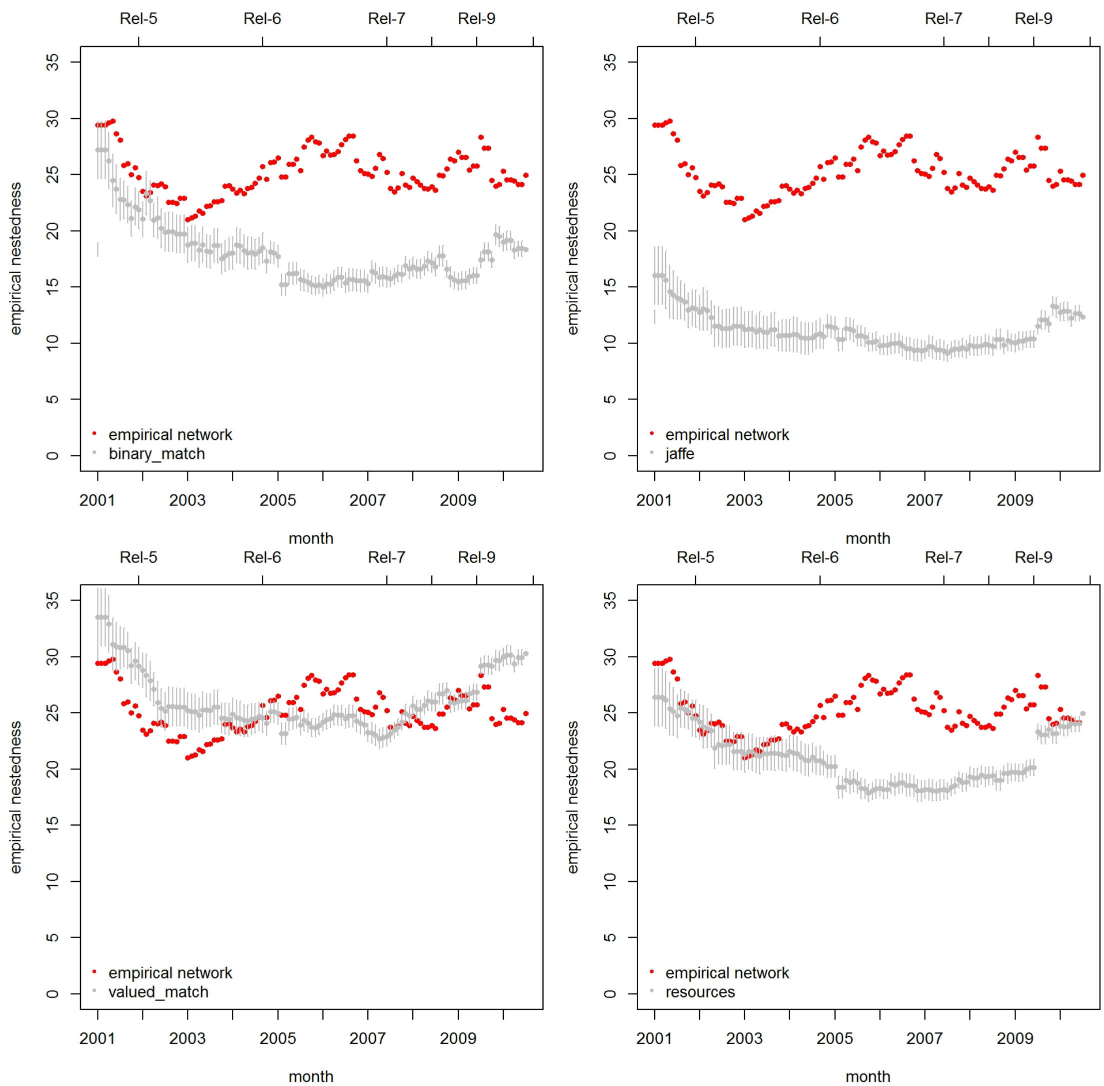

Figure 3.18: Nestedness of innovation networks and four different types of simulation networks.

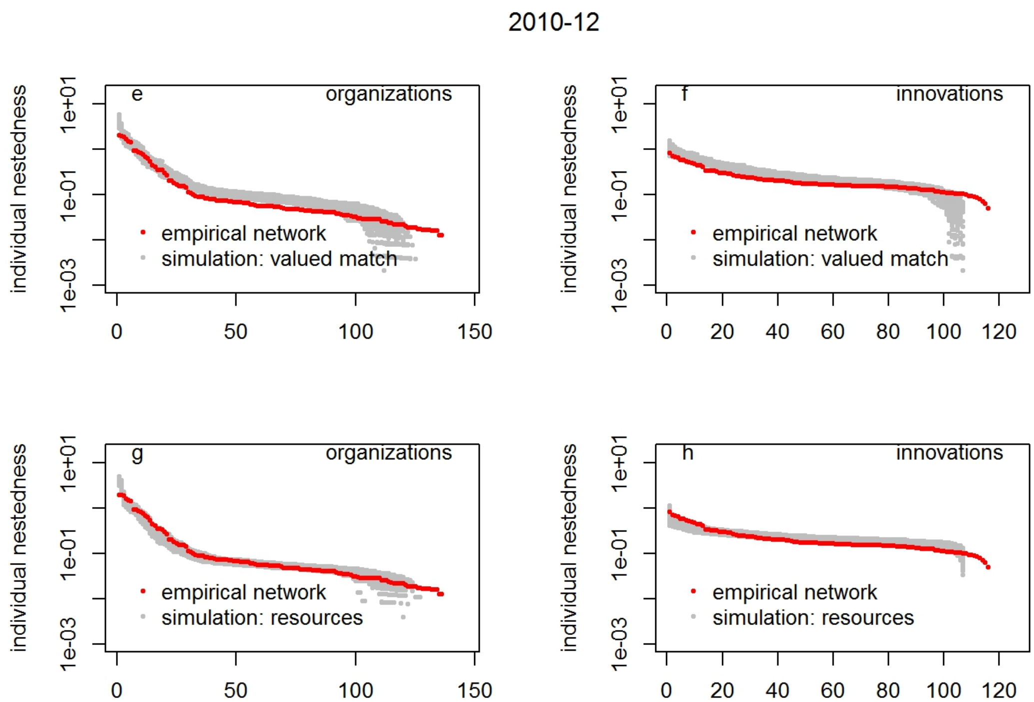

Figure 3.19: Comparison of individual nestedness four different types of simulation networks and the empirical network for December 2011.

Chapter 4

Evolution of Modular Systems — from a Life Cycle to a Life Spiral Model of Technological Change

4.1 Introduction

This study intends to understand the evolution of complex open modular systems through an organization-based standard setting process. The increasing appeal of modularity as a design concept for complex technological systems (Campagnolo and Camuffo 2010) lies in the near-decomposability of modules and the resulting reduction of complexity (Simon 1962). The decoupling of modules and the hierarchical structure of nested subsystems leads to a larger number of possible combinations increasing the pace of innovation (Baldwin and Clark 1997, 2000; Sanchez 1995). The economies of substitution where the reuse and replacement of modules allows the retention of existing knowledge, enhances the system performance (Garud and Kumaraswamy 1995). The technical system is complemented by an organizational system of decentralized networks of actors (Langlois and Robertson 1992) that provide the framework for coordination and competition to create open standards. I ask the question: how do complex modular open systems evolve in an organization-based standard setting and whether such evolution modifies the technology life cycle?

The evolutionary models of technological change primarily focus on the development of a product class or a complex product based on the emergence of a dominant design. For instance, the product life cycle model (PLC) (Abernathy and Utterback

1978; Suarez and Utterback 1995; Utterback 1994) presents the dynamics of product and process innovations in three consecutive phases: the high rate of radical product innovations sharply decreases after the emergence of a single dominant design, the dominant design triggers a substantial increase in the rate of radical process innovations, which is followed by a more balanced rate of incremental product and process innovations. Similarly, relying on evolutionary processes of variation, selection and retention, the technology life cycle (TLC) model (Anderson and Tushman 1990; Tushman and Rosenkopf 1992; Tushman and Murmann 1998) posits that the selection of a dominant design begins an era of incremental change (retention) that will eventually result in a period of radical change (variation), which opens up an era of ferment characterized by competition between old and new technological regimes (substitution), as well as within new technological regime (design competition), leading to a new dominant design (selection). Despite their differences, the underlying principle of these salient life cycle models is that industry or product class standard is set by market forces as the emergence of a dominant design is primarily based on rivalry among competing firms. This perspective, in line with theoretical work in industrial economics, focuses on standard setting by markets (Leiponen 2008).

This study departs from this perspective and focuses on setting industry or product standards through SDOs. The mechanism for setting standards by SDO differs from market-based standard setting as the evolution of technology and emergence of a standard is influenced by a network of actors, where none dominates the technological agenda. Hence, the evolution of new standards, whether those related to the technological system, subsystem, or components (Murmann and Frenken 2006), or those related to core designs or their linkages (Henderson and Clark 1990), are not influenced merely by market uncertainty and rivalry, but are affected by organized, cooperative interactions of the actors. This approach to standard setting gives weight to "social logic" stimulated by actors within the SDO rather than to "technical logic" merely provoked by actors in competing organizations (Tushman and Rosenkopf 1992, page 332). SDO represents an inter-firm organizational form - an organizational form governing inter-organizational interactions among interdependent firms - for choosing an industry-wide technological architecture.

I argue that in an organization-based standard setting the standard emerges at an early stage (pre-product stage), the eras of ferment and incremental change overlap, and are characterized by innovations in both core concepts and linkages between core concepts (Henderson and Clark 1990). A following technological discontinuity is based on these innovations and is the result of a continuous, coordinated search process rather than a random, chance event motivated by rivalry among competing firms. That is, whereas standard setting through market forces results in winners and losers via the emergence of a dominant design by one rival, standard development through organization enables the evolution of a standard accessible to all rivals. The change from a market-based to an organization-based standard setting process creates a new evolutionary model, which I call the life spiral model (LSM).

I study the role of SDOs in the evolution of the second and third generation of the cellular telcommunications standard GSM (Global System for Mobile communications). Cellular telecommunication systems are a prime example of a technology featuring network externalities and the need for compatibility standards in order to reap economies of scale (David and Steinmueller 1994). As standardization by organizations has increasingly gained scholars' attention (Chiao et al. 2007), the implications of this study may stretch beyond cellular telecommunication to other complex infrastructural networks such as utilities, or even a more expansive system such as transportation including the automobile industry. Conceptually the study draws from the literature on system and modularity theory describing the architecture of complexity, product architecture and complex open systems (Baldwin and Clark 2000; Murmann and Frenken 2006; Simon 1962; Ulrich 1995), product and technology life cycle models (Abernathy and Utterback 1978; Tushman and Rosenkopf 1992), and standard development by committee or organization (Besen and Farrell 1994; Chiao et al. 2007; Tassey 2000). In the next section, I first review the extant literature in these three areas of study and then develop propositions. The study's context, the cellular telecommunications industry and its SDO, the data, and methodology are presented next. Finally, I present the results of the analysis and discuss their implications for future research.

4.2 The Life Spiral Model

As the purpose of this study is to examine the evolution of complex open technological systems, I use the framework of modular systems and their characteristics to explain the process of technological change through SDOs. I use the product/technology life cycle model as a starting point and analyze how modularity and economies of substitution impact technological change.

4.2.1 Product/technology life cycle

The description of product or technology development in the evolutionary models follows the pattern of variation, selection, and retention. The life cycle is triggered by a technological discontinuity. "Technological discontinuities are those rare, unpredictable innovations which advance a relevant technological frontier by an order-of-magnitude and which involve fundamentally different product or process design" (Anderson and Tushman 1990, page 613). The discontinuity can be either competence-destroying, leading to obsolescence in the competencies of the former technology or competence-enhancing, building on these competencies (Tushman and Anderson 1986). The discontinuity leads to high innovation activities and competition among variations in product designs (the era of ferment). This period is characterized by high levels of technological and market uncertainties. There is strong competition between old and new technologies, and among designs along "functional dimensions of merit that is, which technological characteristics are important and which design is superior in delivering performance (Clark 1985). With the emergence of the dominant design the technological uncertainty is greatly reduced and the era of incremental change begins. In this era, the dominant design is refined by incremental innovations and common procedures and norms are developed within the industry. With a new technological discontinuity, the next cycle begins.

Tushman and Rosenkopf (1992) further elaborated the technology cycle model, taking into consideration the complexity of the technology and its interaction with the sociopolitical environment in which it is developed. They argued that the emergence of the dominant design is not only based on technological performance, but is primarily a sociopolitical process that spans a variety of non-technological factors within and between organizations. The sociopolitical influence "is shaped by a process of compromise and accommodation between suppliers, vendors, customers and governments" (Tushman and Rosenkopf 1992, page 322). The emergence of the dominant design facilitates the development of common routines and problem-solving approaches within this community. Open systems have the highest complexity and are strongly influenced by non-technical (social, political, organizational) dynamics. In this context, "open" characterizes that different components of the system are provided by different firms. For an open system, the emergence of the dominant design is the beginning of incremental change caused by "technical and social" inertia (Rosenkopf and Tushman 1998), which is required to guarantee standardized products from a multitude of firms.

However, despite acknowledgement of different mechanisms of standard-setting, defacto standards driven by market selection play the dominant role in the life cycle literature and the empirical studies of dominant design (for an overview see (Murmann and Frenken 2006, pages 926:931). This dominance is portrayed by research focus on the battle between standards (Shapiro and Varian 1999; Soh 2010; Suarez 2004; Windrum 2004) and is illustrated by frequent citations of the examples such as the typewriter keyboard QWERTY versus Dvorak, VHS versus Betamax video recording technology, AC versus DC power supply system, OS-2 versus Windows operating systems, and Blu-Ray versus HD DVD systems in academic articles, textbooks, and business press. In the life cycle literature the framework of product as system and modularity in product architecture have been used to explain the emergence of dominant design (Henderson and Clark 1990; Murmann and Frenken 2006; Tushman and Rosenkopf 1992; Ulrich 1995). For example, Murmann and Frenken (2006, page 931) considered products as "complex artifacts that evolve in the form of a nested hierarchy of technology cycles." Tushman and Rosenkopf (1992, page 321) stated that dominant design for simple (non-assembled) products emerge from technological logic, while that for complex (assembled) products emerges from "sociopolitical processes within and between competing technical communities and their contexts". Powerful producers or users, R&D consortia or strategic alliances, and ad hoc industry or government sponsored committees influence the emergence of technological standards. Thus, the evolution of industry-wide standards is based on competition between firms, technologies, and producer or user dominance. The standard setting via SDO provides an alternative, where the evolution of complex open systems is based on continuous cooperation among all major players.

4.2.2 Standard developing organization

De jure standard setting is suitable for developing standards for complex open modular systems within networks by providing an organizational system for the given technological system (Garud and Kumaraswamy 1995). The existence of an independent SDO, which is supported by both of the industry and government, allows resolving the issues of interface incompatibility between competing systems efficiently. The large number of components and subsystems, coupled by multiple interactions between and within subsystems, requires a coordinated approach in developing new standards. Moreover, in the context of complex open modular systems, radical and incremental innovations cannot be neatly separated in the evolution of the product class and the dichotomy of product and process innovations is inadequate because different innovation types co-exist and are developed in tandem. In this vein, the notion that the emergence of a dominant design ends the 'fluid phase' and begins the 'transitional phase' (Abernathy and Utterback, 1978), or ends the 'era of ferment' and begins the 'era of incremental change' (Anderson and Tushman 1990), is not applicable. It is possible that the rate of product innovation is consistently high (Davis and Greve 1997), the era of ferment and the era of incremental change overlap, or search processes for dominant design are continuous (details below). The evolution of a standard is more reflective of this situation than the emergence of a dominant design, suggesting that the evolutionary cycle of technology development, and technological and organizational architectures that govern that, could be different.

4.2.3 Life spiral model

The life spiral model of technological change is the life cycle model adapted for complex open modular systems with network externalities in SDO environment. I offer that both system complexity and network externality provide incentives for coordination through SDO. Complex open modular systems face high technological uncertainty as the interdependencies of the subsystems requires the involvement of multiple players in solving technical problems. The system's complexity also leads to high R&D costs for the manufacturers and substantial capital investments for the users. The high costs prohibit firms from developing products alone in anticipation of a positive market decision. Therefore, the complexity of open modular systems provides a strong incentive for coordination on pre-product, anticipatory standards to reduce the technological and commercial uncertainty (Axelrod and Mitchell 1995; David and Steinmueller 1994; Garud and Kumaraswamy 1995). Network externalities, on the other hand, increase the value of the system with rising numbers of users. To reap benefits of the externalities, coordination among the players is also necessary. Compatibility standards, either de facto or de jure, are the means to achieve such coordination as they necessitate reaching agreements on how components of a technological system interact (David and Steinmueller 1994; Leiponen 2008).

Standard setting through SDO becomes an unavoidable choice where no player is sufficiently strong to bet setting the standard merely through market competition (Farrell and Saloner 1988). The improvement of system-level performance by coordination through SDO will guide an evolutionary approach, on both the system and sub-system-levels, supported by SDO's established coordination mechanisms and governance processes, and helping overcome technological inertia of an uncoordinated approach in standard setting. As Garud and Kumaraswamy (1995) argued, upgradeability and integrity of the system's initial design convey that the existing functionalities are not yet at their performance limit, new functions can be added easily without compromising the existing functionality, and smooth integration of the new and existing functions can occur. The complex open modular systems in the SDO environment fit this set of conditions. First, full functionality of a system cannot be configured initially due to its complexity. Second, because of involvement of a variety of players from different domains, the SDO has more knowledge to master the cognitive complexity and decouple the functions in an efficient way than any player. Third, the costs of standardization, which can be prohibitively high for a single firm, are shared by a larger community.

The LSM follows the same fundamental logic of variation, selection and retention of the technology cycle model and its evolution over time. However, because of the system's modularity, focus of each stage differs. I propose that the evolutionary process in LSM is characterized by: (1) pre-product specification and continuous search activities; (2) standard as retention mechanism for enhancement; and (3) co-existence of old and new dominant designs.

Pre-product specification and continuous search activities

In the SDO environment compatibility standards are specified before the system components are physically designed and produced (Weiss and Sirbu 1990). The pre-product specification has three implications: first, the selection is based on technical principles rather than product designs; second, the standard is sufficiently developed to enable its implementation; and third, the standard is developed without early market feedback on manufactured products.

The development of a standard through SDO can be seen as an early phase of the R&D process (Weiss and Sirbu 1990). The choice is made from a few technical principles rather than from products designed on a multitude of different possible combinations. The size of the "design space", the choice set of possible permutations of technological choices (Murmann and Frenken 2006), is reduced early in the process, which, in turn, reduces variations. For example, in the hypothetical development of the automobile through SDO, the choice of engine will be made from a set of different technical principles (e.g., combustion, steam, and electrical) and only one will be further developed. If the combustion engine is selected, for instance, automobiles with steam or electrical engine will not likely be developed. The first set of specifications selected by the SDO defines the standard of the system. The standard serves as the basis for the implementation (i.e. development of physical components) by manufacturers. To guarantee compatibility between components made by different firms, the standard should be sufficiently mature and should define the details such as characteristics of components based on the selected technical principle. Whereas design competition among vendors continues, the competing designs have to comply with the standard. Hence, in contrast to the market-based era of ferment, there is no room for variation on the details during implementation. However, the major stakeholders including manufacturers and industrial users participate in the SDO and influence the selection of the standard according to their priorities (Rosenkopf et al. 2001; Weiss and Sirbu 1990). As such, the selected standard suffices the needs of both manufacturers and users to reflect a common understanding of technological feasibility and market needs.

However, despite the early reduction of uncertainty from both technological and market perspectives, the pre-product specification has limitations. First, the restriction of the design space and the required early elaboration of the selected standard may lead to focus on basic system functionality due to resource limitation. Second, high complexity may limit the number of functions in the standard. These limitations will in turn lead to a relatively limited set of dimensions of merit (Clark 1985) or unused degrees of freedom (Garud and Kumaraswamy 1995). Third, lack of market feedback requires an anticipation of market needs and an ex-post evaluation of the fit of market needs and the standard. Fourth, the systemic nature of the technological system guides further development for the improvement of performance of the system, the "salients" (parts with performance above system performance), and the "reverse salients" (parts with performance below potential system performance) (Hughes 1992). These limitations drive continuous search activities after the emergence of the standard to enhance both core and peripheral features of the system.

The standard as retention mechanism for enhancement

In the product/technology life cycle literature, after the emergence of the dominant design the building of technical and social inertia is seen as a consequence of necessary routine and norms within the increasingly inter-linked community in order to achieve reliable standards (Rosenkopf and Tushman 1998; Tushman and Rosenkopf 1992). In SDO environment, the standard itself is the retention mechanism, not the routines and working procedures that lead to it. The approval of a set of specifications as standard automatically provides retention as the specifications are binding; that is, each physical component produced by any manufacturer should comply with the standard. The shared values, beliefs, and norms within the SDO community (Pelkmans 2001), coupled with the coordination by SDO at the system-level, drive the enhancement of the standard triggered by new search decisions to continually add new functionalities while retaining the integrity of the system. The potential inertia within SDOs (Farrell and Saloner 1988) is overcome by the ongoing search process. In addition, competition either among the players within the SDO or between different technologies further triggers search activities. Search activities will take place based on the existing set of specifications (the retention mechanism), and changes will be mainly additions to the existing standard while preserving prior specifications. The standard thus establishes a platform for further evolution of the system.

The near decomposability and upgradeability property of complex open modular system allows enhancement of the system and improvement of its performance while retaining its integrity (Baldwin and Clark 2000; Clark 1985; Garud and Kumaraswamy 1995). First, the hierarchy of the system, where a higher-order component is improved by changes in the lower-order systems, will enhance the existing modules by evolving them toward their performance limit. Second, the existing components are replaced ("substituted" in the language of Baldwin and Clark, 2000) when they reach their performance limit. The replacement is achieved by discontinuities in the lower-order systems while retaining the integrity of the higher-order systems. Third, due to the near decomposability, the addition of new components ("augmenting") will have limited impact on the existing system. This limited impact leads to a decoupling of the "genotype" (the level where mutation or change occurs, Murmann and Frenken (2006) of the new and the existing parts of the system, resulting in a small number of changes in the functional level of the existing parts (low "pleiotropy" in the language of Murmann and Frenken (2006). Overall, whereas the search process continuously adds components and interfaces to the system, decomposition allows the introduction of new functionality (via both new components and interfaces) without destabilizing the existing system.

Proposition 1. *In the SDO environment, after the emergence of the standard the technological system is continuously enhanced by new components and interfaces while preserving prior specifications.*

As stated earlier, in SDO environment the era of incremental change (retention) overlaps with the era of ferment (substitution). This property allows technological change without a need for disruptive innovations to obsolete the existing knowledge (Garud and Kumaraswamy 1995). For most industries in their sample, Anderson and Tushman (1990) found that only about 20% of performance improvement can be attributed to the era of incremental change. In the SDO environment, on the other hand, the active search process, triggered by the overall system performance and search in the direction of both salients and reverse salients (Hughes 1992), can lead to substantial increase in the system's performance. The reuse of components allows to keep the existing knowledge and to build on it for steady increase in performance. The performance enhancement based on the existing technological regime is achieved by the three mechanism described above enhancement of existing functions, substitution, and augmentation and is a direct consequence of the basic notion of system upgradeability and unused degrees of freedom. Therefore, the complexity of open modular system is contained by the development of a relatively simple standard (rather than a disruptive standard) that is upgraded by innovations in components and interfaces to increase the performance of the technological system steadily rather than discontinuously.

Proposition 2. *In the SDO environment, after the emergence of the standard the performance of the technological system shows a steady strong increase rather than intermittent stagnation and surge.*

Co-existence of old and new standards

According to life cycle models, a technological substitution occurs when the new dominant design's dimensions of merit surpass those of the old dominant design. Whereas this sequence of technology cycles over time can apply to complex stand-alone products, it may not be suitable for complex open systems in SDO environment. An important element of economies of substitution is the reuse of existing components to provide continuity for customers and enable the suppliers to rely on existing knowledge and cope with a high pace of innovation (Garud and Kumaraswamy 1995). Furthermore, the technological systems with complex infrastructure networks (Davies 1997) are normally in the capital-intensive industries with rather long lifetime of the equipments. Compatibility of the new standard with the legacy equipment is thus a requirement for substitution. For instance, in the currently evolving standard setting for a new electrical grid system smooth transition to and coexistence with the legacy equipment are essential (EPRI 2009). Hence, in complex open modular systems performance based on the old standard can continue to increase after the emergence of the new standard until the old standard reach its performance limit. The performance superiority of the new technology does not necessarily result in the substitution of the old technology as suggested by the life cycle models (Anderson and Tushman 1990; Foster 1986). The old standard might also benefit from augmentation of the system by adding new functions, which may equally complement both old and new standards. Therefore, for complex open systems the new and old standards can co-exist and the old standard will continue to evolve.

Proposition 3. *In the SDO environment, the emergence of a new standard does not obsolete the old standard as the technological system based on the old standard continues to enhance.*

Standard development process in SDO environment

The above definitions and arguments culminate into a three-stage process for complex modular systems in SDO environment. Rather than four stages of the technology life cycle model technological discontinuity, era of ferment, dominant design and era of incremental change the process includes three stages, with one event (search - variation), one activity (selection - elaboration), and one outcome (standard - retention). The proposed process is shown schematically in Figure 4.1, where the 'diamond' represents the search trigger leading to variation, the 'arrow' depicts the selection and elaboration activity, and the 'box' represents the resulting standard that serves as retention mechanism and platform for further evolution.

As stated earlier, the proposed process follows the scheme of variation, selection, and retention, but with different dynamics. Variation is triggered by search rather than chance. The search is guided by the perception of future market needs, anticipated by the members of the SDO, and is based on the existing system with its salients and reverse salients. After a search decision, either for a new function or higher performance of the existing functions, different technical principles are analyzed. The selection will then be based on comparing and contrasting a limited number of technical principles, focusing primarily on the elaboration of the pre-product specifications. The approval of the resulting detailed specifications defines the standard and serves as the retention mechanism. The standard is the basis for the implementation of the real physical

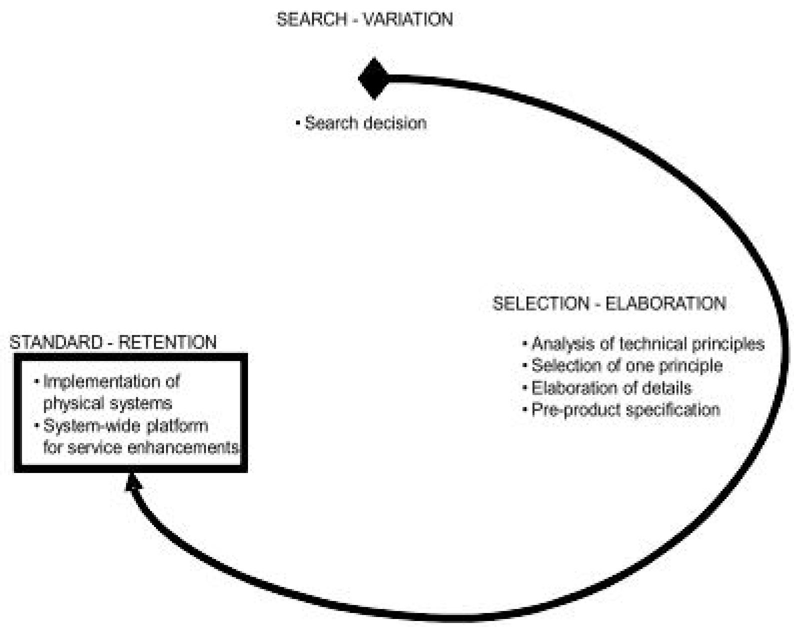

Figure 4.1: Standard development process in SDO environment.

products and serves as a platform for further evolution of the technological system. The search — variation in the Figure 4.1 model can, but need not, lead to a technological discontinuity. The elaboration-selection includes the eras of ferment and incremental change of traditional PLC models. Standard — retention is the result of the selection — elaboration activity and is a retention mechanism for the standard rather than a mechanism for the development of common routines and norms.

In SDO environment, the next search trigger is based on the existing standard and begins a new cycle that includes both refinements and enhancements of the existing functions and the development of new functions with a mix of enhancements and reuse (substitution and augmentation). The fundamental distinction with the technology cycle model over time is that the era of ferment of the new cycle overlaps with the era of incremental change of the current cycle. These continuous, simultaneous processes will form an upward moving and outward reaching spiral indicating the extended system architecture and improved system performance (Figure 4.2). In Figure 4.2, the 'diamond'

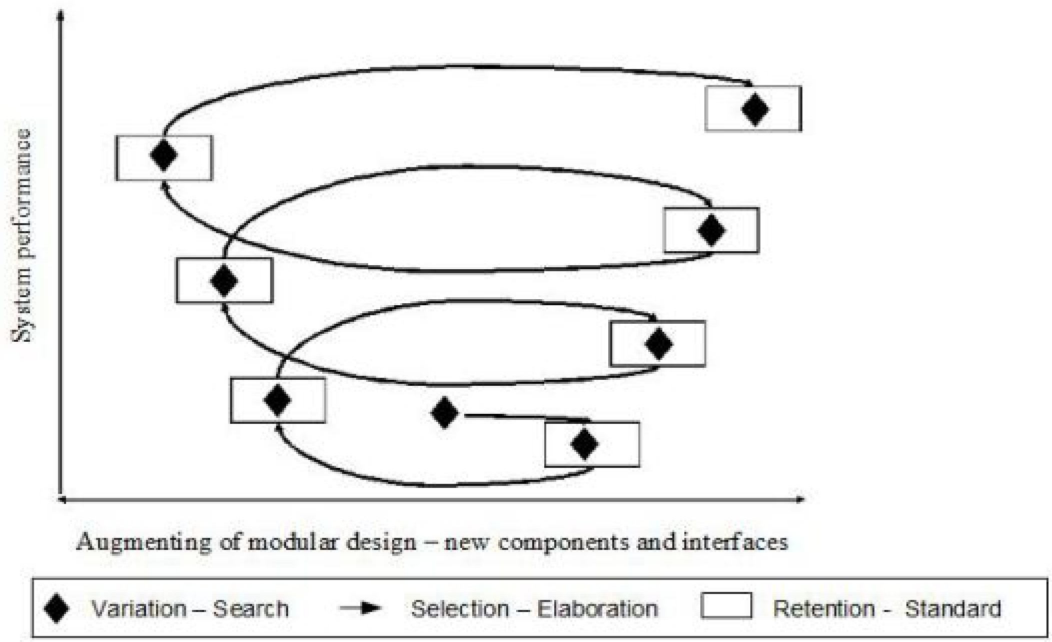

Figure 4.2: Standard development in SDO environment over time.

within a box symbolizes the new search decision based on the latest set of specifications and the 'arrow' represents the selection among technical principles and elaboration of new functions that result in a new set of specifications, the new standard.

4.3 Data and Methods

I studied the role of the ETSI and the 3GPP as standard developing organizations in the development of the second and third generation GSM technologies in the cellular telecommunication industry.

4.3.1 Cellular telecommunication industry

The telecommunication system is a prime example of a complex technological modular system with network externalities. Cellular telecommunications further increased the telecommunication system's complexity by adding the radio network to the core network, enhancing the systemic character of the technological system. In the first generation cellular systems transmission was analog and the base station and switching systems were connected by technical interfaces controlled by individual suppliers (Davies 1997). In the second generation, the transmission of voice and data was changed from analog to digital. Contrary to the first generation systems that were proprietary, at the national levels with a rather small group of users, the second generation technology (GSM or 2G in the following) in Europe was developed for the entire continent. The 2G technology entered the mass market in early 1990s, allowing a study of its full evolution and shift to the third generation technology (3G). I chose the GSM standards, rather than the CDMA standards (CDMAOne and CDMA2000), as both 2G and 3G have been well documented from the beginning and have a worldwide market share well above 50 percent. Also, the GSM system's initial design satisfies the basic assumption of upgradeability that underlies the model of technological change.

4.3.2 Standard developing organization

ETSI, representing the operators and manufacturers of the cellular telecommunication system, was responsible for developing technical standards with the support of EU member nations for 2G (Davies 1997). In year 1999, 3GPP took over from ETSI the responsibility of developing standards for 3G, as well as the maintenance of 2G (3GPP website: About 3GPP home)

Leiponen (2008) and Ansari and Garud (2009) view the shift from 2G to 3G as a technological discontinuity. According to the proposed model (Figure 4.2), this shift represents a change from an old to a new standard. This change in standard coincides with a change in the SDO governance with the transition of leadership from ETSI to 3GPP, and opening of the SDO from a regional (Europe) to a global (North America and Asia as well) partnership. The sample, therefore, includes two standards: the first standard defined with the first 2G release (2G-0), and the second standard defined with the first 3G release (3G-0). Table 4.1 provides an overview of all 2G and 3G releases, the date of each release, the original release name by the SDO, and the release names assigned in this study to reflect the standard and chronological order of its releases.

3GPP's technical work is mainly conducted by work groups. Work groups elaborate technical specifications primarily through collaborative contributions of the individual members. The standards are then endorsed by the organizational partners based on the technical specifications (3GPP website: About 3GPP home: Partner Project Description). 3GPP inherited the working structure and procedures from ETSI and continued using them in the same manner (3GPP website: Specifications/Specification numbering/TR 21.900; Leiponen, 2008). The decision-making within 3GPP is by consensus; however, in rare cases of disagreement the issues are resolved by voting of individual members. Such decisions have usually been made with a majority of more than 70%. The technical work program of 3GPP is organized into studies and features. Studies are programs for examining the feasibility of future features. They are usually conducted to analyze the feasibility of complex functionalities, and may lead to new features. Features are new functionalities that enhance the system, and result in changing existing specifications or adding new specifications. Features, studies, and specifications are combined into so-called releases, which are typically scheduled on intervals of one to two years. Each release is described in a release document, which contains a list of the studies and features, and a short description of each.

An important difference between standards developed via SDOs and those championed by a sponsor is the structure of the network of the involved parties (Langlois and Robertson 1992). In case of a sponsored standard, the network is dominated by the sponsor of the technology that will govern the development of the standard. As numerous studies on networks have shown, the structure of a network and the type of

Release name in 3GPP	Release name	Release number	3G release number	Release date	Number of components	Number of interfaces	Peak data rate (kbps)	Percentage of 2G features
Phase 1	2G-0	0	—	1992	8	9	9.6	
Phase 2	2G-1	1	—	1995	12	11	9.6	
R96	2G-2	2	—	early 1997	14	20	40	
R97	2G-3	3	—	early 1998	16	20	171	
R98	2G-4	4	—	early 1999	16	25	384	
R99	3G-0	5	0	Mar 2000	28	47	2000	9.1
Release-4	3G-1	6	1	Mar 2001	28	51	2000	14.3
Release-5	3G-2	7	2	Jun 2002	39	79	14000	24.4
Release-6	3G-3	8	3	Mar 2005	50	106	14000	23.8
Release-7	3G-4	9	4	Dec 2007	53	109	28000 1900 (EDGE)	26.0
Release-8	3G-5	10	5	Dec 2008	72	157	42000	16.1
Release-9	3G-6	11	6	Dec 2009	76	170	84000	7.5
Release-10	3G-7	12	7	Mar 2011	NA	NA	153000	3

Table 4.1: Overview of releases and variables.

links actors have with each other are essential for knowledge flow, power, and influence (Ahuja 2000; Burt 1992; Coleman 1988; Tiwana 2008). Absence of a dominant sponsor is an important characteristic of a SDO (refer to chapter 3 for the structure of the innovation network). In SDO environment, negotiation among actors with different interests is required. This characteristic broadens the knowledge space for the development of new features.

4.3.3 System architecture and evolutionary approach in 3GPP

Like other modular complex systems, the cellular telecommunication system is a hierarchical system with several levels. At its highest level, it is called Public Land Mobile Network (PLMN). The next level (Level 1) is the network level, which consists of three systems: the radio network, the core network, and the mobile station or cell phone. The next two levels are the domain level (Level 2) and the component level (Level 3), which have five and ten subsystems respectively. Interfaces connect components to provide a coordinated interplay between them in order to accomplish the system functionalities (e.g., transmitting a phone call or a data connection between two mobile users). The fundamental changes from 2G to 3G have been the introduction of a new radio network system at the domain level with new radio transmission principles leading also to a new mobile station at the network level. The old standard with its radio network (base station system) co-exist with the new standard.

4.3.4 Measures

The unit of analysis in this study is the system-release combination (Table 4.1, column 3), which allows to study the evolution of both 2G and 3G systems over time.

Components and interfaces

For each release, the system architecture (i.e., the components of the system and their interfaces) is described in a dedicated specification (3GPP website: Specifications/Specification Numbering/TS 23.002). The content structure of specifications mirrors the hierarchical structure of the system. This allows extracting data at the system level for each component and its interfaces. To capture all components and their interfaces, I collected the data at the component level (Level 3). When a system does not have subsystems (e.g., the mobile station system at Level 1), I included the components and interfaces of that higher level system in the count. The underlying logic for this inclusion is to count the components and interfaces of all subsystems of the PLMN, the overall technological system. Based on the same logic, interfaces are included as long as one of the components they connect is at the Level 3 or higher. The total number of components and interfaces for each release are shown in Table 4.1.

System performance

I measured the performance of the system at each release by the peak data rate, an established performance measure in the industry (Rysavi2009).7 Data rates are performance criteria defined by 3GPP (3GPP website: Specifications/Specification Numbering/TS 22.01) and play an important role in comparison of the two competing technologies of GSM and CDMA. Data rates translate directly into user experience such as the speed of access to the Internet or downloading of files from the Internet. The peak data rate is the maximum possible data rate provided by the system to one end user (Table 4.1). The source for the peak data rates is 3GPP and industry reports (Qualcomm 2009; Rysavi 2009).

Evolution of 2G after dominance of 3G

With the introduction of 3G-0 in March 2000 (Table 4.1), the third generation system performance matched and surpassed the performance and functionality of the second generation system. From release 3G-0 onward, new features may apply to 2G, 3G, or both. Those that apply merely to 2G or 3G affect the enhancement of the system based on that standard only; however, some features introduce new or improved services that enhance both 2G and 3G standards. Release documents distinguish among the 2G, 3G and 2G-3G features (3GPP website: Specifications/Releases/Release-1999 to 10), from which I identified the percentage of features that were introduced after 1999 but enhanced the 2G standard (Table 4.1, last column).

4.4 Results

Proposition 1 stated that the technological system is continuously enhanced by new components and interfaces. The data in Table 4.1 (number of components and number of interfaces) show that the number of both components and interfaces has continuously increased over time. To demonstrate the extent to which the technological system has evolved by the introduction of new components and interfaces, I conducted two OLS regression analysis with the number of components and interfaces as dependent variables, using the first 2G release (2G-0) as a baseline, and the release number (Table 4.1) and its cube as independent variables. Both regression models were significant ($p < .001$) and explained the variance in the dependent variables by 99% (Table 4.2). The regression coefficients for both linear and the cubic term were also significant ($p < .001$), supporting Proposition 1.

Proposition 2 stated that the system shows a steady, strong performance increase over time rather than a discontinuity after a period of stagnation. To illustrate, I present the results for the system performance of all releases (Figure 4.3), 2G and 3G

Dependent variable	Number of components	Number of interfaces	Performance of 2G and 3G releases (exponential curve)	Performance of only 2G releases (logistic curve)	Performance of only 3G releases (exponential curve)	Proportion of features for 2G only after 3G-0 release
Starting level (a)			119.08***	-10.509	2358***	
			(0.0006)	(0.6076)	(0,0008)	
Performance differential (b)				1963.08***		
				(0.0008)		
Growth rate (c)			0.596***	0.993*	0.596***	
			(2.53E-12)	(0.0205)	(3.16E-07)	
Inflection point (d)				5.3810**		
				(0.0017)		
Residual SE			2627	16.72	3526	
Intercept						8.667*
						(0.0207)
Coefficient linear term	2.725***	4.922***				9.917**
	(2.43E-05)	(0.0003)				(0.0024)
Coefficient quadratic term						-1.571**
						(0.0012)
Coefficient cubic term	0.031***	0.088***				
	(2.53E-05)	(8.83E-08)				
Adjusted R^2	0.99	0.99				0.87
p value of model	2.51E-11	5.00E-11				2.53E-03

* p ¡ .05; ** p ¡ .01; *** p ¡ .001

Table 4.2: Results of regressions.

separately (Figure 4.4 and 4.5), and the relationship between 2G and 3G performance.

Figure 4.3 shows the performance over all releases, where the 'squares' represent the data rates based on 2G technology and the 'diamonds' those based on 3G technology. The overall system evolution from the first 2G release in 1992 to the latest 3G incoming release in March 2011 can be described with an exponential curve

$$y = a \cdot e^{cx} \quad , \tag{4.1}$$

where y is the performance, x the release number, a the starting level (i.e., the performance level for $x = 0$) and c the growth rate. The regression results are shown in table 4.2. The fitted curve reflects the overall trend of the continuous, strong performance increase of the technological system, supporting Proposition 2. The exponential curve indicates that the evolution of the system has not yet reached the inflection point of a logistic growth, from where on the growth rates slow down. It also shows that the performance increases within 3G, for instance between 3G-5 and 3G-6, are greater than the increase between the latest 2G release (2G-4) and the first 3G release (3G-0). These results are unlike the life cycle model prediction of stagnation of the system's performance during the era of ferment, and then a steep increase after the emergence of dominant design (Anderson and Tushman 1990). The growth rate of 0.596 (in the exponential curve) indicates that system performance from one release to the next has increased by a factor of 1.8. However, the starting level value of 119 is more than 10 times of the system performance of 9.6 (see 2G-0 peak data rate in Table 4.1), which indicates that the curve does not fit well during the early releases and is dominated by the large values of the later releases.

Therefore, I also analyzed performance of 2G and 3G releases separately. The regression results are shown in Table 4.2. As is customary in the life cycle literature

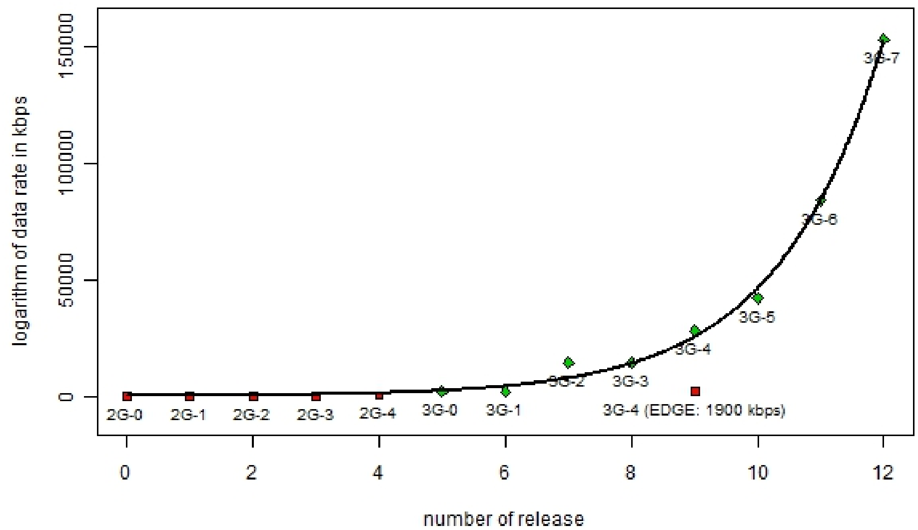

Figure 4.3: Exponential curve of the system performance over all releases.

(Foster1986, Sahal1985), I used a logistic curve (S-shaped) to describe the 2G performance data (Figure 4.4):

$$y = a + \frac{b}{1 + e^{-c\cdot(x-d)}} \quad , \tag{4.2}$$

where y is the performance, x is the 2G release number, a is the starting level, b is the performance differential between the starting and final levels, c is the growth rate, and d is the inflection point. The starting level of -10.509 is not significantly different from 0 ($p > .05$). The performance differential of 1963.08 is slightly higher than 1900, the highest peak data rate of 2G (Table 4.1,"1900 EDGE"). The growth rate of 0.993 is very close to 1.0, indicating a steady increase rather a jump between the starting and final levels. The inflection point is 5.381, which occurs shortly after the first 3G release (3G-0).

Figure 4.5 shows an exponential curve of the 3G performance. The growth rate is the same as that for the all releases, confirming the nearly doubling of the performance from one release to the next. The starting level of 2358 is slightly higher than 2000, the

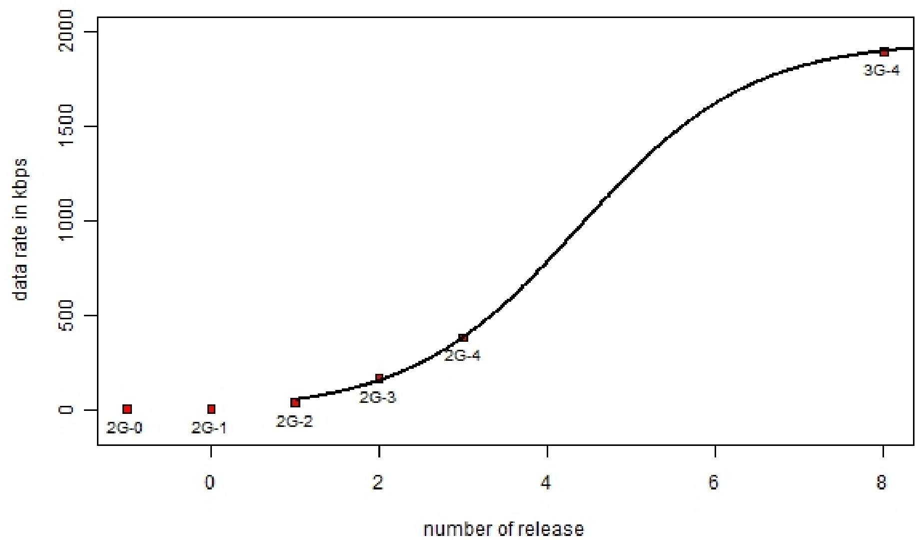

Figure 4.4: Logistic curve of the system performance for 2G releases only.

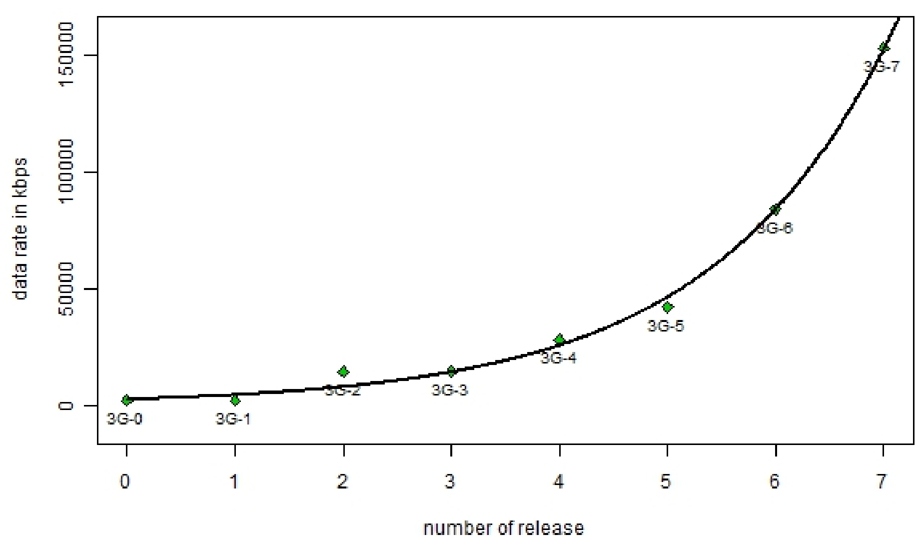

Figure 4.5: Logistic curve of the system performance for 3G releases only.

peak data rate of 3G-0 (Table 4.1). The good fit of an exponential curve indicates that 3G has not yet reached the inflection point of a logistic growth curve with decreasing growth rates.

Two characteristics of the evolution of 2G and 3G standards are noteworthy. First, the performance of 3G was from the very beginning higher than the performance of 2G. This is in contrast to the life cycle literature, which suggests that the new technology starts at a lower performance level than the established technology but exceeds the old technology's performance quickly in its growth phase (Anderson and Tushman 1990; Christensen 1992a,b; Foster 1986). However, it is consistent with the findings of Sood and Tellis (2005), who reported mixed results regarding the performance relationship between new and old technologies. These authors findings show while performance of the majority of new technologies is superior at the time of their introduction, several fail to improve further after the introduction.

Second, though the old technology has the lower performance since the introduction of the new technology, its performance continues to develop to a level close to the final level of the S-curve (Figure 4.4). This step happens in 3G-4, where 3G's performance exceed 2G's highest performance by nearly a factor of 15 (28,000 kbps versus 1900 kbps, Table 4.1). There are two reasons for the further evolution of 2G technology. First, operators that do not have a 3G license use the evolved 2G technology as a means to increase data rates and offer 3G-like services (Ansari and Garud 2009). Second, operators with a 3G license use the evolved 2G technology as a complementary technology in urban areas for 3G-like services at lower costs (GSMA 2010).

Figure 4.6 depicts the results of the analysis regarding Propositions 1 and 2. The three axes are the number of components (x-axis), number of interfaces (y-axis), and system performance (z-axis). The first 2G release is in the origin of the diagram, serving as reference point. The 'dots' are the data points from the system. The number of

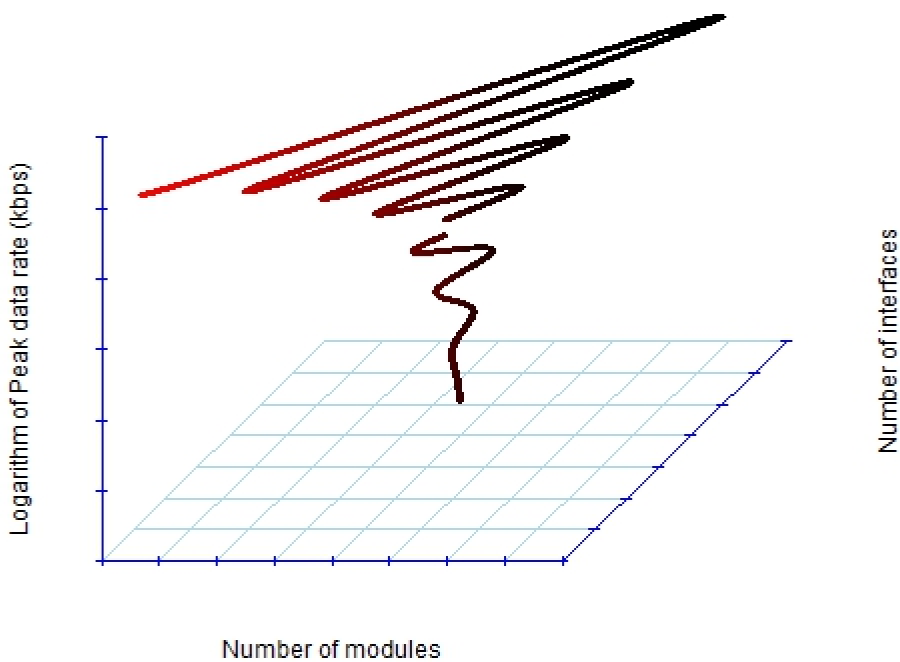

Figure 4.6: The life spiral model for cellular telecommunication system.

components and interfaces is alternately on the left and right side of the origin to resemble the abstract life spiral diagram in figure 4.2. The spiral is based on the regression coefficients from the models presented in Table 4.2 (components, interfaces, and performance of 2G and 3G only). It shows the evolution of the system in three dimensions, underlining the fundamental thesis of this study that a complex open technological system is gradually enhanced over time. The spiral demonstrates that the performance increases within a standard (both 2G and 3G) are greater than those across standards and 3G performance is higher than that of 2G from the beginning.

Proposition 3 proposed that the old and new standards co-exist. I tested this proposition by the percentage of features that apply to 2G only of all features of a given release after the emergence of 3G (Table 4.1). Using OLS regressions, I regressed this percentage on linear and quadratic terms of release number (Table 4.1). The regression coefficients were significantly different from zero (Table 4.2), supporting Proposition 3. Therefore, despite using a conservative test (not including the features applicable to both 2G and 3G), the results suggest that after the emergence of the 3G standard the 2G standard continues to enhance and its performance continues to increase. The percentage of new features that apply to 2G only is relatively low (9.1%) for the first 3G release (Table 4.1). This can be explained by (1) the transfer of the previous 2G features to a 3G environment, and (2) the focus on introducing features for the new standard. The percentage of 2G features increases to a maximum of 26% in 3G-4, and then decreases steadily to low of 7.5% in 3G-6 and 3% in the incoming 3G-7 (Table 4.1). The steep decline in new features for 2G likely indicates that further evolution of 2G may come to a hold with the evolution of 3G towards a new standard (4G).

4.5 Discussion

Using the framework of modular systems, and building on the product and technology life cycle models, I examined the evolution of complex modular systems with network externalities through standard developing organizations. The SDO is an inter-firm organization for setting industry standards that has rarely been examined in the context of technological change. It structures and facilitates the development of industry-wide standards based on cooperation among all major players including producers, service providers, and regulators. I argued that this approach to standardization advances a new evolutionary model of technological change the life spiral model. I illustrated this model by the data for two generations of the cellular telecommunication systems over

18 years. The empirical evidence confirmed the evolution of the technological system by a steady increase in the number of components and interfaces, and a continuous substantial improvement in the system's performance over time. In addition, I found the new standard did not fully replace the old standard; instead, after the development of the new standard (third generation) major and minor innovations enable the old standard (second generation) to continuously evolve and increase performance. Below I discuss the implications of the findings for theory and research.

4.5.1 Evolution of complex open systems

Complex open systems and their attributes of modularity and upgradeability are the central features of the technological change described in this study. These systems require a modular, nearly decomposable design to reduce the complexity, and uncertainty associated with it. The reduction to smaller, less complex and weakly interlinked components opens the design and manufacturing of the system's parts to different firms. This openness necessitates the need for compatibility, and leads to the pre-product standardization. In cases where none of the players is sufficiently strong to bet on the market to set a standard alone, the concerted effort of a SDO is necessary. The pre-product standardization jointly with the systemic approach to standard development via SDO induces a three-stage process: a coordinated search trigger, the subsequent selection of a principle and its elaboration, and selected standard as the retention mechanism. The standard serves as platform for further evolution, allowing simultaneous introduction of various innovation types through overlap of the eras of ferment and incremental change. The three-stage process governed by a SDO results in technological change in the form of a spiral with an evolving standard (figure 4.2) rather than a cycle repeated with the emergence of new dominant designs. In this vein, the LSM describes the evolution of complex modular systems via economies of substitution by extending the traditional life cycle (PLC and TLC) models that have focused either on closed systems or stand-alone complex products to complex open systems with infrastructural networks.

A point of departure of LSM from the traditional evolutionary models is the continuous search that triggers an intentional, coordinated action to improve both the core and peripheral features of the system. In the biological analogy used by Murmann and Frenken (2006), the search for improving the system's traits or service attributes ("phenotype") induces the identification of its components and interfaces ("genotype"). This biological analogy, however, portrays the evolution of complex products through standard setting by markets, where a random change in a genotype would lead to unpredictable phenotypes. The evolution of the technological system through SDO departs from the biological analogy of evolution. On one hand, standard setting through SDO curtails the identification of existing or new components by chance that may result in changes with uncertain outcomes in the service and technical characteristics of the system. On the other hand, because of the near decomposability property of the system, complex tasks are split into sets of simpler subtasks that are performed in a coordinated manner. Therefore, the process facilitates the elaboration of new functionality in each of the identified components and interfaces in a relatively independent way by different players. Using an analogy from natural sciences, the laser triggers a coordinated emission of light in contrast to the unsynchronized emission of a light bulb in all directions. In my case, the SDO serves as the coordinating mechanism that synchronizes evolution of the technological system by providing a special organizational form that governs the system and enables the incorporation of innovations from multiple players through a cooperative, coordinated process.

Another point of departure of LSM is simultaneous, rather than sequential, introduction of different innovation types. In the studies of product/technology life cycle, innovation types occur mainly sequentially. For instance, distinguishing between component and architectural knowledge, Henderson and Clark (1990) identified four types of innovation that influence technological change: radical, architectural, incremental, and modular. The product cycle begins with a radical (disruptive) innovation, followed by architectural and then incremental innovations. In the LSM, because of the overlap of the eras of ferment and incremental change, these innovation types could occur simultaneously. Whereas this assertion should be scrutinized and empirically examined at the level of industry or product class, it has been supported through the concept of ambidexterity at the organizational level. The ambidextrous design emphasizes simultaneous introduction of radical and incremental innovations for long-term growth and short-term efficiency and argues that a firm's sustainable success depends on its strategic leadership of active management of innovation streams over time (Tushman and O'Reilly 2002). Recent longitudinal investigations of the innovation-performance relationship have confirmed positive influence of the composition of different innovation types on organizational performance (Damanpour et al. 2009; Roberts and Amit 2003). The standard development process in SDO environment provides a framework for extending the concept of ambidexterity from the strategic management of streams of innovation types at the firm level to inter-firm integration of streams of innovation at the industry or product class level. The continuation of this line of research can help advance the application of the concept of ambidexterity beyond organizational context and provide a fuller understanding of the evolution of complex open technological systems in SDO environment at the industry level.

A consequence of the simultaneity of innovation types is the steady performance increase within a standard. Furthermore the dedicated search process in the SDO environment allows improving prime merits leading to higher performance of the new standard from its very beginning. While the new standard is superior in several prominent technical characteristics, it may be inferior in other merits (e.g., economic parameters) compared to the old standard. This will lead to complementarity rather than substitution of the old standard, resulting in co-existence of the two standards. The superiority of the new standard in the prime merits will drive the further evolution of the old standard in the case it has not yet reached its technical limit. When the new standard becomes superior in the other merits as well, it will weed out the old standard.

Hence, in the LSM, the technological development process is different from that in the traditional life cycle models (LCM), where the new technology comes into life inferior in the prime merit, but superior in other merits (e.g. lower storage, but smaller diameter as in the hard disc drive, Christensen (1992b), and when the new technology becomes superior to the old technology in the prime merit the old technology will vanish. I suggest that the multi-dimensionality of performance and the relative performance of the old and new technology in the prime and secondary merits will determine the extent of co-existence of the two technologies and thus the survival of the old technology.

The co-existence of old and new technology have important consequences on the investment behavior of technology providers and users. While following the logic of LCM both manufactures and operators would shift their investments to the new technology Sood and Tellis (2005), based on LSM they might support both technologies during their co-existence. For technology users, in this case network operators, co-existence of the technologies will increase strategic choices enabling more differentiationAnsari and Garud (2009).

4.5.2 Implications for future research

The development of industry standards with SDO architecture and the resulting LSM offer two possibilities for future research one with a narrower scope to further develop the life spiral model, and the other with a broader scope to apply it to other industries.

Elaboration of the model

This study focused on the outcome of the technological change in cellular telecommunications. My analysis of the evolution of the system was at the release level that usually includes innovations of different types. Further research at the level of innovation type and/or innovation can help develop a more in-depth understanding of the evolution of complex open systems. At the level of innovation type, classification of innovations will allow an understanding of the stream of innovation types introduced in the evolutionary process. This will advance the application of the concept of ambidexterity to inter-firm integration through SDO. At the level of innovation, future research can examine the rate and speed of the adoption of innovations by the operators. Whereas the life spiral model deals with the generation of innovations via SDO, it does not imply that each innovation is adopted by each individual member at the time of release. Research beyond case studies (e.g., Ansari and Garud, 2009; Davies, 1997) is needed to explore the diffusion of SDO generated innovations, implication of coexistence of old and new standards on the member firms' strategic decision-making, characteristics of early- and late-adopter operators, and performance consequences of continuous evolution of the standard on the member firms.

A second line of research can focus on the SDO's architecture. For example, the transition from ETSI with regional members to 3GPP with global members is a natural experiment where the SDO member firms had to develop new strategies or modify the existing strategies. The new members needed to strategize how they can influence existing working and decision making processes and deal with the incumbent members to get their proposals accepted. Incumbent members needed to understand and adapt to the new members strategic intents and change their positions, especially those related to coping with the technical challenges that follow the introduction of a new standard. Another promising line of research can aim to provide a fuller understanding of working procedures of SDOs. For instance, what roles do supporting firms and their position in the value chain play? What roles do organizational partners play? Does the type of innovation influence cooperation and coordination between work groups? How decisions are made and consensus is reached? Does the decision making process differ for different innovation types (e.g., component vs. interface innovations, radical vs. incremental innovations).

Application to other industries

Whereas the choice of the cellular telecommunication system allowed studying an exemplary case that has all the characteristics of a well-developed complex open system, the ideas expressed in this paper can also be applied to other less developed open systems such as the emerging Smart Grid standard in the energy sector (Electrical Power Research Institute, 2009), as well as the future evolution of current complex closed systems. For instance, the automobile industry is considered a complex closed system because while different components are provided by different firms (the suppliers), they are still coordinated by one dominant player in the system (the manufacturer). I point out three trends for this industrys potential evolution into an open complex system: (1) environmental standards imposed by governments; (2) the pervasiveness of the information and communications technologies (ICT) as a general purpose technology (Helpman 1998); and (3) and the application of system perspective at higher order systems.

First, regulatory requirements such as the air pollution standard in many states in the US and the fuel economy standard in China has increasingly forced the industry to introduce more advanced technologies in the cars manufactured for those market (Oliver et al. 2009). Second, most cars already have several integrated minicomputers that are controlling important functions and a communication system for ease of driving and navigation. The newly founded "car 2 car consortium" in Europe is a SDO whose mission is to create an "open European standard for cooperative Intelligent Transport Systems" to improve traffic safety and efficiency (car 2 car consortium, 2009). Third, as system theorists have long pointed out (Ackoff and Emery 1972; Emery 1969; Churchman 1968), a system's effectiveness depends not only on the fit among its subsystems but also a fit with the subsystems of its larger system (the environment). The internal fit reflects congruency among the system's parts enabling it to operate efficiently for short-term performance; the external fit represents the system's adaptability to its environment maintaining its viability and long-term effectiveness. More complex a system, larger the number of environmental subsystems it should interact with and adapt to for being effective. In this vein, the automobile industry can be seen as a complex open system with the transportation system as its environment, and the roads, traffic systems, gas stations, and regulatory requirements as the subsystems of this larger environment. A recent statement from Mr. William Ford Jr., the Executive Chairman of Ford Motor Co., can serve as an example. Mr. Ford pleaded for a "collective job" of the automobile industry, government, utilities and other key players to get the required electric charging infrastructure in place as a condition for the successful switch to electrical cars (Hoffman 2009).

In summary, the potential opening of a complex closed system such as automobile industry toward a complex open system could unleash new architectures for governance and innovation in mature industries. It provides research opportunities for answering practical questions associated with the formation, operation, and governance of SDOs, role of regulatory institutions, differences in business and regulatory requirements in the global context, and so on.

Limitations

I have examined technological change in a single industry. While the choice of cellular telecommunication systems is justified because of its exemplary nature, the generalization of the findings of this study to other complex open systems has to be done with caution. For example, regarding the setting of an international inter-industry standard for wireless power charging stations for a variety of products such as cell phones, remote controls, and cameras (Wireless Power Consortium 2009) the assumption of capital-intensity does not hold. Therefore, an overlap of the old and new standards may not occur. More generally, the complexity of other open systems may be less pronounced than cellular telecommunications, leading to a dilution of the evolution of the system in a spiral form. It is also possible that other salient factors (e.g., regulations) may prevent the evolution of the technological system as advanced here. However, as discussed above, participation of all the players in the SDO (including the regulators) can mitigate this possibility.

A second limitation is that the resolution of change in this study is on the system, rather than the innovation. The inference regarding the simultaneity of innovation types is indirect. From the introduction of new components and interfaces in the system, I have inferred that architectural, modular, and radical innovations (with either new core concepts or linkages or both) are introduced simultaneously with incremental innovations. Third, I have observed only two standards covering two generations of the system with the evolution into the next generation (4G), which is a rather short period in the overall evolution of a complex open technological system. Whereas I have had the advantage to examine the evolutionary process from an early stage, where the evolution is probably most dynamic, there may be a point in time where the spiral will finally flatten or even overcome by a completely new technological system.

Despite these limitations, this study contributes by bridging the life cycle literature of technological change with the emerging literature of SDOs in management. This rather new form of organization and its special architecture may help strategy and technology management scholars gain a deeper understanding of the technological evolution and its underlying processes for complex open systems. Management scholars can also make important contribution toward a better understanding of the design and behavioral processes of these global cooperative organizations. The importance of research on SDO architecture will be more pronounced if, as discussed above, complex open systems become more prevalent by spilling over to other industries that are still dominated by market-based standard setting.

Chapter 5

"Future is Evolution" — Locus, Tempo and Mode of Evolution in a Technological System

5.1 Introduction

"Future is evolution not revolution" is the first assumption in 3GPP's roadmap of the future development of the 3G network of 2003, shortly after the commercial introduction of 3G networks (specification 21.902). With the worldwide commercial introduction of 4G networks currently under its way, this anticipated future is now the past and accessible to the study of the mode and tempo of the evolution

At the center of the technological life cycle model in the previous chapter and of the evolution of systems in general is the debate of punctuated equilibria (PE) versus gradualism. Mores specific questions are about the of mode and tempo of evolution and implications for locus of change and types of innovations. The PE paradigm in biology challenged the more than 150 years "Darwinian orthodoxy"'s premise of gradual evolution by incremental steps (Prindle 2012) and suggests revolutionary change after a long period of equilibrium characterized by stagnation and subsequent new equilibrium. PE as a model for stability and change in complex systems was adopted in many disciplines besides biology (Gersick 1991; Prindle 2012).

This study questions some of the assumptions in the transfer from evolutionary theory in biology to technological evolution with the key elements of variation, selection and retention. At the heart of the PE model is the core (Murmann and Frenken 2006) or the deep structure (Gersick 1991) of the system. It remains mainly untouched during the periods of stagnation or stasis and its sudden change leads to punctuation, a jump in trait characteristics, followed by long periods of stagnation again based on the new deep structure.

A key distinction between technological and biological evolution is the engineered design of the former — change is not by chance, but by intent. This difference is well acknowledged by biologists — "natural selection is not an engineer" (Hansen 2003, 85) — as well as by evolutionary economists (Dosi 1982). The notion that change mainly occurs in the periphery rather than the core of the system (Murmann and Frenken 2006) is based on the assumption of uncoordinated and therefore detrimental change of service characteristics (*phenotype*) in case of core elements of the technological characteristics (*genotype*). The engineering process however has the reverse direction: it begins with the desire to change the function or service characteristics of the system and then changes the required components and interfaces based on the architectural knowledge of the system. Furthermore, modularity of the system contains impact largely to within the same module (Simon 1962). As a first consequence change in the core is possible and will happen in contrast to the assumption of change dominantly in the periphery of the system

A second consequence, without its basic assumption of stable deep structure, the PE model of change is questioned and I posit a dominant mode of gradual change with varying pace, including stagnation and rapid change. Stagnation and PE are in this perspective more extreme points on a continuum rather than two distinct types of change as pointed out by Hunt (2008, page 361) with "How rapid is punctuation, and how sluggish is stasis?" However, it matters were the change occurs, and gradualism will be the major mode based on a changing core or dominant design driven by augmentation and substitution in the modular system as described in the previous chapter. Substitution of a core element can lead to rapid change and the resulting mode of change will be punctuated gradualism rather than PE.

The third consequence is the simultaneity of different types of innovation due to the continuously growing system In a typology of innovations based on the novelty of service and technological characteristics (Murmann and Frenken 2006) all four types of innovations, including radical ones, will occur.

The major theoretical contribution to the literature of technological change is that in the engineered process of the evolution of a modular system the distinction between gradualism and PE is more a matter of degree and perspective, rather than a fundamental difference. The empirical contribution is the transfer of recently developed methods of determination of mode and tempo of change in paleontology to technological change.

This chapter proceeds in the following: In the next section I provide the literature and development of hypothesis, then I describe the data and methods, present the result and end with a discussion.

5.2 Locus, Tempo and Mode of Evolution

This study builds on the literature of evolutionary change that was largely borrowed from biology and Darwin's theory of evolution. I focus in particular on two important, interrelated aspects: the role of a designer in evolution and the contrast of gradualism versus PE. I first provide an overview of evolutionary models as the point of departure of this study. I posit that the key distinction between the evolution of biological and technological system is the purposeful design that leads to a different locus of change in the core, rather than the periphery of the system. This results in rather gradual than punctuated change and simultaneity of innovation types.

5.2.1 Evolutionary models

In this section I first turn to the literature of biological evolution, then to the adoption of PE models of change and the underlying patterns and finally the application of PE models in technological evolution.

The dominant lens of evolution of species in the pre-Darwinian era was the intelligent design with God as designer. For instance Paley, a British philosopher, argued based on the complexity of living organisms and the analogy to technical systems that change in such complex systems can only occur by the planning of a designer or engineer. He used the complexity of the eye with its different components and their relations to provide a desired function to argue that such a system could not be developed by chance (Ayala 2007). He further used the analogy to the telescope and watch to posit the purposeful action of a designer. Paley with his description of complex entities consisting of parts with a relation between them to provide the desired function can actually seen as an early system theorist[1]

In his article on Darwin's evolutionary theory Ayala (2007) claimed that Darwin's fundamental discovery was that of an "creative, though unconscious" process and hence design without designer. This process rests on three elements: mutation, natural selection and retention. While the retention process was not yet known at Darwin's time, with the discovery of Mendel's laws and DNA, the genome, the full set of genes of an organism, is now established as retention mechanism. The random change in the genome or genotype leads to changes in the traits or phenotype of the species on which natural selection acts upon and mutations that provide better fit to the environment are retained. A species is defined as "a population of interacting individuals, reproductively isolated from all other groups" (Eldredge and Gould 1972, page 92). The

[1] Intriguingly, the example of the watch was used more than two centuries later by Herbert Simon to explain the reduction of complexity via modularity.

key process is natural selection, rather than the mutation. Darwin predicted gradual change of species and their characteristics or traits via a chain of incremental steps that accumulate over time, leading to the development of new species (Ayala 2007; Eldredge and Gould 1972; Hunt 2010). As a consequence, fossil records, the trace of ancient species, should show this development over time. However, the records showed breaks in morphological traits rather than smooth transitions. Darwin was aware of the lack of support by fossils and ascribed it to poor data quality. This view on fossil data was retained over 150 year and biological evolution as gradualism was the accepted theory among biologists and paleontologists.

This perspective was challenged by Eldredge and Gould (1972) who suggested a model for species evolution characterized by stagnation or stasis over long periods of time, interrupted by a rather rapid speciation event resulting in a new equilibrium of little change. Eldredge and Gould coined the term *punctuated equilibria* for this change patterns. In contrast to Darwin, who suggested that new species arise via transition from the ancestor to the descendant, they posited a speciation event in such a way that a small part of the population becomes isolated in a distinct different geographic area and hence experience different selection criteria. They further claimed that the adaptation to the new environment happens in a short period of time and hence gaps in the fossil record are the expected pattern. The model of PE was for many years disputed in the biology and paleontology literature and the same fossil records were interpreted either as gradual or punctuated, depending on the preferred theory of the researcher (Hunt 2006). Only recent advancements in methodological analysis of fossil records allowed to see a dominance of stasis over gradualism in a large number of fossil sequences (Hunt 2007).

Despite its controversial reception in its home discipline, PE as a general model of change of complex systems was adopted in several disciplines or independently developed (Gersick 1991; Prindle 2012). The "species" or units of change can be individuals, groups, technologies, physical adaptive systems, political systems and scientific paradigms. Gersick analysed six theories of revolutionary change from different disciplines[2] and identifies three core elements shared across the six theories of revolutionary change: deep structure, equilibrium period and revolutionary periods. The deep structure is at the core of the PE paradigm and is mainly the notion that the units underlying change are systems, that consists of parts and relations among each other to generate the system function. The deep structure is then the specific choice of parts and the activities to maintain its existence. The stagnation of human systems is mainly based on cognition, motivation and obligation. In the revolutionary period the previous deep structure is replaced by a new one triggered either by internal or environmental change.

While this is rather abstract, in the application of PE to technological change the model becomes clearer as well as the basic choices to be made in the transfer of biological evolution to technological evolution. Levinthal (1998) used the PE framework to reconcile the two contrasting models of technological change — gradual and incremental on one hand (Dosi 1988) and disruptive on the other hand (Tushman and Anderson 1986). His main tenet was that the application of a technology in a new domain is a speciation event, which does not require necessarily large changes of technology itself. The new domain constitutes different selection criteria to those in the original domain and it may result in different resource abundance due to the size of the domain. The novelty of the environment will lead to a distinct evolution — a very similar argument as in the biological PE. The mode of change is dictated by the new requirements and the pace by the resource abundance. A key point is whether the technology as it develops

[2] One of the six theories is Kuhn (1962)'s model of scientific paradigms and the distinction between revolutionary and normal science. It anteceded the PE model and was discussed by Eldredge and Gould (1972) not as analogy to the PE model, but as explanation why gradualism persisted for such a long period despite the lack of support by fossil records.

in the new domain or niche is able to enter other domains. Levinthal applied his model to the wireless communication technology where his definition is broader than the one I use in my dissertation, and encompasses a much longer history from early lab systems of Heinrich Hertz to wireless telegraphy, telephony and broadcast. Levinthal's model is rather close to the biological PE model with technologies as species and the entry into a new domain, a new market, as speciation event. However there is not much description of the system(s) and its deep structure — only the function as e.g. telegraphy. Schot and Geels (2007) defined the species of technological change as the socio-technological regime, that includes the technology itself as well as community of actors, similar to Rosenkopf and Tushman (1998). The regime is mainly a community of actors, firms, users and government, that follow the rules in the production, usage and regulation of the technology. The rules can be considered as the genotype and set the boundaries between species, while products of the technology are the phenotypes.

In summary I conclude that the study of an evolutionary model requires several definitions. First the "species" and speciation events. This specifies the unit of analysis, the lineage, which is the concatenation of ancestors and descendants. Second, the deep structure, the choice of elements and governing rules that define the function of the system. This also implies the definition of the genotype-phenotype map (GPM), i.e. which change of rule or genes leads to which functional or characteristics change. This allows to map a mutation into a phenotype that underlies the natural selection. Third, the definition of the environment and its selection criteria on the new phenotype.

There is a fundamental distinction between the evolution of biological and social, including socio-technical systems, with two important consequences. As Ayala (2007) put concisely, Darwin's theory is a theory of "design without designer", while social systems have actors as individuals, groups or larger communities. The first consequence is the socio-technological regime as defining boundary of technological species. In a socio-technical regime the full complexity of the interaction of social rules and technical feasibility is confounded in the PGM, the map of the change in rules and the resulting technical characteristics. I choose a simpler approach by focusing on the technological system, whose evolution is embedded in the innovation ecology of the SDO. I use the stable rules of the SDO to operationalize the evolution of the technological system. The interaction of actors and the innovations in the technological systems are covered in chapter 3 and 4.

The second consequence is in the order of evolutionary steps because of the engineered process. There is first the decision on a desired functionality and then the change of the system based on a detailed analysis (this is the search and elaboration in the LSM in contrast to variation and selection in the LCM.) The market environment, the major selective environment, is part of the SDO in the form of network operators, whose support of an innovation signals market acceptance. In the following sections I elaborate the locus, the mode and pace of change and finally the typology of innovations.

5.2.2 Locus of change: Core or periphery

Murmann and Frenken (2006) used the distinction between core and periphery to identify the dominant design by the choice of core components of a system. This requires the identification of the core-periphery structure. They followed the analogy in biology of the phenotype-genotype distinction, where the genotype contains all the hereditary information and the phenotype the traits or characteristics of the organism. The genotype is the part where mutations occur that lead to changes in the phenotype, which underlies natural selection based on fit. The number of phenotypes affected by a given genotype is called *pleiotropy*. The mutation of a high-pleiotropic genotype will affect many traits and it is very unlikely that the combined change of these many traits will overall improve the fitness of the new phenotype. This argument leads to the conclusion that retained mutations mainly occur in low-pleiotropic genotypes. With the identification of the high-pleiotropy elements as core and low-pleiotropy as periphery, the locus of change in this line of argument takes mainly place in the periphery. The mapping of the genotype to phenotypes, the genotype-phenotype map (PGM) is a two-mode directed network and defines the architecture of the system (Murmann and Frenken 2006; Wagner and Altenberg 1996; Wagner and Zhang 2011) or the deep structure in the language of Gersick (1991).

Similar concepts are known for technological systems. Saviotti and Metcalfe (1984) defined the mapping between the service (phenotype) and technical (genotype) characteristics of a technical system as the key element of a framework of technological change. They used this mapping to define different types of services and innovations. Services can be either main services, complementary services or externalities, where the complementary services support the main services and externalities are unwanted services. In systems engineering the *design matrix structure* or *dependency structure matrix* (DSM) define the system architecture between the elements of the system (Baldwin and Clark 2000; MacCormack et al. 2006; Sharman and Yassine 2004). However, the DSM is a one-mode network with relations between system elements, the technical characteristics, while the two-mode GPM maps technical to service characteristics.

Though Murmann and Frenken (2006) acknowledged that a designer is manipulating the technical characteristics, they stuck to the biological constraint that changes of high pleiotropic technical elements will most likely not lead to successful phenotypes. I posit that the purposeful design based on an engineered design process has two important consequence: First, it reverses the dependence between genotype and phenotype and second, it allows the change of high-pleiotropic genotypes. In an engineered process the change of the technical characteristics or genotype do not occur randomly as in nature, but are guided by the desire or need to implement a new functionality or service into the system. This key distinction is well acknowledged by biologists. "An engineer has a preconception of what the design is supposed to achieve and will select suitable materials and arrange them in a preconceived manner so that it fulfills the intended function." (Ayala 2007, page 8572).

At the beginning of 3GPP's development process is the approval of a new work item, which defines an innovation. After the approval of an innovation the development process proceeds in three sequenced stages: in stage 1 the services are identified and described – either existing or new services. In stage 2 the architectural description is provided, a step between service and technical description. It defines the parts of the systems that are affected by the new or extended services and how the functions and interfaces need to be changed. Stage 2 provides the roadmap for the implementation of the detailed changes in the technical characteristics in stage 3. In analogy to the phenotype and genotype I call this the *archotype* of the system. Each of these steps undergoes an approval process, which may lead to several revisions before approval or final rejection. In case a change is finally approved it will be integrated into an implementation specification, which is part of the genotype of the technological system. This staged process is applied to several innovations simultaneously. The transparency of all ongoing changes allows to detect inconsistencies and resolve them. For instance, each specification has a rapporteur, who among other tasks, has the responsibility to "identify and resolve clashes" (3GPP specification 21.900). This process is very different to the unconscious, random mutations in biology and it directs from the services (phenotypes) to the implementation (genotype) rather than the other direction. With the reverse direction of dependence in the change process, the argument that a random mutation affecting many phenotypes is unlikely to result in better fit, is not any longer valid. The change can be designed in such a way that detrimental affects to traits not affected by the innovation, do not occur, while simultaneously the intended change is implemented. The engineered process enables changes in high-pleiotropy genotypes. It requires a lot of coordination, which is the major rational for creation of a SDO and distinguishes the process to market-driven evolution. It allows the change of the deep structure of the system.

On the other hand the high pleiotropy of a genotype makes it much more likely that this genotype will be needed to be changed in case of a service change. While this argument applies to a random choice of an existing service, the distinction of main and complementary services (3GPP actually calls them supplementary services) makes it even more likely. The first system release focuses on basic or main services and functions, which are implemented by the core elements of the system. The core elements are defined by the underlying technical principle that have not yet reached their full technical potential. In order to improve their performance from a basic level they need to be extended and this will occur in the core elements, that develop along their technological trajectory to their full potential (Saviotti and Metcalfe 1984).

The argument, that change occurs in high pleiotropy elements does not exclude other changes as augmentation, i.e. adding of new components and interfaces or change in the periphery, but it states that change in high pleiotropy elements happens and is dominant.

Hypothesis 4. *There is a positive association between the degree of pleiotropy of genotypes and their change.*

5.2.3 Gradualism versus Punctuated Stasis

The stability of the deep structure, the parts of the system and its architecture, and its sudden change is the key proposition of the PE paradigm. With the possible change in core elements the rigidity of the core structure is not any longer given and gradualism is a viable option. The technological characteristics of the core elements define the technological regime or dominant design (Nelson and Winter 1982; Saviotti and

Metcalfe 1984) and the technological trajectory is the improvement of the system to its full technological potential (Dosi 1982; Saviotti and Metcalfe 1984). The technological trajectory is an accumulation of many changes and follows a gradual development rather than stasis. A new set of technological characteristics define a new technological regime with its own gradually changing trajectory. The PE paradigm is replaced by a punctuated gradualism

While the development of the new technical regime can be rather fast, it still takes some time. Gould suggested one to two percent of the whole life time as the span for the species creation based on a similar percentage of the gestation of human beings (Prindle 2012). The fuzzyness of the definition of punctuation and the unclear distinction between the modes of stasis and punctuation was pointed out by Hunt (2008, page 361) "How rapid is punctuation, and how sluggish is stasis?". Hunt (2006) solved the issue by introducing mathematical models for stasis and gradual change and allowing for shifts in modes of models. Statistical analysis allows then to decide on the best model (a more detailed description is provided in section 5.3.2). Hunt (2008) introduced the so-called *sampled punctuation*, which is a rapid, though gradual change from one level of stasis to a new level, and contrasts it to the standard notion of PE with a sudden shift (*unsampled punctuation*). Figure 5.1 contrasts the unsampled punctuation (left side) with a sampled punctuation (right side), which is a gradual change from one level to another.

The distinction between the both types of punctuation depends on the trajectory itself as well as the granularity of measurement. A measurement on a coarser scale will not allow to detect the gradual transition. It is therefore important to have the appropriate time resolution in the empirical data based on the theoretically expected dynamical range. The sampled punctuation implies that on a sufficiently fine-grained resolution of time the distinction between punctuation and gradualism may become

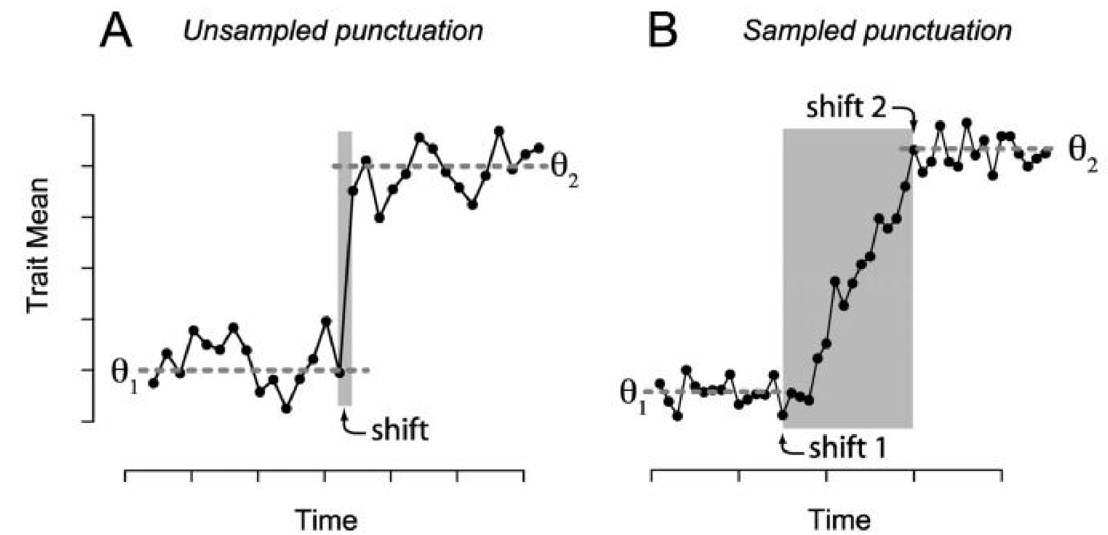

Figure 5.1: Unsampled versus sampled or gradual punctuation (adopted from Hunt (2008), figure 1).

more a matter of different pace rather than different modes. Together with the previous argument, that PE in a coordinated SDO environment is replaced by a punctuated gradualism, the evolution will be dominated by gradual change with different pace or tempo over time. In the development process of the SDO the change is triggered by the phenotype change that leads to a phenotype change. The evolution of the system includes both, the evolution of the phenotypes and the genotypes.

Hypothesis 5. *The evolution of the phenotype (a), archotype (b) and genotype (c) of the technological system is dominated by gradual change, allowing for different tempo over time.*

This is equivalent to proposition 2 of the LSM, that posits that after the standard the performance of the system shows a steady strong increase, rather than intermittent stagnation and surge, with refinements of the time resolution in the operationalization, distinction between different modes and tempo and distinction between phenotype and genotype.

5.2.4 Typology of innovations

Murmann and Frenken (2006) introduced a classification of radical innovations based on the novelty of required knowledge and the improvement of system performance. Innovations can be either incremental with little new knowledge and minor performance improvements, radical, type 1, with little new knowledge, but large performance improvement, radical, type 2, with a large new knowledge base, but small performance improvements and finally radical square with large performance increase based on a new knwoledge base.

The dimension of knowledge novelty is closely related to the distinction between exploitation and exploration in organizational learning (March 1991). Exploitation is based on the current knowledge base and its refinement and is associated with rather low uncertainty. In contrast exploration targets the unknown, which inherently includes a high level of uncertainty. While March (1991) saw them as two opposite sides of a continuum and incompatible, Gupta et al. (2006) argued, that exploitation and exploration are orthogonal and differ in the type and amount of learning. Based on an extensive review of the literature on the different definitions of the concept, Li et al. (2008) developed an unifying framework of exploitation and exploration, extending the distinction between type and amount of learning. They distinguished between two domains, where exploitation and exploration can occur: the *function domain* and the *knowledge distance domain*. In the "function domain" learning crosses various functions along the value chain. In the "knowledge distance domain" the distinction is between local and distant search or depth versus breadth. Following the exploitation-exploration framework in the alliance literature (Koza and Lewin 1998) Lavie and Rosenkopf (2006) identified partnering downstream the value chain as exploitation of existing technological capabilities, while partnering upstream the value chain as exploration of new technologies. Similarly Danneels (2002) argued from an intra-firm perspective, that in

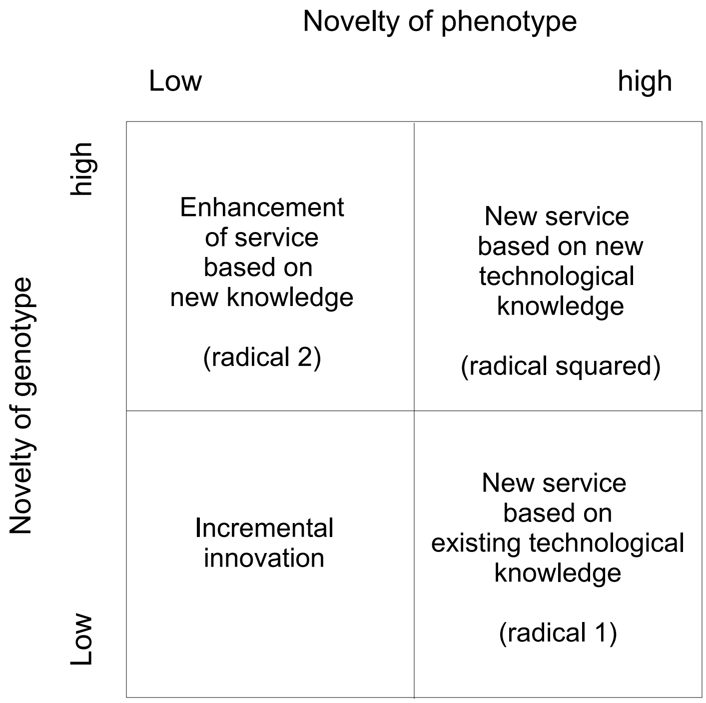

Figure 5.2: Innovation typology based on novelty of phenotype and genotype.

product innovation technological competence and customer competence, the knowledge about customers need to be linked together. Depending on the novelty of these too competences to the firm, the innovation can be either exploitation, exploration or two intermediate cases: in the first case, existing technological knowledge is leveraged to extend the customer knowledge and in the second case knowledge about customers is used to develop new technological knowledge. The common theme of Murmann and Frenken's and the organizational learning literature are two dimensions of knowledge, technological and customer-oriented, and the level of novelty. The differences in the level of these two knowledge dimensions lead to distinct types of products or innovation. The system performance can generally be described by the phenotype of the system and the technological knowledge by the genotype.

Though the major motivation for most firms to participate in the SDO is the influence of the standard, access to and sharing of knowledge is one of the benefits (Rosenkopf et al. 2001). SDOs have the potential of simultaneous exploitation and exploration due to their diversity of different member organizations. Due to the complexity of the system new services are introduced as basic functionalities that are extended in future releases. These extensions will have low novelty of the phenotype and often exploit the existing genotype, but can also require new technological knowledge. In addition 3GPP allows an easy implementation of small technical enhancements via the CR process without the administrative overhead of the work item process for larger innovations.

The balance between exploitation and exploration are important for organizations' sustainable innovation performance: exploration allows for novelty, exploitation for stability and efficiency. Tushman and O'Reilly III (1996) coined the term ambidextry for the simultaneous balance between exploitation and exploration. An alternative way to achieve the balance is a sequenced approach as punctuated equilibria (Gupta et al. 2006). The system modularity and the hypothesized gradual change allow for simultaneity of exploitation and exploration. The separation does not occur via distinct organizations, but on the innovation project level with the four innovation types of figure 5.2 occuring simultaneously.

Hypothesis 6. *Four types of innovation, based on the novelty of phenotype and genotype, exist simultaneously.*

5.3 Data and Methods

5.3.1 Data

For this study I use three data sets from 3GPP: the specifications, the change requests and the work item plan.

The major data source are 3GPP's specifications. First I define the master list of all specifications. Then I use the references that specifications make to other specifications for the definition of the PGM and changes of specifications for the definition of mode and tempo. The specifications are the ultimate result of the standardization work, where the full set of specifications completely defines the technological system, phenotypes, archotypes and genotypes. In the following I give an overview over the specification system, in particular the numbering scheme and version control, which are the basis to define lineage and technological trajectories. I use the example of the "60"-specification to illustrate the specification system.

Each specification covers a rather narrow technical function. Specifications are uniquely defined by their number and their evolution is tracked via the version. The specification number consists of two parts, the two digit series number and an unique number within the series (either two or three digits). The series serves three purposes: First, it distinguishes between 2G and 3G specifications, it groups specifications into functional areas and it indicates the stages of 3GPP's development process.

Figure 5.3 provides the overview of the currently existing series. Three set of series exist that distinguish between the 2G (GSM only) and 3G development and beyond, that is further divided into 2G only and 2G and 3G. The *GSM only* series were used until Release 99 and from then on evolved further in the two descendent 3G series. The distinction within 3G became necessary as not every 2G operator gained a 3G license and pure 2G systems continued to exist. Most 2G specifications were carried over to the 3G series with a new series number and an additional 0 added to the number. The series distinguish functional areas as e.g. the 25-series is covering all specifications of the radio sub-network or the 32-series is specifying charging and billing items. In addition to the functional categorization the series also reflect the staged development process. Stage 1 (series 02, 22, 42) is the service description or phenotype, stage 2 (03, 23, 43)

Subject of specification series	3G and beyond / GSM (R99 and later)	GSM only (Rel-4 and later)	GSM only (before Rel-4)
General information (long defunct)			00 series
Requirements	21 series	41 series	01 series
Service aspects ("stage 1")	22 series	42 series	02 series
Technical realization ("stage 2")	23 series	43 series	03 series
Signalling protocols ("stage 3") - user equipment to network	24 series	44 series	04 series
Radio aspects	25 series	45 series	05 series
CODECs	26 series	46 series	06 series
Data	27 series	47 series (none exists)	07 series
Signalling protocols ("stage 3") -(RSS-CN) and OAM&P and Charging (overflow from 32.- range)	28 series	48 series	08 series
Signalling protocols ("stage 3") - intra-fixed-network	29 series	49 series	09 series
Programme management	30 series	50 series	10 series
Subscriber Identity Module (SIM / USIM), IC Cards. Test specs.	31 series	51 series	11 series
OAM&P and Charging	32 series	52 series	12 series
Access requirements and test specifications		13 series (1)	13 series (1)
Security aspects	33 series	(2)	(2)
UE and (U)SIM test specifications	34 series	(2)	11 series
Security algorithms (3)	35 series	55 series	(4)
LTE (Evolved UTRA) and LTE-Advanced radio technolgy	36 series	-	-
Multiple radio access technology aspects	37 series	-	-

Figure 5.3: Overview of specification series (taken from 3GPP website).

the description of the technical realization or archotype and stage 3 (remaining series with the exception of 01, 21, 41[3]) the detailed implementation or genotype. Stage 1 and stage 2 have each dedicated series and can be identified by them[4] , which identifies indirectly stage 3 specifications.

For example, the specification 02.60 is the service description for packet data service (General Packet Radio Service or GPRS). It was introduced in Release 96 and was dubbed *2.5G* (Ansari and Garud 2009), as the introduction of data services in parallel to voice service was a crucial step into high speed data networks as we know them today. The 2G specification *02.60* descended into *22.060* with 3G. The stage 2 specification is 03.60 respectively 23.060. If possible, the number for a service and its stage 2 and 3 is the same across series, however this is not a strict rule and often not accomplished. With GPRS also several new stage 3 specifications were created as 04.60, 04.61, 04.62 or 09.60.

The version of a specification tracks the release and technical editions within a release. The list of specifications is based on the status file of specifications available of 3GPP's website that includes for all release all specifications and their versions with the according creation date. I used the version of March 2012. I extracted the specification number, title, the list of versions with the creation date for each release. The version identifier consists of three elements: the release identifier, the count for technical updates within a release, and an editorial count, which is only used in case of changes for editorial purposes only. Each active specification will have at least one edition for a release, which can be an identical copy of the specification of the previous release in case no changes occur. Specifications with many changes can have more than twenty

[3] The 01-,21-, 41-series includes high level general descriptions and requirements, including the specification 21.801 that describe the specification drafting rules and 21.900 that describes 3GPP's working rules. It can be seen as level 0.

[4] Occasionally stage 2 specifications can be found in the 25 series — these can be identified by having *stage 2* or *technical realization* in the title of the specification.

different technical editions within a release. For instance 04.60, member of the above mentioned GPRS family, had 28 technical editions in Release 99. Each changed specification will incorporate one or more change requests (these will be described below) into the specification. I exclude draft versions (release identifier less than 3). This results in 27.595 entries of specification-version combinations for 1941 unique specifications. This list of all instances of specifications defines the population of specifications for the analysis. I downloaded the specifications to extract their references to other specifications. I use specifications until March 2012.

After a newly created specification reaches a completion level of about 80 percent it leaves the draft status and can only be changed via change requests. The list of all CRs includes the specification, work item and release it belongs to as well as a category and status. I keep only CRs that are finally approved, leading to change in specifications. In total 91.366 CRs are kept. The category of a CR can take following values: new feature/innovation, functional modification of innovation, corrections, editorial changes. The number of change requests per specification is the measure change of a specification.

The work item plan is used to define the innovations and the mapping of innovations to specifications. The definition of innovations is identical to chapter 3 and 4, with the difference that innovations including Release 99 and Release 4 are considered. Related to the work items 3GPP provides a mapping table of work item identifiers and affected specifications, which allows the mapping to phenotype and genotype. Innovations can map either to one or more phenotypes.

5.3.2 Methods

In this section I describe the three major tasks to construct the variables to test the hypothesis: the identification of the core-periphery structure of the system, the measurement of change and the statistical description of the mode and tempo of change.

Core-periphery identification

There are several ways to define the core-periphery structure of the technological system. I choose the approach based on the PGM following Murmann and Frenken (2006) with adaptations from the literature on DSM (MacCormack et al. 2006; Sharman and Yassine 2004). I use alternative ways to test for robustness of the results.

The phenotype-genotype map. The PGM is a bipartite network with phenotypes or services as one type of node and genotypes or implementation specification as the other type and a relationship that defines the ties. First, I define the services (phenotypes) and the implementation specifications (genotypse) and then the relationship between them. The staged development process of 3GPP starts with the beginning of the service description in dedicated stage 1 specifications. These specifications are identified via the dedicated stage 1 series. All service specifications define the phenotypes of the system. The implementation specifications are the stage 3 specifications. They provide the detailed technical description and characteristics. The archotype in stage 2 specifications have a different level of detail than stage 3 specifications. Though I do not include them in the default definition of genotypes, for robustness tests I define alternative PGMs that include them.

The relationship between the service and technical implementation is the references in specifications, which I will call citations. Each specification contains a list of other specifications it relies on, either 3GPP specifications or those from other standardization bodies. I keep only citations to 3GPP specifications. The citations have a dedicated section in the content structure of specifications and the specification number and title is referred to. This allows an easy and reliable extraction of citations from the specification documents and mapping to the master list of specifications. The citing relationship is a directed relationship, where information flow is established from the cited specification to the citing one, similar to citations of academic papers. Citing specifications depend on cited ones. This is in particular important as it allows to prove the basic assumption of hypothesis 1, that the service is first defined and then the technical implementation follows and hence the definition of a phenotype-genotype map rather than a genotype-phenotype map as in biological evolution is justified. The normal citation flow is that stage 1 specifications are cited by stage 2 specifications, which are then cited by stage 3 specifications. With the list of directed ties extracted from all specifications for each release I construct release specific directed citation networks. In the first step I construct one-mode networks, where each specification can be cited by each. In the second step the cited specifications are restricted to service specifications and the implementation specifications to stage 3 specifications (with alternatively including others for robustness). This implies the transition from a one-mode to a two-mode network with two distinct set of nodes where only ties between nodes of different sets are considered. I proceed in two alternative ways to construct the PGM, however both allow for indirect citation via an intermediate specification. A restriction to only direct citations is too strict with the staged approach in 3GPP with archotype specifications as intermediate level.

The first approach, which defines the default PGM, follows 3GPP's development from stage 1 over stage 2 to stage 3. I include all (stage 3) specifications that either cite directly the phenotype or archotype that cites the phenotype specification. I call this *staged process* PGM. In the second approach I remove the restriction for the indirect citation via the archotype specification and allow for any indirect citation to the service specification. For instance a specification in series 25 can cite another 25-specification that cites the service specification. This approach is very close to the definition of the DSM via indirect linkages (MacCormack et al. 2006; Sharman and Yassine 2004). Besides the different type of tie there are two logical differences: The PGM is a two-mode, not a one-mode network, network, and I only allow paths of length two or in other words only one intermediate specification is allowed. The major reason to be more restrictive with the path length (or order of neighborhoods included) is that inclusion of additional path lengths, i.e. nodes that reach a given service specification via two or more indirect ties leads to a strong increase of pleiotropy for most specifications. I call this *DSM: only stage 3 genotype*. Alternatively I remove the restriction of stage 3 specifications as genotype, resulting in *DSM: genotype all stages*.

In all cases the resulting PGM satisfies the basic idea of coupling the service and technical characteristics of the system (Murmann and Frenken 2006; Saviotti and Metcalfe 1984). The distinction between core and periphery is based on the pleiotropy of implementation specifications. The pleiotropy of a genotype is identical to the degree centrality in the two-mode network, defined as the number of services it is citing. This can be done for each release-specific network. The pleiotropy is only one perspective on the network — the dual perspective for services or phenotypes is called *polygeny* and is the services' degree or number of implementation specifications it impacts.

3GPP's distinction into basic and specific entities of the system. Another way to categorize the core-periphery structure of the system is provided directly by 3GPP in its architecture specification (23.002). For each release the network elements and interfaces are shortly described, including the specifications that define them. 3GPP distinguishes between basic and specific entities. The specific entities are providing specific services, which can be interpreted as complementary services as defined by Saviotti and Metcalfe (1984). They are peripheral in so far, that they have little effect on the system. "The fact that they are implemented or not in a given PLMN[5] should have limited impact on all the other entities of the PLMN." (page 21 in specification 23.002). I categorize additionally the high pleiotropy specifications based on this categorization.

[5] PLMN stands for Public Land Mobile Network, the term with which 3GPP refers to mobile networks.

5.3.3 Change of specifications

The change of specifications is measured in two ways based on the CRs: I use either all CRs or only those that lead to a functional change rather than a correction or editorial change. For each specification change is measured as the number of CRs in a given release — either all CRs or only CRs leading to a functional change.

Construction of the lineage and trajectory.

The lineage is "a continuous line of descent", in the case of specifications the descent along different versions, either within a release or across releases. With the introduction of the new numbering scheme with 3G the lineage can also proceed across generations. 3GPP explicitly uses the term "descendant" to indicate the continuation of a specification from 2G series to a 3G series. I construct the lineage in the following way: All versions of a specification are ordered along the month of creation. Within a release this also orders along the technical identifier and the lineage runs from 0 to the maximum value. In addition editorial versions can branch off, however this is rather rare.

The transition from release n to release n+1 is handled in the following way: The last created specification in the previous release at the time of creation of the new release version is the ancestor. The lineage of a specification created in an early release and with many changes is presented by a by a lineage with several branches, where specifications still change in several releases (refer to figure 5.4). In order to define the trajectory, the part of the lineage where progress happens, I switch to the specifications of a new release as soon as they are created as this will include all changes in the new release as well as in previous ones. Furthermore I treat the number of accumulated CRs as trait of the specification. This allows together with the month of change to test for the mode of change as well as the tempo.

In figure 5.4 I show the lineage of a high pleiotropic specification (25.331) that

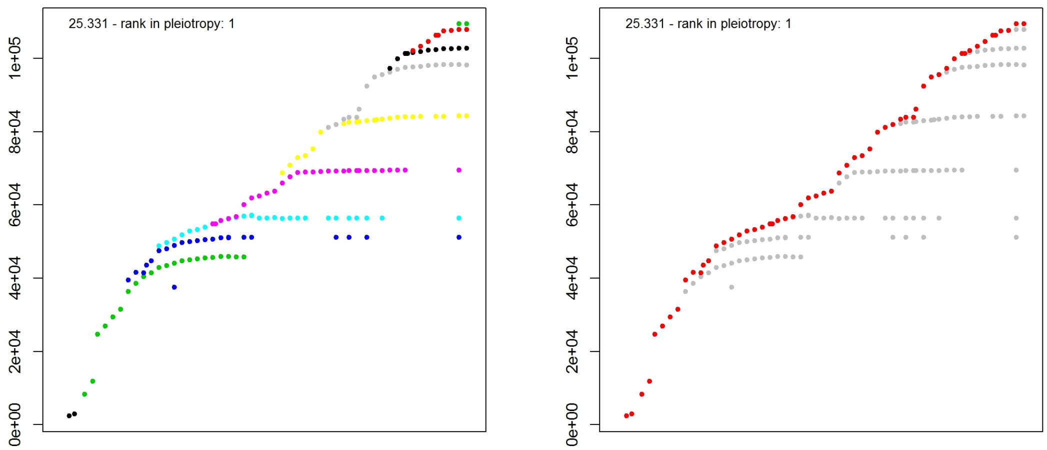

Figure 5.4: Lineage for a specification with high pleiotropy over all 3G releases with color codes for each release (left side) and the evolution along functional change (right side).

experiences many changes. Each point stands for a version of the specification with its month of creation and its length in line numbers. The colored points define the trajectory where different colors indicate different releases. While the trajectory shows a high, though varying, rate of change, the rather long release branches become flat soon after the bifurcation into the new release as they mainly contain corrections.

In this operationalization each specification is treated as a "species" or unit of analysis. Service description specifications track the evolution of the phenotype, stage 2 specifications the archotype, and stage 3 specifications the evolution of the genotype. While specification 25.331 is exceptional regarding the change it is underlying, many specifications have much less observation points. In order to cover the full standard, I aggregate the trajectories of single specifications to series-level trajectories by adding up the length for each specification of this series. In a similar way the trajectory of the whole system is obtained by adding the trajectories of all series. This allows to study the system at different levels.

Tempo and Mode

I follow the recently developed methods in paleontology (Hunt 2006) to distinguish between different modes based on maximum likelihood models. Based on the best model I derive the parameters of change (Hunt 2006, 2008). First I give an overview of three basic modes, random walk (unbiased and general) and stasis, and their statistical representation. Second I describe the procedure to select the best model based on the log likelihood and third I discuss the split of the lineage in sets of possible segments with differing mode and tempo along the trajectory.

The modelling is based on the lineage of species or entities whose traits or properties change over time. In the general random walk model the ancestor species at the begin of the sequence has a given mean of the trait X_A of interest. After t discrete time steps the descendant at the end of the observed lineage has a trait mean of X_D with

$$X_D - X_A = \sum_{i=1}^{t} s_i \quad , \tag{5.1}$$

where s_i is the change at step i. The s_i are random variables drawn from a probability distribution with a mean μ_{step} and standard deviation σ_{step}. With the assumption of independent steps s_i and a sufficiently large number of discrete steps the central limit theorem applies and the expected difference between descendant and ancestor is normally distributed with a mean of μ and a standard deviation of σ. This allows to maximize the log likelihood of the observed trait differences which will result in the estimates of μ_{step} and σ_{step}. In the general random walk model the mean μ is different from zero, while in the unbiased random walk model the mean μ equals zero. This implies, that the GRW model has two parameters (mean and standard deviation of the steps), while the URW requires only one parameter, the standard deviation of the steps.

While stasis appears intuitively clear as a model of stagnation and no change, it is not uniquely defined. Hunt (2006) adopted an approach with the underlying assumption of an optimal trait level θ with some allowed variation about this level, however without any net change in the trait level. The trait means are normally distributed with the mean of the optimal trait level θ and variance ω. It is a model of the trait values rather than the steps of change. As a consequence the difference to the random walk model is that the expected mean of the steps is not constant, but varies with the traits of the ancestors. As the trait level is assumed to be constant, a level larger than θ will lead to negative steps and vice versa. The maximization of the log likelihood model of the stasis model defines the optimal trait level θ and the variance ω.

For each three models (general random walk, unbiased random walk and stasis) the log likelihood is maximized. The best model is selected based on a modified Akaike information criterion AIC with

$$AIC = -2l + 2K, \qquad AIC_c = AIC + (2K[K+1])/(N-K-1) \tag{5.2}$$

where l is the log likelihood, K the number of free parameters. The AIC penalizes for additional parameters and favors the more parsimonious model, which gives preference to the URW in case of equal log likelihood. The modified AIC_c is a better criterion than the AIC in case the number of observations N is less than approximately 40 times the number of parameters

$$AIC_c = AIC + (2K[K+1])/(N-K-1) \tag{5.3}$$

The model with the lowest AIC_c is chosen as the best model. The chosen model defines the mode of change.

The procedure introduced so far allows to choose the best model for the whole lineage or trajectory. However, a key element of hypothesis 2 is, that the mode and tempo of change varies in the development process. In order to account for this, the time period of the trajectory is cut in up to $n_{segment}$ segments with a minimum number of observations $n_{minimum}$ in each segment. For each possible combination of segments the three models are calculated and the best model combination determined. For instance in case of a combination of five segments I calculate for each segment the three models and choose as best the one with the lowest AIC_c. The overall best model for the segment combination is the combination of the best models for each segment. The AIC_c is the sum of the single AIC_cs. The model over all possible segment combination with the lowest AIC_c is the overall best model. This procedure allows for different modes and tempo in each of the segment. The split into segment can occur in two ways: either allowing for overlap of segments or clearly separating them. The non-overlapping segments allow for punctuated change with jumps between levels. The model of punctuated equilibrium with stasis over a period, sudden change and stasis on a different level is in this approach modelled by two non-overlapping segments with two different stasis models, varying in the trait level θ and ω. In contrast, gradual change will result in GRW models.

Two parameter choices enter into the modelling: the minimum number of observations per segment $n_{minimum}$ and the number of segments. Hunt (2006) reported that models with five or more observations work rather well. While ideally the number of segments would be chosen as high as the number of observation N in the trajectory and $n_{minimum}$ allow, the rather long trajectories and N higher than 70 in many cases lead to a too high number of possible segment combination to be executable in a reasonable time. I therefore choose $n_{minimum}$ to be six, large enough to produce stable models and small enough to detect short periods with different mode and tempo. I choose a maximum of five segments, which makes the modelling tractable and allows for different modes and tempi within 3G as well as shifts with the evolution to 4G.

There is an important difference to the approach in paleontology, that leads to an conceptual and an empirical difference. Paleontologists model the traits of species as e.g. the beak length or beak shape, while I model the accumulated change measured in CRs, which is a measure of individual changes in the specification, not a direct property of the technological system as e.g. the data rate in the previous chapter. The underlying assumption is, that the change of system characteristics are proportional to the number of CRs. The advantage is that it applies to all specifications and series (in the aggregation) and number of CRs are comparable across specifications. The species I am modelling is either a specification or aggregation to series and system level, where each is unique, while paleontologists study samples of species with an observed variance. I therefore apply the modeling to samples of size one.

5.3.4 Innovation typology

Each innovation consists of one or more work items that can be mapped to phenotype and genotype specifications. From the master specification data set I infer whether the specification is new or already existing. Furthermore based on ancestor information of specifications I distinguish between truly new specifications and those that are successions of 2G specifications in 3G. Based on the number of total pheno- and genotype specifications and new ones the number of innovations in each quadrant can be conferred. The analysis is performed on release level.

5.4 Results

Here I present the tests for the hypothesis as well as some exploration of the PGM. I use the statistical package R, version 14.1, to perform the analysis. The package *igraph* (Csardi and Nepusz 2006) was used to construct the directed networks and the PGMs based on neighborhoods in the network, the package *bipartite* (Dormann et al. 2008) for the degree calculation and plots of the incidence matrices. The package *paleoTS* (Hunt 2006) was used for the evolutionary models for the specifications.

5.4.1 The PGM and hypothesis 1

Hypothesis 1 states that there is a positive association between the degree of pleiotropy of a design specification and its change.

	Staged PGM	DSM: all stages	DSM: only stage 3
Release 97	0.071	0.107	0.068
Release 98	0.255*	0.192**	0.185*
Release 99	0.287**	0.152**	0.198**
Release 4	0.274**	0.141**	0.164*
Release 5	0.244**	0.154**	0.183**
Release 6	0.399***	0.207***	0.275***
Release 7	0.402***	0.206***	0.285***
Release 8	0.284***	0.138***	0.166***
Release 9	0.413***	0.33***	0.411***
Release 10	0.453***	0.261***	0.32***

Table 5.1: Correlation between pleiotropy and counts of all change requests with three different PGMs.

Table 5.1 shows the correlation between the degree of pleiotropy and change in the specifications for Release 97 to Release-10 for three different PGMs as described above. The change is measured by the count of all approved CRs. The correlations for each PGM and for each release are positive. With the exception of Release 97 the correlations are significant. There is a growing trend from Release 97 to Release 10 across all three PGMs with a dip in Release 8. While the values differ, the level of 0.15 to 0.3 or even higher applies to most releases (earlier releases are not included due to small number of genotypes). These results are confirmed when only functional CRs are considered, those CRs that induce true functional change, as shown in table 5.2. For most releases the correlation values are slightly lower, but still in the range between 0.15 and 0.3 or higher.

Overall I conclude that hypothesis is confirmed with some caveats for early releases, which may be due to data issues rather than lack of correlation. While the correlation

	Staged PGM	DSM: all stages	DSM: only stage 3
Release 97	0.212	0.238**	0.169
Release 98	0.343**	0.304***	0.299**
Release 99	0.336***	0.211***	0.271***
Release 4	0.347***	0.233***	0.257***
Release 5	0.220**	0.164**	0.146*
Release 6	0.420***	0.225***	0.278***
Release 7	0.354***	0.259***	0.325***
Release 8	0.420***	0.244***	0.272***
Release 9	0.233***	0.263***	0.311***
Release 10	0.429***	0.239***	0.272***

Table 5.2: Correlation between pleiotropy and counts of only functional CRs.

is positive and in many cases significant, the median value in the range of 0.2 to 0.3 also suggests that there may be high pleiotropy specifications with little change and/or low pleiotropy specifications with high change.

Figure 5.5 shows the top 10 pleiotropic specifications based on the staged process PGM (these largely overlap with those based on the DSM-based) and their rank over several releases. The specifications are ordered along their numbers, where 2G specifications are combined with their descending 3G specifications when they are both within the top 10. The darker an element in the matrix, the higher is its pleiotropic rank, i.e. the specification with the highest pleiotropy are nearly black. Ranks less than 10 are not considered. While a couple of specifications appear only for one or two releases in the top 10, there are a few persistent top 10 specifications. This persistence occurs across generations — several 2G specifications are still high pleiotropic in their 3G incarnation and they persist also with the advent of 4G in Release 8. This persistence cannot be taken as granted, as the PGM is growing by an order of magnitude over the observation period, which allows new specifications becoming high pleiotropic. In the following I have a closer look in table 5.3 at these persistent high pleiotropic specifications (at least in 4 releases in the top 10) with their first release, their z-transformed counts of change

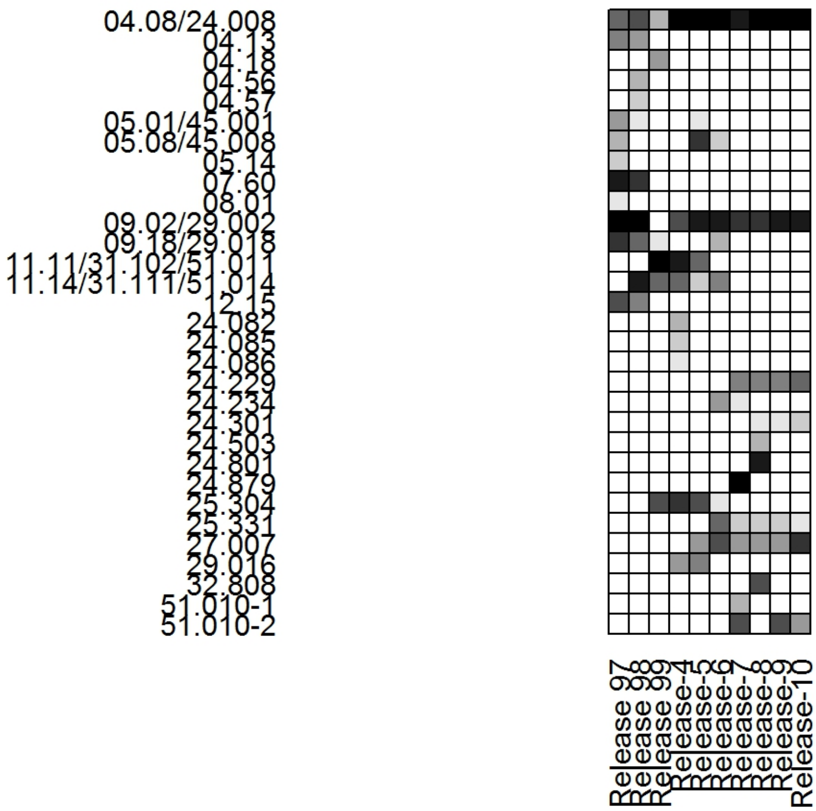

Figure 5.5: Top 10 pleiotropic specifications.

requests for Release 6 and Release 10, and the categorization in 3GPP's architecture.

Specification	First release	Rank CRs Release 6	Rank CRs Release 10	z change Release 6	z change Release 10	3GPP category
04.08/24.008	Phase 1	11	5	1.81	5.32	basic
05.08/45.008	Phase 1	33	44	0.62	0.55	basic
07.07/27.007	Phase 2	69	21	0.04	1.23	basic
09.02/29.002	Phase 1	16	33	1.38	0.83	basic
09.18/29.018	Release 97	199	58	0.27	0.33	basic
11.11/31.102	Phase 1	22	75	0.99	0.11	basic
11.14/31.111	Release 96	42	54	0.39	0.36	basic
24.229	Release 5	5	1	4.63	7.27	specific
24.301	Release 8	NA	3	NA	5.79	
25.304	Release 99	59	98	0.10	-0.10	basic
25.331	Release 99	4	4	6.80	5.79	basic

Table 5.3: Persistent top 10 specifications and their rank in change.

Six out of eleven of these specifications are actually quite old and were created in the very first release of the 2G or 3G system. In particular the four specifications created in the very first release (Phase 1) can be considered at the heart of the system. Only one specification is part of the specific configuration, while the other ten are part of the basic configuration according to 3GPP's own classification of core and periphery. 24.301 was included in the list, though it has only three appearances as it was created only in Release 8 and describes part of 4G.

While these persistently high pleiotropic specifications are not all among the top changing crowd, they are all within the top third or higher. Three specifications stand out: 04.08/24.008, a specification of the heart of the system, is in the top 10 (or top 11 in this case for Release 6) changing specifications, 24.229, a specific entities describing specification is on the top together with 25.331 a core specification. Nearly all have positive values of the z-score of the number of CRs, indicating that there change is above average.

The other perspective to the bipartite PGM is the one of services. Are there core

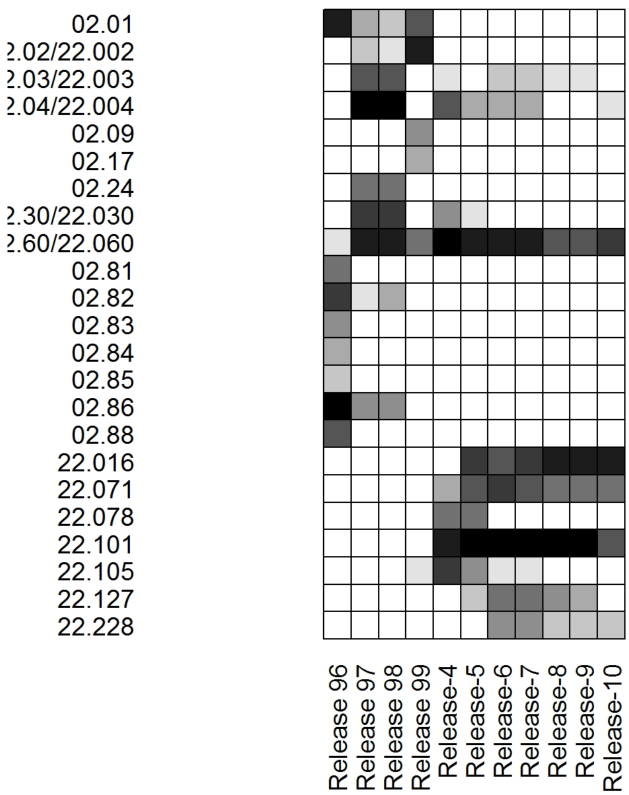

Figure 5.6: Top 10 polygenic services.

services persistent over the observation period? Figure 5.6 depicts the top 10 of polygenic services, i.e. services that require most specifications for their implementation. Similar than for the top 10 of the high pleiotropy implementation specifications, there are services already defined in 2G with descendants in 3G and newly created services in 3G as well as persistently high in polygeny as well as only in one or two releases. The three persistent services are 02.03/22.003, 02.04/22.004 and 02.60/22.060. The first two were introduced in the very first release and describe very basic services as *Circuit Teleservices* and *General on supplementary services* and the third one is the data service *General Packet Radio Service*, the 2.5G step in the evolution of the system. Of the consistent 3G services one is very general (22.101: Service principles), while others are specific services with specific network elements (22.071: Location Services and 22.228: IP-based Multimedia Service). Location Services were introduced in the last 2G release, Release 98, however are only two releases later among the top 10 polygenic.

5.4.2 Hypothesis 2: Mode and Tempo

In this subsection I discuss the results of hypothesis 2 that postulates that gradualism is the dominant mode of change with changing pace over time for phenotypes, archotypes and phenotypes. General random walk models are associated with gradualism, while unbiased random walk and stasis are associated with stagnation.

I look first at change at the system level from the beginning of 2G to the evolution of 4G, then on functional areas (series) that define pheno, archo- and genotypes from the period of 3G and 4G development. 2G is excluded as many of its specifications have a rather short period, which makes the modelling unstable. In the following figures the trajectories for the fill system as well as different functional areas and selected specifications are shown with the number of accumulated change requests (CRs) on the y axis. Blue dots indicate unbiased random walk with step length of zero, red points

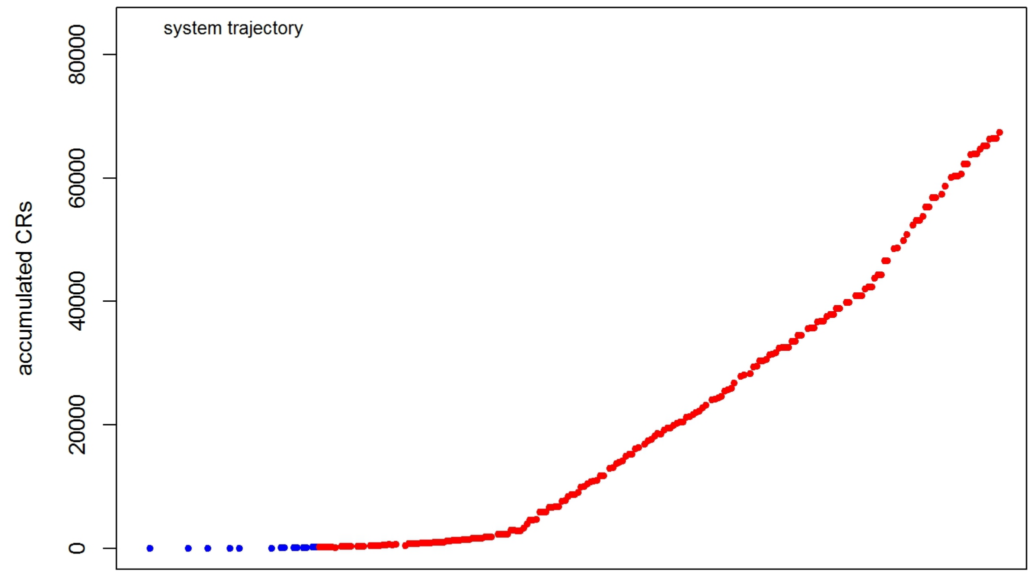

Figure 5.7: System trajectory from 2G to 4G

general random walk and black points stasis. For each segment the type of model and parameters are given. The parameters for random walk models are length and standard deviation of steps, for stasis model the optimal levels and standard deviation of steps.

Figure 5.7 shows the trajectory of the whole system, including all specifications. The system trajectory shows four distinct periods of change. With the exception of the first two years that are characterized by unbiased random walk, the evolution is characterized by general random walk with varying step length and standard variation. The transition from 2G to 3G is not a punctuated change, but a shift in gears with an increase of the step length in the random walk model by an order of magnitude. While this indicates a shift in the evolution dynamics, it is not a short-term sudden change, but prevails during the 3G evolution. With the advent of 4G the dynamics is increased again, however with a lower increase in step length by nearly a factor of two. While

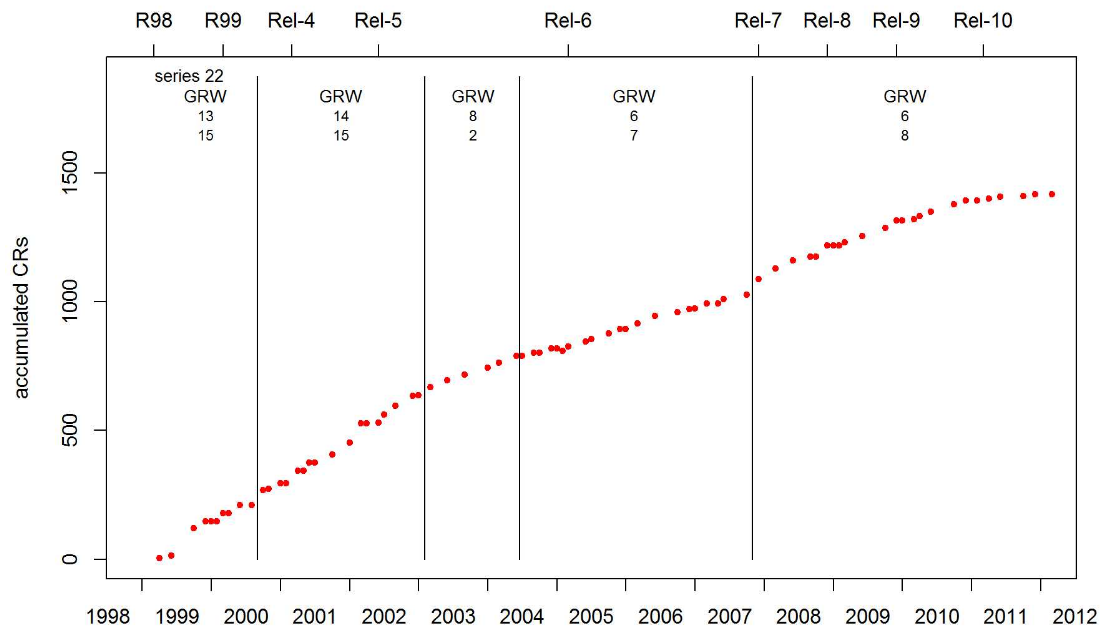

Figure 5.8: Phenotype trajectory for 3G and beyond

the system trajectory is very smooth with increasing tempo of evolution from 2G to 4G, different parts of the system can show different patterns of change. In March 2012 the system trajectory had accumulated 67.343 CRs, about two third of total CRs. The difference to the total number of CRs is due CRs in the branches of the lineage that are not on the trajectory. I will come back to this point later. The GSM evolution accumulated 4033, the 3G and 4G evolution, excluding the GSM part, accumulated 55.023 CRs and the GSM part within the 3G period 8297 CRs.

Figure 5.8 shows the trajectory of all phenotype specifications (series 22) with five different GRW models. Overall the change is very low with values between six and fourteen CRs per month. The phenotypes show greatest change after the introduction of 3G and then slows down. The shift to 4G is characterized by an increasing variance in step length, rather than increase of step length. With less than 1500 CRs the phenotype change contributes 2.5 percent of the 3G changes.

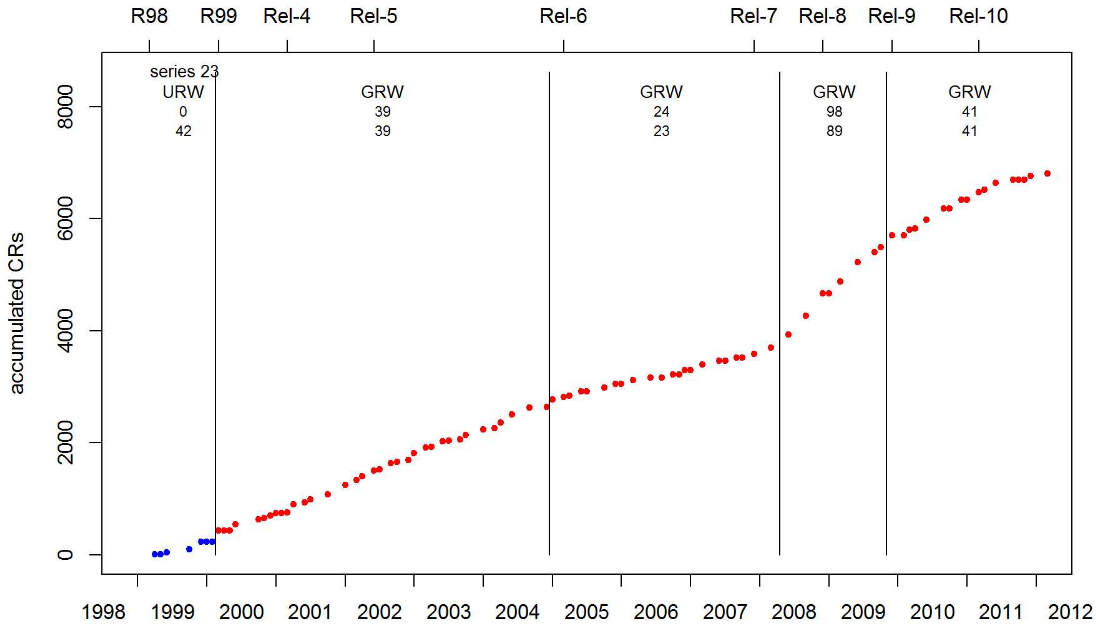

Figure 5.9: Archotype trajectory for 3G and beyond

Figure 5.9 shows the trajectory of archotype specifications (series 23). Again gradualism is the dominant mode with a slowing down in tempo for later 3G release and an increase of approximately an factor of four prior to the first 4G release (Release 8). After two years the evolution slows down to less than half the previous level. The accumulated number of CRs of 6811 is 12.4 percent of the system trajectory, emphasizing the importance of the archotype descriptions of the system. In the following the largest functional phenotype areas are displayed.

Figure 5.10 shows the trajectory of the interface between the user equipment and the network (series 24). It shows a steady increase of pace during the 3G part of the trajectory and increase of nearly factor three prior to the first 4G release and a decrease of factor 1.6 after one and a half year. This trajectory covers approximately nine percent of the 3G trajectory.

Figure 5.11 shows the trajectory of the radio network (series 25). The largest change

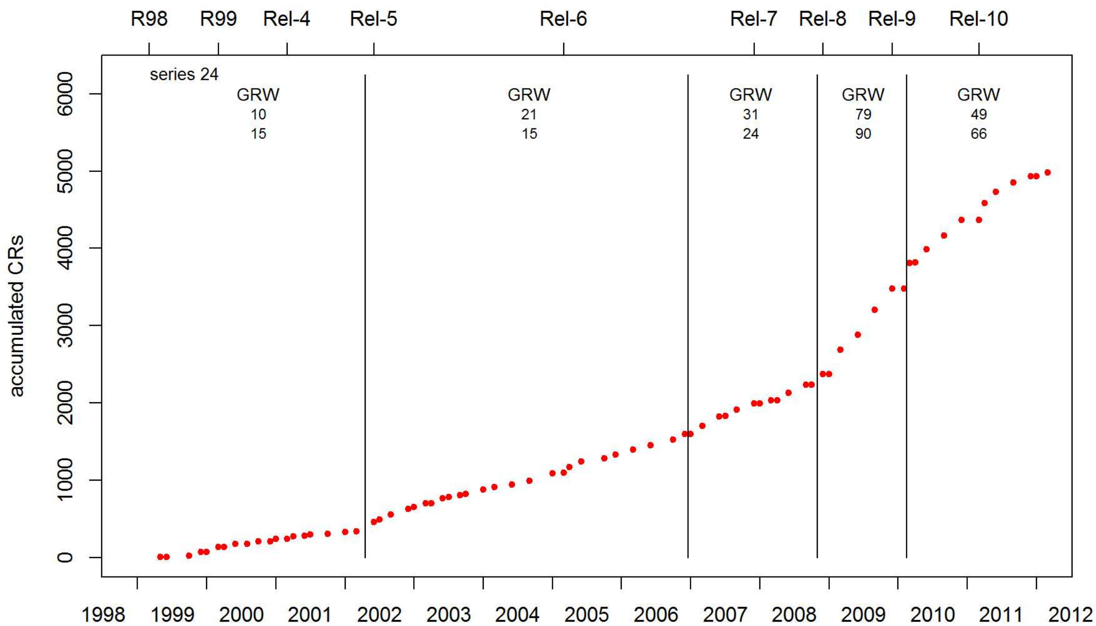

Figure 5.10: 24 series trajectory for 3G and beyond

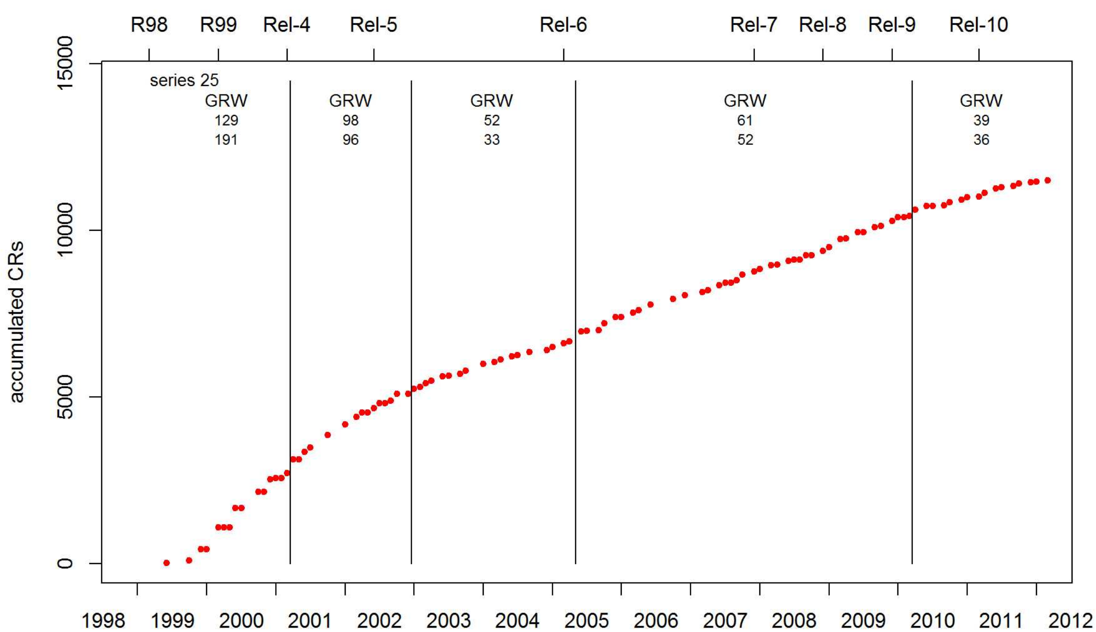

Figure 5.11: 25 series trajectory for 3G and beyond

Figure 5.12: 29 series trajectory for 3G and beyond

rate was during the early period of 3G with a slow down during later releases and slight increase previous and during the introduction of 4G. The highest pace at the beginning reflects the introduction of a new radio network with 3G. This trajectory lacks the strong increase of pace with 4G, because a new specification series for 4G radio network was created. Its development shows the ongoing change within 3G even after the introduction of 4G. With 11.504 accumulated CRs, 21 percent fo the 3G trajectory, the radio network is the largest single functionality within the system and it still surpasses the new radio network by 40 percent in number of accumulated CRs on the trajectory.

Figure 5.12 shows the trajectory of the core network (series 29). Similarly than the trajectory of series 24 it shows a steady increase of pace during the 3G period and increase of tempo by a factor of approximately 2.5 prior to the first 4G release and slowing down again to the previous level after three years. With 6377 accumulated

CRs this trajectory contributes 11.6 percent to the 3G trajectory.

While the figures provide an overview of the most important series, table 5.7 shows the models for phenotypes and archotypes and table 5.8 for all 3G genotype series with up to five segments. The tables provide the series number, the mode of change, the number of months covered by the segment, the AIC_c, the mean and the standard deviation of step length. By definition the mean for the URW is zero. Only random walk models occur for series trajectories, with GRW models being dominant.

With the length of segments in five-segment models varying from 6 to 100 months rather short periods with different mode and tempo are identified, while also rather long periods exist. The very short periods exist for the new 4G series The mean step length in the GRW model can shift by a factors of three and four between segments — for instance for series 23 the mean changes from 24 in the third segment to 98 in the fourth segment. In series 33 the mean changes from the first to the second segment by a factor of 2.9. Shifts by a factor of two occur quite often. The five-segment models however also allow to detect more nuanced shifts where for instance only the standard deviation is changing. The series vary largely in the number of accumulated CRs. The accumulated CRs in the last month (March 2012) and the percentage of the 3G trajectory is given in the last two columns of the table. There is a high correlation of 0.957 between the mean and the standard deviation for the GRW models, hence a higher mean leads to more variance. The standard deviation is 1.02 times the mean.

The tables 5.7 to 5.9 in the appendix of this chapter reveal that the GRW model is by far the most dominant mode for phenotypes, archotypes and genotypes. Furthermore the tempo varies along the trajectories with the largest increase in the period prior to the first 4G release, though rate change by a factor of approximately two occurs also during the 3G period. Figure 5.13 shows the ratio of mean path lengths of the new over the last period. The size of the dot indicates that size of the trajectory. The largest

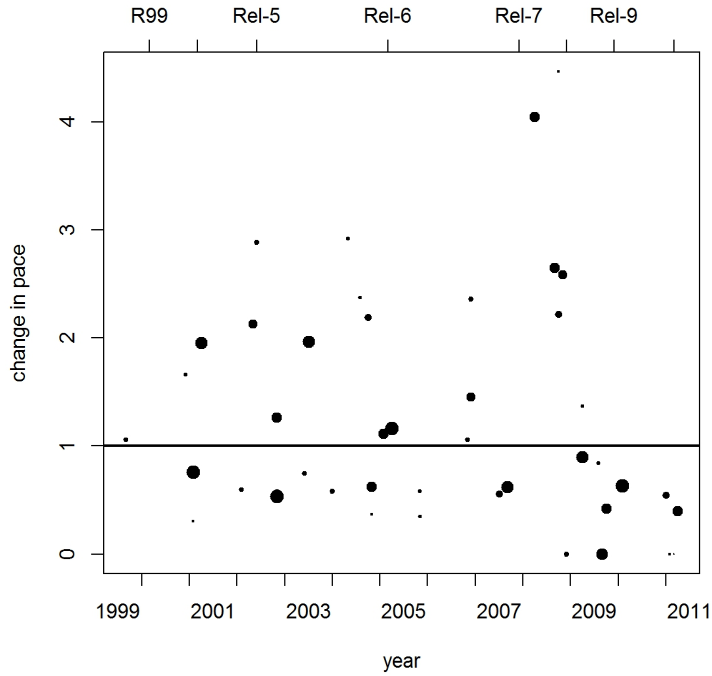

Figure 5.13: Ratio of mean step length over time.

change of a major series is the archotype change with an increase by a factor of four.

The dominance of the GRW model does not yet allow the conclusion whether there are punctuations between the models, i.e. jumps between the models. The rational is to compare the jump, the difference between the level of the last data point of the previous model and the first data point of the new model, with steps of the model with higher dynamics. First I substract from the mean jump (the total jump divided by the number of months between the models) the mean path length of the model and then divide by the standard deviation of the model path length. While there is no clear definition of what constitutes a punctuation, often an order of magnitude is used (Anderson and Tushman 1990). Figure 5.14 shows the distribution of jumps expressed in terms of the standard deviation of the more dynamic model. All are below ten and even a more conservative approach of two standard deviations will lead to smooth transitions between models in most cases. Table 5.14 shows the jumps with more than

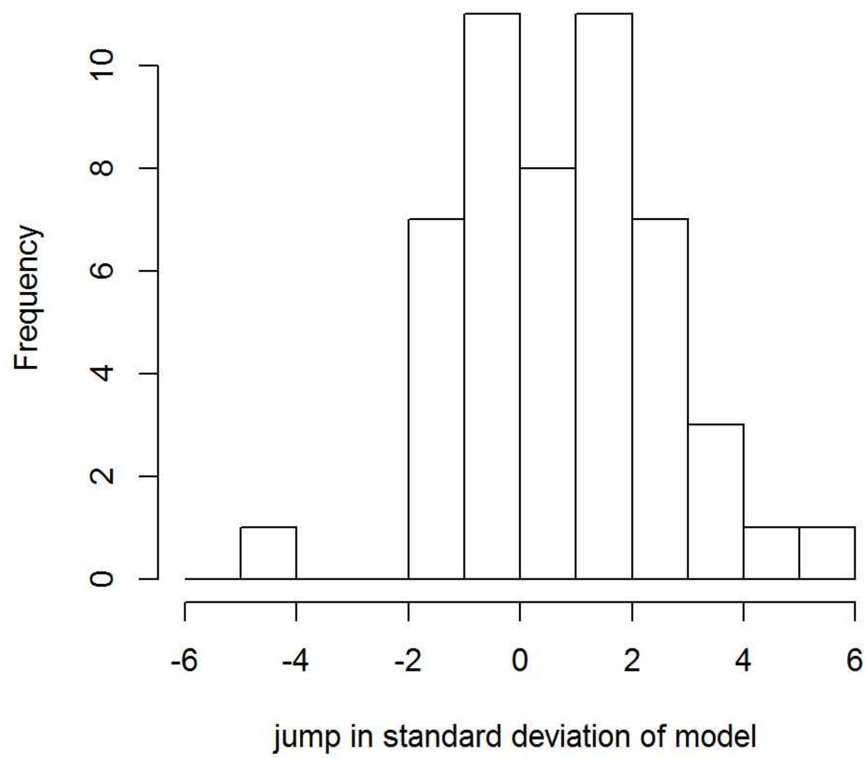

Figure 5.14: Distribution of jumps in standard deviations of the change model.

two standard deviations. Jumps occur through the whole period with the largest values either at the early 3G or 4G periods. Phenotypes (series 22), archotype (series 23) and genotypes show small to moderate jumps.

I conclude that hypothesis 2 is supported with gradual change the dominant mode of change for all three types of specifications.

In the test of hypothesis 1 part of the robustness test was the to test the PGM for only functional CRs. Figure 5.15 shows in addition to the trajectory based on all CRs (red points) also the trajectory taking only functional CRs into consideration (blue points). While the overall trajectory of functional CRs is similar to the trajectory of

Series	Month of shift	Jump
22.0	216.0	3.0
23.0	123.0	4.2
23.0	181.0	2.5
24.0	243.0	2.8
25.0	244.0	2.6
26.0	136.0	4.0
29.0	157.0	2.9
29.0	184.0	3.4
31.0	178.0	2.2
32.0	256.0	5.2
34.0	244.0	2.0
36.0	256.0	2.1

Table 5.4: Model transitions with deviations larger than two standard deviations.

all CRs, the functional CRs are doubled within half a year prior to the first 3G release.

The functional trajectory reveals two important issues: First, a fine-grained temporal resolution is crucial in the distinction between punctuation and gradualism or unsampled and sampled punctuation (Hunt 2008). While this appears to be a measurement issue only, it relates to the research question and the appropriate unit of analysis. If the research interest is for instance how releases of the standard evolve, measurement at the freeze date of each release would be appropriate and an unsampled punctuation between 2G and 3G occurs for functional change. However, if the interest is the continuous technological evolution based on the process, the more fine-grained resolution of the working process is required. Second, corrections (non-functional CRs) are the majority of all CRs. On average each functional CR creates 4.4 corrections. Though new functionality is added to the standard via the functional CRs, the system will not function properly without corrections and improvements. According to 3GPP corrections increase when firms start to develop real systems based on the standard. They are an essential part of the pre-developmental standard setting as only then the functioning of real products can be tested.

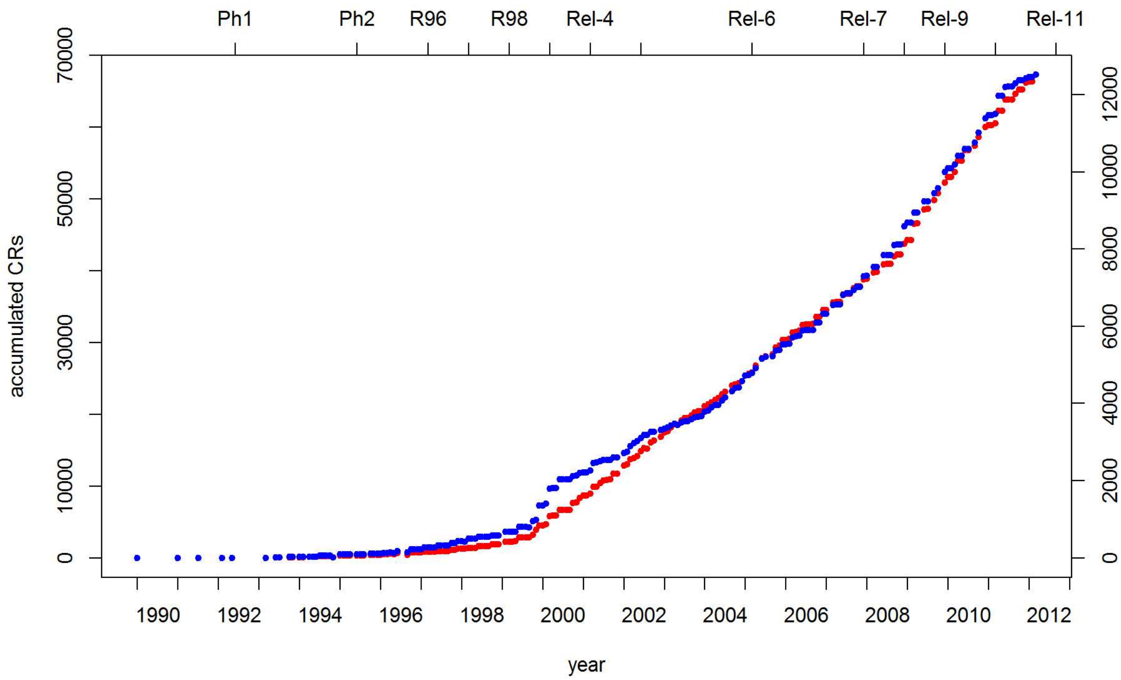

Figure 5.15: System trajectory with all CRs and only functional CRs.

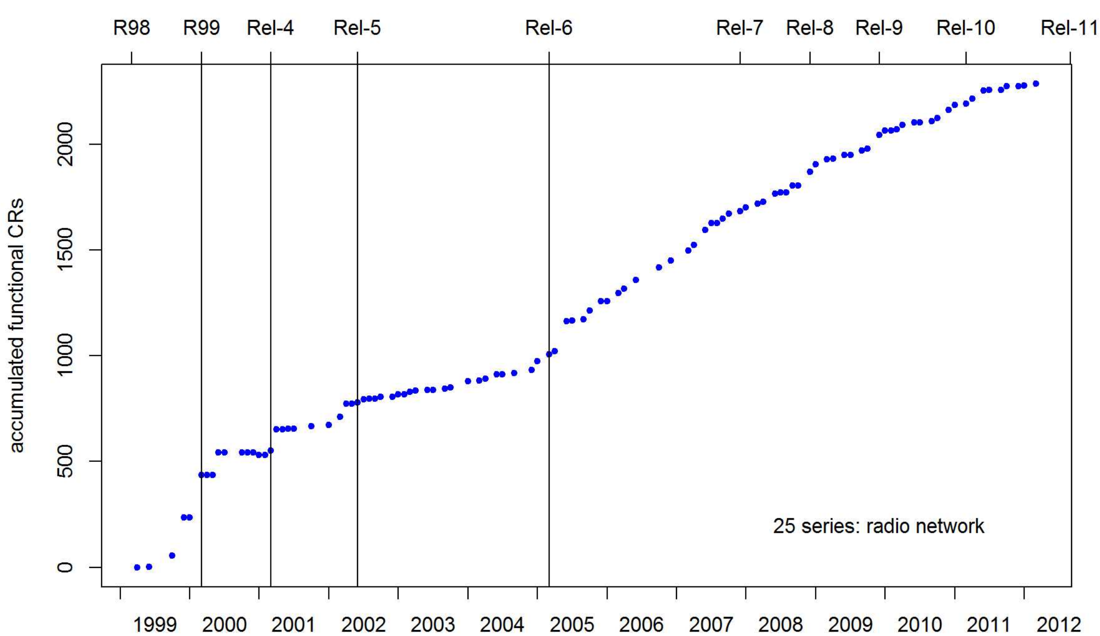

Figure 5.16: Trajectory of 25 series with only functional CRs.

The example of the purely functional trajectory of the radio network is shown in figure 5.16. The early 3G releases are characterized by punctuated equlibria with jumps between releases and flat trajectories during the release development. This illustrates that the question of PE versus gradualism is not only a question of time resolution and modelling, but also what comprises technological change. I argue that corrections are an indispensable element as only they provide the correct functioning of the system.

5.4.3 Innovation typology

Figure 5.17 presents the empirical innovation types. The distinction between low and high in the typology is drawn by the mean value for new phenotype and genotype specifications respectively. The size of each data point indicates the total number of specifications it impacts. On the left side all new specifcations are considered, independent on the existence of an ancestor specification in 2G, while on the right side only truly new specifciations without ancestors are considered.

All four types are populated. A couple of innovations impact a rather high number of new services, however when the ancestry is taken into account the number is reduced. This implies that these innovations impact several 2G services. For the typology I use the truly new specifications.

The quadrant of new phenotype/new phenotype contains several innovations. The innovation with three new services is the introduction of the new radio network with 3G. It impacts three new, general service specifications: *Service aspects* (22.101), *Services and service capabilities*, and *Service aspects, charging and billing* (22.115). This is an innovation that is regarded in the literature as radical (Ansari and Garud 2009). The two major innovations for 4G are in the radio and core network. The core network innovation has one new service (*Service requirements for Evolved Packet Service*) and 32 new implementation specifications (*3GPP Architecture Evolution Specification*

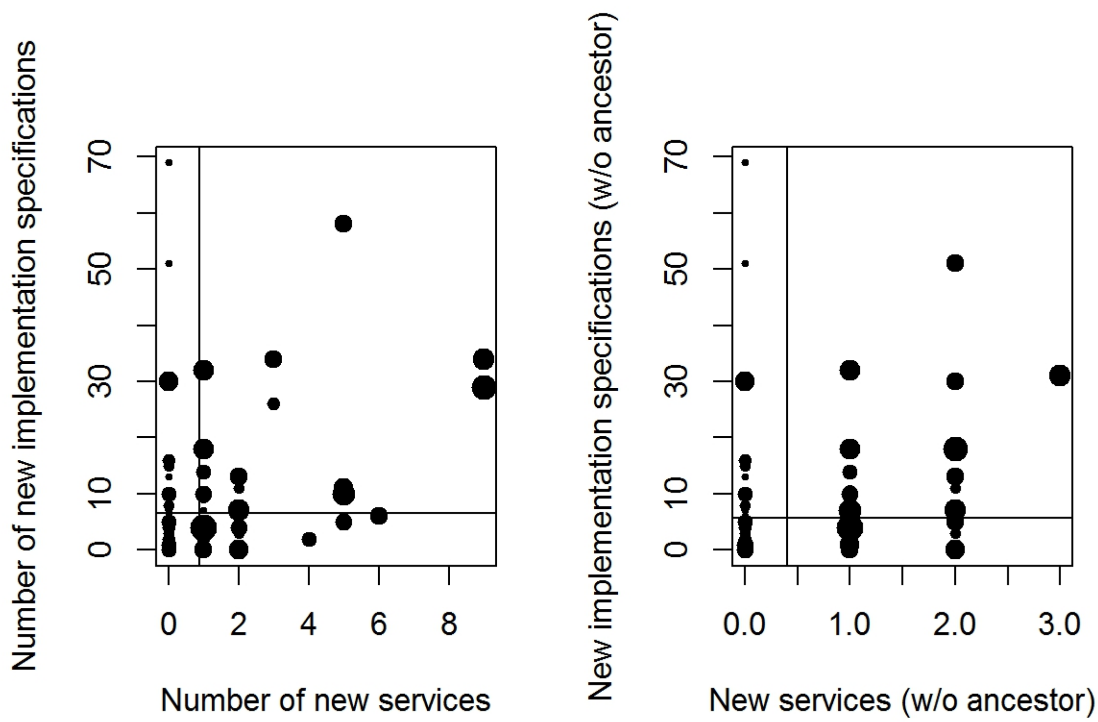

Figure 5.17: Empirical innovation types for all new specifications (left side) and new specifications without ancestor (right side).

- *Evolved Packet System*). The radio innovation in 4G has no new service, but 69 new implementation specifications (*Long Term Evolution - Evolved Packet System RAN part (LTE)*). It is an example of a radical 2 innovation that enhances existing services with new technology.

While figure 5.17 shows that all four types occured during 3G and 4G, it does not yet prove simultaneity. In table 5.5 the number of innovation types for each release is presented. While Release 99, 5,6,7, and 8 have all innovation types, Release 4 has only incremental innovations, Release 9 lacks radical 2 innovations and Release 10 radical 2 and radical square. With this hypothesis 3 is partially confirmed.

	incremental	radical 1	radical 2	radical square
R99	9	4	1	7
Rel-4	8	0	0	0
Rel-5	7	1	1	1
Rel-6	5	5	5	3
Rel-7	10	3	2	1
Rel-8	11	2	3	2
Rel-9	7	2	0	1
Rel-10	7	1	0	0

Table 5.5: Innovation types for all 3G releases.

However, table 5.5 also reveals a data issue: the included innovations are much less than those developed during this period. For many innovations no phenotype specification information is provided. While this suggests a conservative test of hypothesis it also raises questions regarding the distinction of quadrants based on the mean. While the above discussed innovations and their classification makes sense, results need to be interpreted with care. In particular no conclusions can be drawn regarding the number of innovations for each type.

Though the definition of the innovation type based on new service and implementation specifications is straight forward, it ignores the total scope of the innovation and

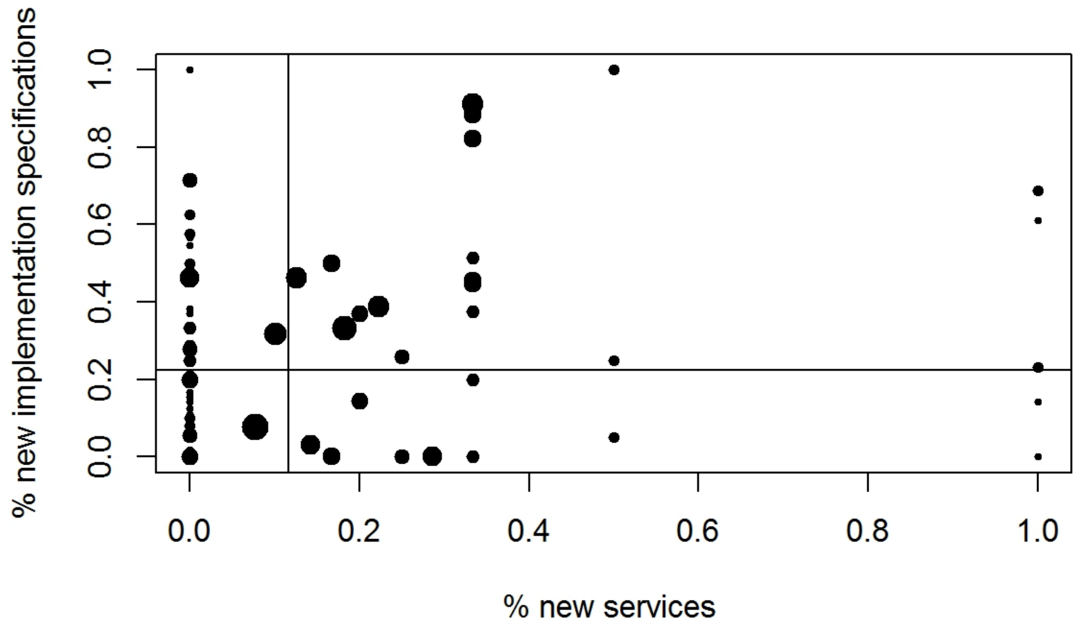

Figure 5.18: Empirical innovation types based on percentage of novelty for all new specifications.

to which degree the affected specifications are novel. Two different innovations, both with one new service specification, differ very much in their service novelty if one affects only one service, while the other affects seven services. In order to capture the relative novelty figure 5.18 shows the innovations based on the percentage of new phenotype and genotype specifications. Again, all four type quadrants are populated, however only few innovations affect only the new service.

The distribution of innovation types on release level is similar than in the previous, however there are some shifts between the types.

5.5 Discussion

The literature of technological change, either as life cycle models or technological trajectories, follows a paradigm of revolutionary change based on punctuated equilibria

	incremental	radical 1	radical 2	radical square
R99	7	2	4	8
Rel-4	8	0	0	0
Rel-5	5	0	4	1
Rel-6	3	3	7	5
Rel-7	11	3	1	1
Rel-8	5	2	9	2
Rel-9	7	1	0	2
Rel-10	6	1	1	0

Table 5.6: Typology of innovations based on the percentage of new services and new implementations for all 3G releases

with a stable core or deep structure (dominant design) underlying the stagnation and its change the sudden shifts or punctuation. The key thrust of this study is that the engineered process in a SDO with a modular system is largely different to biological processes, on which the PE paradigm is built upon. The designed evolution in the system's core structure leads to gradual change with varying tempo. The distinction between revolution and evolution in such a regime is more a matter of degree rather than fundamental shift. The fine-grained data of the development process of the standard together with recently developed methods of modelling the evolutionary allow the determination of mode and tempo of the trajectory.

5.5.1 Change process

The development process in the SDO differs from the biological-oriented process by the direction of causality between genotype and phenotype and a correction process. First, in the SDO the definition of new service characteristics start the change, and the genotype specifications and their relationship are identified in an archotype and finally the genotype specifications are changed. This also occurs for product development in firms and for systems with low complexity via the coordination by a hub firm or platform leaders (Gawer and Cusumano 2008). However with increasing complexity one firm may not be able to perform this task as it requires sufficient knowledge to define the architectural structure of the whole system. Mondragon et al. (2009) described this shift in the automotive industry, where the high complexity of electric and electronic architecture lead to the formation of AUTomotive Open System ARchitecture (AUTOSAR), a development partnership of car manufacturers, suppliers and firms from the semiconductor and software industry. The fundamental distinction between an ecology lead by a platform leader and a SDO or innovation partnership is the broader base of involved firms in the architectural definition. It leads to reduction of uncertainty with the combination of technological and market knowledge that shapes a common understanding of the development direction. It also allows to integrate a broader range of knowledge from the whole innovation ecology. Consensus-driven decision making, the approval process for service, architecture and technical changes, and transparency about all ongoing changes provide the routines to let a SDO act as a single designer.

Second, the comparison of the trajectories based on all CRs and functional CRs revealed the different behavior of functional and correctional CRs. Functional CRs implement the designed change, the correctional ones rectify errors and allow proper functioning, a distinction that does not exist in biological change as there is no design. Functional changes are mainly at the beginning of the development of a new release leading to a strong increase in the underlying functional trajectory and flattening afterwards. They show a behavior complying with the PE paradigm. Functional changes act only on one release. The correctional CRs follow the functional changes and the early real life implementations, which detect incomplete, inconsistent and ambiguous specification of the system. They continue for a long time after the functional change as the full trajectory in figure 5.4 shows, because real life systems in use will detect further errors. They not only facilitate a functioning system and concordant interpretation of the standard by different organizations, but also corrections across several releases. An error detected in an older release, which is still active in the field, will also exist in later releases and need to be fixed there, too. Their trailing dynamics leads to the smoothing of the overall change trajectory. The correcting CRs outnumber by a factor of more than four the functional CRs and they are an importance part of the CR process as they guarantee proper functioning. The distinction between functional and correctional change help to reconcile different shapes of technological trajectories. Trajectories based on a market-oriented perspective will focus on functional change only as the functional and service characteristics are those on which the selection process acts upon and will see more likely punctuation. Trajectories based on a perspective of the development process, of which corrections are an inevitable part of, will see a gradual development. This raises the question of the unit of analysis, or the species in the biological picture.

5.5.2 The *species* — the unit of analysis

In biology a species is defined as a group of interacting individuals that are isolated regarding their retention mechanism. I choose as species the trajectory of the technical system, which is a concatenation of several releases of the system along the functional change and study the dynamics of phenotype, archotype and genotype. Each release segment can be seen as a distinct species as the functional change acts only on this release. However, there are three important caveats: First, some innovations and their functional change refers to 2G and 3G, both covered in the same specification. Hence, there is a retention connection between 2G and 3G and they are not independent in their development. Second, as discussed above, the correction process acts on several releases simultaneously and they are not independent in this respect. Third, while functionally an old release migrates into a new one and results in the studied trajectory, it still coexists for a long period with the new release. This behavior is different to the gradual speciation in biology where a large part of the ancestor population transforms. Also in a broader scope independence between different species or trajectories will be given only approximately at best. For instance in the broader scope of cellular telecommunications 3GPP incorporated interworking with the competing technologies as Code Division Multiplexing Access (CDMA) and Wireless Local Area Network (WLAN). Technological progress and learning is driven by imitation and spillovers that leads to exchange among technological trajectories. The independence of species will often not be given for technological systems.

Levinthal (1998) defined the technological trajectory based on new market niches. The approach in this study differs by studying a technical trajectory, that implicitly covers diverse applications. With a global standard that provides the technology for a variety of applications all potential applications and their requirements need to be fed into the SDO as there is no adaptation of the standard outside of it. As a consequence 3GPP has liaison relationships to an extended list of other standardization bodies and groups to align development work. Further coordination is facilitated by the partner organizations, which are SDOs themselves. For instance begin of 2012 the organizational members announced to form a global initiative for machine-to-machine communication (ETSI 2012) and ETSI, one of the partner organizations is involved in standardization activities regarding health, transportation and utility systems, all areas into which cellular telecommunications is migrating. With the increasing pervasiveness coordination effort across industries will become increasingly difficult and new models of coordination beyond a single SDO may be necessary.

The technological trajectory under study is a species with a population of one in contrast to biological species. The standard and its trajectory can be seen as an umbrella trajectory or a catalog of service characteristics and their implementations, from which firms can choose. Network operators will choose the service characteristics relevant for their market, system providers will choose what to implement based on their customer base and specialist firms will develop only products on a small part of the standard. While the standard development provides a pre-selection of services and their technical implementation, the final market selection will occur after the product development.

The standard trajectory is the trajectory of the development process, where the relevant time resolution is monthly or quarterly based on 3GPP's meeting schedule, while the implementation of real systems and their components occur based on releases, which are typically annual or biannual. The different time resolution can lead to different modes of change, in particular when applied to functional change only.

5.5.3 Innovation typology and ambidexterity

The innovation typology is based on new phenotype and genotype specifications, where new genotype specifications are largely due to augmentation of the system by new system components. Despite a reduced innovation set there is some evidence that for most releases all four type of innovations exist, underscoring the ambidexterity of 3GPP.

The merit of this typology is the distinction between novelty in service versus technical characteristics (Murmann and Frenken 2006). The distinction in novelty in terms of number of specifications and percentage is important. It allows in particular to distinguish between radical square innovations due to augmentation, i.e. a new service is introduced by new network elements and a new core structure. Both will have a high percentage of new genotype specifications, but differ in the percentage of new services. A new core structure needs to provide a similar functionality as the old core structure and will impact many old, basic services, while the augmentation will focus largely on the new service. Both, the introduction of the new radio network in 3G and 4G have a high percentage of new genotype, but a rather low percentage of new phenotype.

The simultaneity of innovation types identifies 3GPP as an ambidextrous organization with exploitation and exploration at the same time, in both dimensions, technical and service-oriented. The exploration on the technical level can be the extension, substitution or augmentation on the level of a subsystem. The SDO as open system with influx of resources from outside by the participating member organization alleviates the resource constraint in the balance of exploitation and exploration. Furthermore the openness leads to a large heterogeneity of knowledge resulting in a broadening of the knowledge base within the SDO, even when member organizations perform rather local search The separation between exploration and exploitation occurs on project level of single innovations, where however in most cases exploitation, the building on existing services and knowledge occurs in parallel with the creation of new services and knowledge. This implies that contributing firms to an exploratory innovation do not necessarily perform an exploratory task — they can contribute on the exploitative part. The creation of new specifications is a joint effort of member organizations, where proposals are presented, discussed and refined based on other proposals. However, the detailed process goes beyond the scope of this study, which is empirical built on the CR process.

5.5.4 Limitations and future research

This study has several limitations. First, the study of change is based on the CR process, which only covers change after specifications reach a certain maturity. It does not cover the creation of new specifications. Second, while the system trajectory is studied from 2G to 4G, the analysis of phenotype, archotype and genotype is restricted to the period of 3G and 4G development. Third, the functional areas of genotype are rather broadly defined and do not allow the resolution on component and interface level of the system below the distinction of first level subsystems as core and radio network and terminal equipment. Fourth, while the measurement of change based on CRs is close to the monitoring of the change process within 3GPP, it is only an indirect measure of system characteristics. Fifth, the lack of identification of phenotypes for all innovations weakens the test of the simultaneity of innovation types and is more an indication rather than a rigorous test.

The findings of this study and above mentioned limitations points to several promising avenues for future research. First, as the standard defines the umbrella technological trajectory based on which firms make the decision of implementation of real products, the study of commercial products based on the standard as mobile devices can shed light on the difference between *technical* and *market* trajectory.

Second, though 3GPP is identified as ambidextrous organization based on the simultaneity of innovations, the antecedents and process remain largely descriptive. While ambidexterity is normally applied to a single firm, the SDO is a community of diverse organizations. This raises questions whether the concept, antecedents, process and outcome are still the same as within firms. The study of the process of creation of new specification and the interplay of the diverse input by various organizations can help to understand the exploration within SDOs. While it is acknowledged that the balance of exploitation and exploration is crucial for the performance of firms, the question arises whether this is also true for SDOs and if so, what defines the performance of SDOs? This questions becomes increasingly important with the pervasiveness of cellular telecommunications and ICT in general and emerging SDOs in industries traditionally void of them. 3GPP and its rival SDO, 3GPP2, can serve as a natural experiment with a comparison in the same industry.

5.6 Appendix

Series	Mode Mode	Shift (month)	Period (months)	AICc AICc	Step mean	Step std	Pace CRs	Percentage
22	GRW	99	17	84.6	12.9	15.1		2.6
22	GRW	117	28	143.2	13.6	14.8	1.1	
22	GRW	146	16	34.8	8.1	1.7	0.6	
22	GRW	162	40	148.8	6.1	6.8	0.7	
22	GRW	203	52	181.8	6.5	8.1	1.1	
23	URW	110	11	66.8	0.0	41.6		12.4
23	GRW	121	58	363.7	38.8	38.9		
23	GRW	179	39	206.7	24.2	23.1	0.6	
23	GRW	220	17	90.2	97.8	89.3	4.0	
23	GRW	238	28	176.1	41.1	41.3	0.4	

Table 5.7: Evolutionary models for specification series: phenotype and archotype

Series	Mode Mode	Shift (month)	Period (months)	AICc AICc	Step mean	Step std	Pace CRs	Percentage
24	GRW	112	35	162.7	9.9	14.8		9.0
24	GRW	149	55	220.4	21.0	15.2	2.1	
24	GRW	204	22	112.2	30.6	23.5	1.5	
24	GRW	227	15	82.0	79.1	90.0	2.6	
24	GRW	242	25	136.5	48.6	66.0	0.6	
25	GRW	112	22	195.7	129.2	190.8		20.9
25	GRW	134	21	171.2	98.2	95.6	0.8	
25	GRW	155	28	178.0	52.3	32.7	0.5	
25	GRW	184	58	424.4	60.8	51.8	1.2	
25	GRW	242	24	160.6	38.6	35.9	0.6	
26	GRW	114	18	61.2	2.4	3.9		1.7
26	GRW	132	40	121.6	4.0	5.3	1.7	
26	GRW	173	16	54.4	11.7	7.7	2.9	
26	GRW	191	44	117.0	6.8	4.3	0.6	
26	GRW	236	28	74.1	5.7	4.7	0.8	
27	GRW	112	20	54.0	5.3	4.4		0.6
27	GRW	134	42	82.3	1.6	2.0	0.3	
27	GRW	179	45	43.3	0.6	0.5	0.4	
27	GRW	226	26	52.2	2.6	1.9	4.5	
27	URW	254	12	26.9	0.0	1.8	0.0	
29	GRW	112	43	249.7	23.3	22.4		11.6
29	GRW	155	27	162.9	29.4	27.7	1.3	
29	GRW	182	43	233.2	32.7	27.3	1.1	
29	GRW	225	30	239.7	86.7	99.2	2.6	
29	GRW	256	10	78.2	34.4	35.4	0.4	
32	GRW	120	56	231.6	12.3	11.9		5.7
32	GRW	178	33	173.6	26.9	26.7	2.2	
32	GRW	211	15	64.8	14.9	11.0	0.6	
32	GRW	226	27	131.6	33.2	23.8	2.2	
32	GRW	253	12	61.9	18.1	16.6	0.5	
33	GRW	90	58	148.9	5.4	4.7		2.9
33	GRW	150	19	66.1	15.4	10.7	2.9	
33	GRW	169	34	111.9	9.0	7.5	0.6	
33	GRW	204	23	85.7	21.1	21.7	2.4	
33	URW	228	16	52.7	0.0	9.9	0.0	
34	GRW	114	22	109.3	24.5	20.3		16.2
34	GRW	136	27	154.0	47.8	38.6	2.0	
34	GRW	163	48	294.1	94.1	88.2	2.0	
34	GRW	213	19	128.6	58.3	88.5	0.6	
34	GRW	232	24	154.7	52.5	60.4	0.9	

Table 5.8: Evolutionary models for specification series

Series	Mode Mode	Shift (month)	Period (months)	AICc AICc	Step mean	Step std	Pace CRs	Percentage
36	URW	208	9	40.9	0.0	8.4		14.8
36	GRW	219	17	114.3	142.1	139.5		
36	URW	237	6	74.7	0.0	304.7	0.0	
36	URW	243	10	77.4	0.0	248.9		
36	GRW	253	12	98.0	201.9	160.1		
37	GRW	240	14	49.1	4.2	5.3		0.3
37	URW	255	10	53.0	0.0	13.2	0.0	

Table 5.9: Evolutionary models for 4G-specific specification series

Chapter 6

Discussion and Outlook

6.1 The triad of organizations, technology and innovations

This dissertation studied the evolution of the innovation network and the technological system in a SDO. Both streams of research combined studied the interplay between organizations, innovations and technology, with innovations linking the innovation network and the technological system.

The first major finding of this dissertation is that the tie formation in the bipartite innovation network is mainly driven by the matching of available and required resources of organizations and innovations, resulting in a nested structure of the network. The nested structure is an example of self-organization in an environment without one single coordinator. The second major finding is the life spiral model of search, elaboration and standardization that leads to a gradual development of the technological system rather than punctuated equilibrium. The key distinction is the coordinated development approach where the definition of the system's archotype, the mapping of services into affected network architecture, is exemplary for the designed approach. The third finding is the provided by the combining link between these two streams of research are the innovations. The simultaneity of innovation types identifies the SDO as an ambidextrous organization with separation by innovations and the degree distribution of innovations facilitates the nested structure of the innovation network. The dissertation

provides theoretical, empirical and managerial contributions. The theoretical contributions are intertwined with and enabled by the transfer of methods developed in other fields to the management literature.

6.2 Theoretical contributions

The first major contribution is the perspective of the activity, the innovation development, in addition to the actor perspective in a bipartite network, where both types of nodes are equally important. This novel perspective improves our understanding of the tie formation process and the emergent order via a self-organizing process. The tie formation is largely driven by technological capital, that reproduces the position within the innovation network. The process of match of possessed and required resources can be mapped into a three-mode network of organizations, innovations and technological modules as shown in figure 6.1.

The organizations are symbolized by squares, innovations by circles, and technological modules by triangles. The three-mode network can be viewed as three, two-mode networks with different relationships: The organization-innovation dyad forms the two-mode innovation network, the meeting participation of organizations' delegates, the

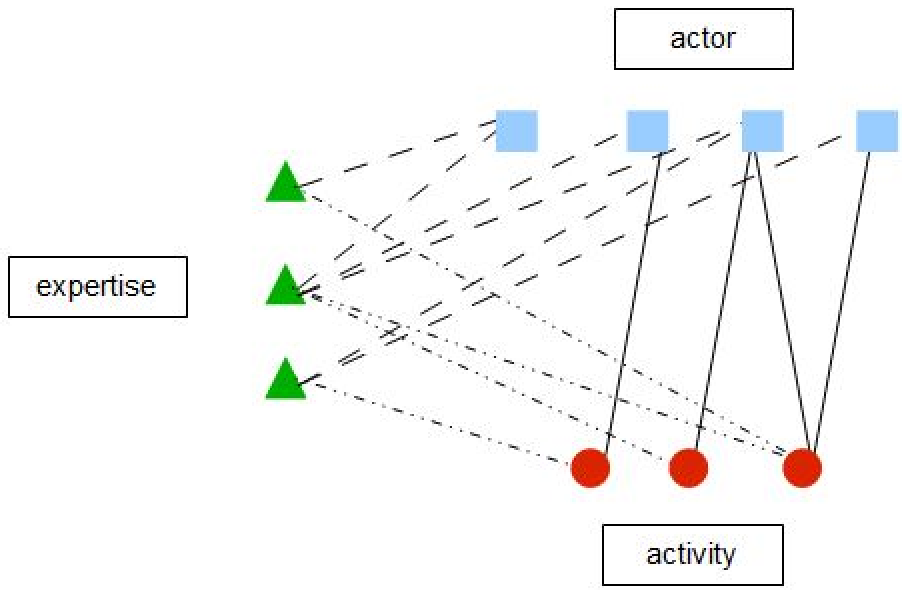

Figure 6.1: The three-mode network in 3GPP with organizations, innovations and technological modules.

two-mode meeting network, and the affiliation of innovations with technological modules, the innovation-module network. The two firm-related networks, the innovation and meeting network, can be projected into one-mode firm networks, the one-mode meeting and one-mode innovation network. The technological profiles of organizations and innovations are the degree or weight (for weighted networks) in the meeting and innovation-module network and are defined in the according neighborhoods consisting of technological modules. The overlap of these two bipartite neighborhoods can be interpreted as a three-mode clustering coefficient.

The extension of bipartite networks to a three-mode or tripartite network seems to have little value, in particular as the analysis of bipartite networks trails that of one-mode networks and tripartite networks are even less understood. I argue that it provides two interrelated benefits. With a nascent literature in tripartite networks, in particular in online communities (Cattuto et al. 2007; Ghoshal et al. 2009; Lou and

Song 2010; Neubauer and Obermayer 2011), but also board interlocks (Bohman 2012), necessary measures are under development and similar arguments as for bipartite networks for generalizable notions apply (Latapy et al. 2008). It allows faster accumulation of knowledge as similar measures are not developed in parallel for special cases and generalizations allow easier transfer from one context to another. Though the literature on tripartite networks appears to be a recent development, the idea is actually rather old and goes back to a generalization of bipartite networks by Fararo and Doreian (1984) based on the work of and the ideas of Breiger (1974) and Wilson (1982). Their concept of *interpenetration* is defined by "three levels of analysis and state this idea in terms of what we call "the shared subparts criterion of structure"." (Fararo and Doreian 1984, page 142). As examples they used board interlocks and the connection with industries as well as journals, scholars and scientific fields. Combining the early insight of social structure based on overlap joint subparts or neighborhoods with recent development in bipartite and tripartite networks as well as data availability can provide new avenues in understanding social networks. In addition, the perspective can provide a general framework of tie formation for different settings. Actors can be individuals, groups or organizations. The activity can be joint projects as research papers, new product development or alliances. The modules underlying the profiles can be many types of expertise or interest. Different ties can exist between the actors as friendship ties and joint collaboration or a competitive relationship in the market and a joint alliance. In the example of alliance formation the framework can help to identify first suitable alliance partners for a given alliance and the partner decision will be made on the reduced set of potential partners. Each alliance will have its own set of suitable partners, where the potential partner identification is mainly defined by required complementary capabilities.

The second contribution is the identification of the global (on the network level) order of bipartite nestedness created by a local (neighborhood-based) process of matched resources. It is a network of self-organization via actors' choice of an activity based on match of competence profiles. The competence profiles and their match define the schema of the agent, the rules on which they act. The competence profiles themselves are the coupling to the external environment as the resources of delegates are provided by the member organizations and they are knowledge flow from the environment into the system. In a one-mode network perspective of organizations the network has a rather dense core without any obvious structure. A blockmodel of the one-mode network reveals three distinct and stable roles, however it neither defines an overall network structure nor does it explain how the roles emerge. Only the perspective of the bipartite network and the analysis of nestedness reveals the order. Theoretically this process of self-organization can be applied to many other research settings where the tie is mutualistic and can guide organization principles in communities where there is no single entity to coordinate the activities.

The third contribution is life spiral model of evolution of a technological system within a SDO environment with a process of search, elaboration and standardization. The main process of search, elaboration and standardization is complemented by an ongoing correction process that corrects errors and inconsistencies in the functional change of the system. The key distinction in the LSM is that in the coordinated environment of the SDO desired new services or extension of existing services are mapped into identification of modules of required changes and changes of the system architecture. It is this design step, the archotype, that allows the change of detailed implementation specifications in a consistent way that guarantees system integrity. It reverses the direction of dependence compared to biological evolution and uncoordinated development. The archotype is crucial as it accounts for the systemic nature of the technology and identifies required changes throughout the technological modules. Based on the archotype specification work can be performed independently within single modules. The designed evolution has important implications for the technological evolution: First, core modules are underlying strong change, second, new modules and interfaces are added rather easily, and third, different types of innovations occur simultaneously.

The radical innovations with either new services and/or new technological knowledge, can be identified with exploration regarding the dimensions of technology and market. With the simultaneity of incremental and radical innovations 3GPP is an ambidextrous organization with separation on innovation level. With the further split of innovations into building blocks and working tasks radical innovations are split into rather small pieces with reduced complexity. Each working task on the deepest level is within one technological module and has only limited interdependence with other working tasks. The modularity of the system and the archotype lead to a hierarchy of work tasks with decreasing complexity with each split. This allows for instance specialist firms without architectural knowledge to contribute to radical innovations.

The innovations are joint element in the analysis of the innovation network and the technological system. The radical innovations identified in the study of mode and tempo are also the generalist innovation with a rather high degree, i.e. number of supporting firms. This is plausible, as radical innovations, either with new services or new technological knowledge, or both, require more input that adaptations to existing services and knowledge. Organizations may be also more motivated to participate as these are innovations with new market potential for network operators and technology providers. As the generalist innovations play an important part in facilitating the nested structure of the system, the radical innovations are crucial in generating the order in the innovation network. The designed technological evolution with its life spiral model and its sequence of phenotype, archotype and genotype creates the radical, generalist innovations that together with the diverse membership of organizations create the stable, nested structure of the innovation network.

6.3 Empirical contributions

The empirical contributions are in the context of SDOs as well as methodological contributions. First, it examines the tie formation and structure of the innovation network in a SDO and focuses on what Borgatti and Halgin (2011) called theory of networks, the antecedents of network structure and the structure itself. Previous work on SDOs studied either the influence of SDO networks on alliance networks (Rosenkopf et al. 2001) or the impact of the network on success in the SDO (Dokko and Rosenkopf 2010; Fleming and Waguespack 2007; Leiponen 2008). With the tie formation largely driven by technological resources and their match with required resources, the influence by network position can be seen as a further expression of technological leadership. The structure of the network, its moderate level of nestedness and lack of modularity are indicators of cohesion of the innovation network. With the modularity of the working organization this is a nontrivial result. The generalists on both sides, organizations and innovations, can be seen as the nodes that pull specialized modules apart into a nested structure. The generalist organizations create the pull by being active in innovations across all technological modules and the generalist innovations allow specialist organizations to contribute with a wide range of actors. The lack of modularity indicates that the boundary spanning across modules is more the norm than the exception within 3GPP. In contrast Fleming and Waguespack (2007) identified the leadership of WG chairmen and their boundary spanning position as an important element to avoid balkanization within IETF, a SDO with membership of individuals rather than organizations. In many small world networks with a clustered or modular structure the boundary spanners are the actors that realize short path lengths within the network, while modules lead to a high clustering — both characteristics combined define a small world behavior of the network. Nestedness can be seen as another structure that leads to short path lengths by the connection of specialists to generalists and with the similarity of the nestedness measure and bipartite clustering coefficient is also an expression of clustering.

The study of the structure of the innovation network is methodologically based on the analysis of bipartite networks and it makes use of recent advances in their analysis in social networks as well as ecological networks. One result of this fusion is the extension of the NODF measure of nestedness in ecology from network level to individual level (refer to appendix B). This methodological improvement can have important impact in the analysis of mutualistic networks as it allows the identification and study of idiosyncratic nodes (nodes that decrease the overall nestedness of a network) and the antecedents and consequences of idiosyncracy (Atmar and Patterson 1993; Almeida-Neto and Ulrich 2011). It also allows future research of the differences between the degree and nestedness distributions for different types of networks.

Second, the application of recently developed methods of modeling change in paleontology allows the identification of punctuated versus gradual change without any assumptions regarding the timing when change occurs nor the mode of change. It further provides a method to measure the change and compare across different periods. The flexibility of the methods allows to identify change patterns that follow different curves that the s-curve that characterizes the adoption of change, which is also often used in modelling the change of the system.

6.4 Managerial implications

Within SDOs there are both implications for the management of an SDO as well as implications for individual members. First, measures of network structure and change allow to develop key performance indicators to compare SDOs among each other or one SDO over time. While there are not yet established optimal target values for network structure indicators, a modular structure is an indicator of rather loose coupling between modules and according influence of the boundary spanners, while a nested structure is an indicator of more cohesion and connection between specialists and generalists. SDOs may prefer a nested structure as it gives less influence to a few players and provides more integration of generalists and specialists. Individual members can benchmark their involvement in the innovation network with their peers and monitor their contribution over time. While SDOs cannot control the input profiles of participating organizations, they can control to some degree the resource profiles of innovations and monitor the distribution of innovations and ensure sufficient generalist innovations. As generalist innovations are typical radical innovations, either on the service or implementation side, they also guarantee sufficient novelty of the technological system. Or the lack of these radical innovations can be an early indicator of the slow-down of the technological evolution and modularization of the innovation network. With the use of these measures across several SDOs the understanding of network structure on SDO success will increase.

Statistics of CRs is already an established tool within 3GPP. The refined measure of tempo of change allows to anticipate the number of change requests based on the current GRW model and its mean and standard deviation for single, often changing specifications, series or WG and TSG level. The modeling provides the basis for forecasting of correction CRs based on functional CRs.

6.5 Limitations

This research has several limitations. The first and most severe limitation is that the analysis is restricted to only one SDO. This provides the advantage that the conditions under which the evolution of the innovation network and the technological system took place are stable, but it limits the generalizability of the findings to other SDOs or in a broader scope to other two-mode networks of actors and their activity. In particular in the context of a SDO procedures of knowledge mobility and appropriability are well defined. The extension of the framework to other, non-SDO settings requires the establishment of similar rules that may be difficult to achieve in a self-organizing environment.

The second limitation is that the innovation network is operationalized as a binary network, without taking the actual contributions of the organizations to specific innovations into account. Though the working rules of 3GPP require active contributions by supporters of innovations, the level of contributions will vary considerably and may further distinct specialists and generalists. Furthermore, the innovation is treated as monolithic, though complex innovations are further split into building blocks and working tasks.

Third, the study of the evolution process considers only CRs and not the drafting of new specifications. Though the correction CRs also cover the new specifications, the functional development may differ for new specifications and is currently not covered. The contributions of technical proposals, the combination of them and their mutual dependence can provide not only important insight into the creation of new knowledge by a diverse set of sources, but also couples the technological evolution closer to the innovation network.

Fourth, the context and focus is on the SDO and it ignores its relationships to other SDOs. This approach makes implicitly use of the concept of modular systems and assumes that the interaction within the module of 3GPP is higher than its interaction with other SDOs in a system of SDOs. This approach is justified as the number of CRs and technical proposals and internal liaison statements are much higher than liaison statements to other SDO and the references of specifications are higher to 3GPP specifications than to external ones. However, it is an approximation and previous research (Leiponen 2008) has shown that external network position has influence on the success within 3GPP.

6.6 Future research

The introduction of the novel perspective of bipartite networks and the generalized framework of a three-mode network of the triad of organization, innovation and technological module and the according methodological approach is only a very first step in the analysis of these type of networks.

The above mentioned limitations provide some guidance for future research: The resolution of the binary tie in the innovation network into the specific technical proposals for new specifications and CRs allows to address several research questions: How is the interdependence pattern of specialists and generalists based on their actual interaction. Can the analogy of ecological networks extended to weighted networks? How is the diverse input from different organizations recombined to create new knowledge that is approved by the majority of the organizations. How do organizations and the technology co-evolve? Furthermore, the hierarchy of tasks can influence the decision process of contribution. In particular the distinction between phenotype, archotype and genotype and according specification work provide different opportunities for organizations based on their capabilities. Definition of the phenotype (new services and their extension) requires market knowledge, the archotype requires architectural knowledge, while the genotype requires specific technological knowledge.

The model of the three-mode network can be further developed in several directions: First, the simulations can be extended to the technological profiles of organizations and innovations and their distribution. This can in particular help to improve our understanding of the difference between sponsor-coordinated innovation networks that are characterized by one firm with broad resources (generalists) and many specialists in contrast to SDOs with a spectrum of organizations from specialized to multi-technology firms. How sensitive is the resulting structure on the input of profiles. How critical is the existence of innovations with a broad requirement profile? Second, the picture of nodes pulling modular structure to a nested structure suggests that there is a transition from modular to nested structure. Does this transition exist? On what parameters does it depend on? What does this tell us about the relationship of modular and nested structure? Third, the relations in the three-mode network need to be further understood. For instance each node has two degrees — e.g. organization has the degree of technological modules it has resources and the degree of innovations it is involved in. What are the correlations between the degree distributions and what drives these correlations? How are the bipartite clustering coefficients related to each other and is there a generalization of the clustering coefficient and nestedness to three-mode networks?

The limitation of the isolated study of 3GPP can be overcome in two ways: First, the most simplest case is the study of the coupling between 3GPP and its rival SDO Third Generation Partnership Project 2 (3GPP2) that develops a cellular standard based on another technology. Both SDOs are coupled via joint member organizations and by the competition between the two technologies. The structure and evolution of both innovation networks can be compared and contrasted with simulations. Second, 3GPP is part of a network of SDOs with which it has liaison relationships and overlapping memberships. What is the process of tie formation of liaisons? Is it increasing technological convergence, spin-out of activities, joint memberships and how does the tie formation influence the standardization work and in which direction? What are the roles of generalist and specialist organizations in this process? The increasing pervasiveness of cellular telecommunication is likely to increase the embeddedness of 3GPP in broader standardization work and importance of these questions.

Appendix A

The Analysis of Two-mode Networks

A.1 Introduction

The last decade has seen an exponential growth in studies of social network analysis (Borgatti and Halgin 2011). The vast majority of these studies examine one-mode networks, where the nodes are one type, e.g. individuals or firms and ties between the same type of node. However a considerable number of inter-organizational networks are two-mode networks, also known as bipartite or affiliation networks, where ties are formed between two different set of nodes. Examples include directors on the board of firms (Conyon and Muldoon 2006; Davis et al. 2003; Shipilov et al. 2010), underwriting syndicates of investment banks (Baum et al. 2004), multi-party alliances (Greve et al. 2010; Mitsuhashi and Greve 2009), meeting networks in standard setting organizations (Dokko and Rosenkopf 2010; Leiponen 2008), country and product networks based on trade (Schweitzer et al. 2009), production networks in the musical and film industry (Uzzi and Spiro 2005; Zaheer and Soda 2009), and collaboration and co-authorship networks (Goyal et al. 2006; Newman 2001b). In empirical work, most two-mode networks are projected to one-mode networks, despite the issues of information loss and interdependence of ties (Opsahl 2011) due to a lack of measures and methods for two-mode networks (Latapy et al. 2008; Opsahl 2011; Wasserman and Faust 1994). While the two-mode network analysis is still trailing one-mode network analysis, advances have been made since the seminal papers of Borgatti and Everett (1997) and Faust (1997) in sociology, physics and biology. However, this progress has rarely found its way into the management literature.

In this appendix, I introduce important advances in the analysis of two-mode networks in other disciplines and thereby build a bridging tie between nearly separated research agendas. Two-mode networks have a long tradition in social network analysis (Breiger 1974; Davis et al. 1941). The standard book of social network analysis (Wasserman and Faust 1994) and extensions of one-mode measures to two-mode networks (Borgatti and Everett 1997) sparked progress in other fields such as biology (Ings et al. 2009) and physics (Newman et al. 2001). However, little has been reintegrated or harvested from these seeds. For instance of the 721 studies in the Web of Science database in December 2011 citing Newman et al.'s paper that challenged the empirical findings of the small world characteristic of affiliation networks due to their naturally higher clustering, only ten are within the management field.

I believe the reasons for this sporadic knowledge transfer are three-fold: First, research in physics and biology is very distant and normally not included in the process of the literature review. A further obstacle of the search in distant disciplines is different terminology. For instance, networks are called *graphs* in physics and *webs* or *foodwebs* in biology. Second, an important outlet for advancement in social network analysis is the journal of *Social Networks*, a multidisciplinary journal, rather close to sociology, with relatively sparse links to the management literature (Leyesdorff 2007). A rather mundane reason for the lack of awareness within the management literature may be the lack of inclusion of the journal *Social Networks* in academic search engines such as *Business Source Premier*. Third, the approach of natural scientists in network research is often phenomenological, driven by the comparison of a given network with those of a random network to detect non-random properties and then deduct possible antecedents and outcomes. Management scholars take a more inductive approach by hypothesizing antecedents and outcome and test these via regressions.

The major reason why we as management scholars should take the efforts for this excursion into foreign territory are the limitations introduced with the projection of two-mode networks to an one-mode network (Opsahl 2011). In a projection the network of one type of nodes, e.g. firms, is formed, when they have at least one affiliation in common. For instance when two investment banks are member of at least one investment syndicate they have a tie (Wasserman and Faust 1994). First, the tie between one type of node often no longer carries the information on how many affiliations the two nodes have in common. Even when this information is carried as weight of the tie, the well-known network measures do not take these weights into account. Second, the formation of ties is interdependent. For instance, when four nodes are members of one affiliation, they are all connected with each other in the one-mode projection, leading to six simultaneous ties. It will, in particular, lead to a clique of four and a high clustering coefficient. Third, it is not acknowledged that two-mode networks can have characteristics which are unique to their specific nature, and are not sufficiently captured in a one-mode network perspective.

To address these limitations of one-mode network analysis, I present three different streams of research related to two-mode networks. First, I introduce refinements related to projections of two-mode networks to one-mode networks. This includes weights for the ties in the projection process and network measures for weighted networks as well as implications of two-mode networks on one-mode measures. While this is still in the tradition of one-mode network analysis, it reduces the issue of information loss via the projection. Second, I introduce the extension of networks measures from one-mode networks to two-mode networks, where the focus is on clustering coefficient, a key measure for small world characteristics and network cohesion. These measures based on clustering coefficient, avoid the problem of interdependence of links and allow the analysis of two-mode networks. Third, I introduce approaches unique to two-mode networks. One such approach is the measure of nestedness, a prominent feature of mutualistic ecological networks. In a nested two-mode network specialists (nodes with few ties), are connected to proper subsets of nodes which are connected to generalists (nodes with many ties) (Bascompte et al. 2003; Ulrich et al. 2009). The implications of nestedness are, that generalists are connected to generalists of the other type of nodes and that specialists are connected mainly to generalists. Nestedness is a property of two-mode networks without a direct counterpart in one-mode networks. Another approach is the use of different constraints to random two-mode networks. While for one-mode networks the most often used constraints are the number of nodes and ties, which are the same as those for the real-world network under study (Watts and Strogatz 1998), in two-mode networks additional constraints can be the degree distributions of the two types of nodes. The suitable choice of these constraints as benchmark network is an important decision to be made (Gotelli and Ulrich 2012; Ulrich et al. 2009).

A.2 Two-mode network and projections to one-mode networks

Two-mode networks are networks with ties between two different types of nodes (Wasserman and Faust 1994). Examples of two-mode networks include the networks of directors and corporate boards, multi-party alliances of firms, the Southern women network of women who went to different events (Davis et al. 1941). Two-mode network can be described with an incidence matrix with elements a_{ij}, where the N rows (index i) are the one type of nodes, e.g. directors, and the M columns (index j) the other type as corporate boards. The incidence matrix is generally rectangular due to different number of nodes for the two types. The row nodes are often called bottom or primary nodes, while the column nodes are referred to as top or secondary nodes (Latapy et al. 2008; Opsahl 2011). In case the primary node i has a tie to the secondary node j the incidence matrix element a_{ij} has a value larger than zero, otherwise zero. In many cases networks are binary networks with values of either zero or one. For the following discussion, I assume two-mode network to be a binary network, though some methods are also applicable to weighted two-mode networks.

A.2.1 Projections of two-mode networks to one-mode networks

Researchers often transform two-mode networks to one-mode networks via a projection. In a projection, primary nodes which have a joint tie to a secondary node are connected to each other (the same logic applies to secondary nodes connected to the same primary node). The projection results normally in undirected networks, which will be my assumption for the following discussion. Though the projection can be applied to both, primary and secondary nodes, in most cases researchers focus on the projection of only one type of nodes, where the choice of node depends on the research question. In the case of corporate boards, scholars have examined either the director network (Geletkanycz et al. 2001), in which case directors sitting on the same board form a tie, or the firm network or board networks, in which case firms are connected when they share a director (Davis et al. 2003). Furthermore the projected one-mode network is often a binary network, where all existing ties are equally important with the strength of one. However, giving equal weights to different shared events results in information loss. For example, firms that have two common directors on their boards may be closer linked than firms sharing only one director. The assignment of a weight for ties, equal to the number of co-occurences, accounts for this different strength of ties and has been applied in several studies. For example, Kogut et al. (2007) used the number of deals between two venture capital firms and Greve et al. (2010) used the number of shared routes between two shipping liners as weights for ties. While the weight by co-occurence accounts for the number of links, it ignores the acquaintance of the focal actor with the other actors in the affiliated organization. Newman (2001a) argues in the case of a scientific collaboration networks with researchers as actors and joint publications as affiliations, that the number of co-authors matter and that authors' interaction with their co-authors should be scaled with $1/(n-1)$, where n is the number of co-authors. In case of a two-author collaboration, the focal author will dedicate the interaction completely to the second author, while in the case of three authors the interaction will be shared between the other two authors.

A.2.2 Measures of weighted one-mode networks

Though the assignment of weights via projection of two-mode networks helps retain important information, this can only be exploited if methods for weighted networks are available. In the following I discuss extensions of centrality measures and clustering coefficients to weighted networks based on the work of Barrat et al. (2004) and Opsahl et al. (2010). I use w_{ij} as notation for the weight of the tie between the nodes i and j.

Centrality Measures

Barrat et al. (2004) introduced extension to the degree centrality from binary to weighted networks, in the form of *strength* s_i, which is the summation of the weights of the focal node's ties in the one-mode network (Equation A.1).

$$s_i = \sum_{i=1}^{N} a_{ij} w_{ij} \tag{A.1}$$

While the definition of strength is straight forward and is used in management research as weighted degree centrality (Lin et al. 2007), it ignores the number of neighbors. For instance, a node that has one strong tie of weight ten, has the same strength as a node that has ties with ten other nodes of weight one. To overcome this weakness Opsahl et al. (2010) defined centrality measures that take both, the weight of ties and the number of ties, into consideration and allow for the relative importance of the strength via a positive tuning parameter α. Equation A.2 below presents the weighted degree centrality measure:

$$weighted \quad degree = k_i \cdot \left(\frac{s_i}{k_i}\right)^{\alpha} = k_i^{1-\alpha} \cdot s_i^{\alpha} = k_i^{\beta} \cdot s_i^{1-\beta} \quad \text{with } \beta = 1 - \alpha, \tag{A.2}$$

where k_i is the degree of node i. For α equal zero the weighted degree centrality is equivalent to the degree and for α equal to one it is equivalent to the strength. For values between zero and one, a higher degree will increase weighted degree centrality for a given strength s_i; for α larger than one, less ties will increase the weighted degree centrality for a fixed strength. Consider an example of board of directors in two firms, A and B. Firm A has two directors in common with all its neighbors (weight of two), while firm B shares only one director (weight of one). Keeping the strength fixed, implies that firm A has only half of the number of ties than firm B. An alternative way to look at formula A.2 is to keep the degree k_i constant and change the β and hence the influence of the strength. However in this case the effect of β will depend whether the strength is less than one, which is possible with the weighting scheme suggested by Newman (2001a).

Both, the betweenness and closeness centrality measures for weighted networks proposed by Opsahl et al. (2010) are based on extensions of the shortest path g_{ij}^{w} for weighted networks (Brandes 2001; Newman 2001a). They add a positive tuning parameter α that defines the relative importance of the weight of ties over the number of intermediary nodes on the path:

$$g_{ij}^{w} = \min\left(\frac{1}{w_{ia}^{\alpha}} + \ldots \frac{1}{w_{dj}^{\alpha}}\right) \tag{A.3}$$

For α equal to zero, g_{ij}^{w} is equivalent to the shortest path for binary networks and counts the number of intermediate nodes, including the end point of the tie. For α equal to one, g_{ij}^{w} is equivalent to the shortest path for weighted networks suggested by Brandes (2001) and Newman (2001a), where the inverse weight measures the resistance of transmission over the tie. For α less than one, a small number of intermediate nodes with small weights are preferred over a longer path with large weights of the ties. For α larger than one, the weight of ties gains importance over number of intermediaries and longer, but stronger connected paths are be selected. Based on the weighted shortest path as defined in equation A.3 the closeness centrality and betweenness centrality measures are defined as usual: closeness centrality is inverse of the sum of all shortest paths and betweenness centrality is the ratio of shortest paths through the focal node. In the example of a board network, the α is most likely much closer to zero than to one as boards are less likely to act as transmitters of information, while for technical networks as the internet, an α much larger than one is likely. As Opsahl et al. (2010) pointed out for knowledge networks, an α larger than one with attention to strong ties is more appropriate for tacit knowledge transfer, while α less than one is more appropriate for codified knowledge. All three extensions of the centrality measures are identical to the well-defined measures in binary networks for all weights equal to one. A major limitation of the introduced measures is the assumption that the weights are on a ratio scale. Though the appropriate choice of α is an issue in specifying a certain centrality measure, it provides the opportunity to distinguish whether the weight of ties or the number of intermediate nodes is important by comparing results with the unweighted measure with those with the weighted measure.

Clustering coefficient

The clustering coefficient measures the cliquishness of the local environments, as average of the local clustering of the nodes in their neighborhood. The neighborhood of node i with k_i neighbors can have at maximum $k_i \cdot (k_i - 1)/2$ ties among each other. The local clustering coefficient c_i for node i is then given by the number of actual ties t_i divided by the maximum number of ties (Equation A.4). The global clustering coefficient C

is the average of the node-specific clustering coefficients over all nodes in the network (Equation A.5).

$$c_i = \frac{t_i}{k_i \cdot (k_i - 1)/2} = \frac{2 \cdot t_i}{k_i \cdot (k_i - 1)} \tag{A.4}$$

$$C = \langle c_i \rangle = \frac{1}{N} \sum_{i=1}^{N} c_i \tag{A.5}$$

This definition departs from the more well-known definition of transitivity in the sociology and management literature that measures in how far the friend of a friend is a friend. It leads to closure in a connected triplet, where two of the three nodes are already connected via friendship and the missing tie is formed, building a fully connected triangle. The transitivity is defined on a global network level as three times the ratio of number of triangles (fully connected triplets) and the number of triplets. The factor of three accounts for the fact that each node is part of three triplets and assures the range of the coefficient between zero and one. The difference between these two measures is the reverse order of clustering and averaging (see Newman (2003b) for a more detailed discussion).

The clustering coefficients were refined in the recent literature in two ways: First, by correcting for the greater cliquishness of projected two-mode networks (Newman et al. 2001) and second by taking into account extensions for weighted networks (Barrat et al. 2004; Opsahl and Panzarasa 2009). The projection of two-mode networks leads to a natural clustering of the projected two-mode networks. For instance in the case of board of directors, all directors sitting on a board are connected, building a clique of the size of the board. Hence, the projected one-mode networks are a collection of cliques that are connected by directors sitting on multiple boards. The analogue picture applies for the board interlocks. Newman et al. (2001) provide a comprehensive framework, based on the concept of generating functions for the degree distribution, that allows to account for this clustering and also derive a proper path length. The generating function for the degree distribution is defined as

$$G_0(x) = \sum_{k=0}^{\infty} p_k x^k \tag{A.6}$$

with following properties:

$$G_0(1) = 1 \tag{A.7}$$

$$\langle k \rangle = \sum_k k p_k = G_0'(1) \tag{A.8}$$

where the first equation ensures that all the probabilities p_k add to one and the second gives the average degree in terms of the first derivative of the generating function. For an observed network the probabilities p_k can be directly measured by looking at the degree distribution of the network n_k, where n_k is the number of nodes which have degree k. In this case the generating function is obtained by

$$G_0(x) = \frac{\sum_k n_k p^k}{\sum_k n_k} \tag{A.9}$$

In the case of a two-mode network there are two generating functions f_0 and g_0, with f_0 generating the type 1 network (e.g. directors) and g_0 the type 2 network (e.g. boards).

$$f_0(x) = \sum_j p_j x^j, \qquad g(0) = \sum_k q_k x^k \tag{A.10}$$

and as in the case of the one-mode case following relations hold

$$f_0(0) = g_0(0) = 1, \qquad f_0'(1) = \mu, \qquad g_0'(1) = \nu \tag{A.11}$$

with μ and ν the average number of the node types in the network (e.g. number of boards and number of directors). Newman et al. derive formulas for the average path length L and the clustering coefficient C_G based on the two generating functions:

$$L = \frac{ln(N/z_1)}{ln(z_2/z_1)} + 1 \qquad \text{with} \tag{A.12}$$

$$z_1 = G_0'(1) = f_0'(1) g_1'(1) \tag{A.13}$$

$$z_2 = G_0'(1) G_1'(1) = f_0'(1) f_1'(1) [g_1'(1)]^2 \qquad \text{and} \tag{A.14}$$

$$C_G = \frac{M}{N} \frac{g_0'''(1)}{G_0''(1)} \tag{A.15}$$

where N is the number of nodes of the type 1 network (e.g. directors) and M the number of nodes in the type 2 network (e.g. boards). My goal in this appendix is not the detailed derivation of the equations A.12 to A.15, but their applications on two-mode networks[1] . I therefore provide explicit formulas for the derivatives in equations A.12 to A.15 by applying the chain rule to calculate the derivatives and substitute $x = 1$ (equations A.16 to A.22).,

$$f_0'(x) = \sum_j j p_j x^{j-1} \qquad f_0'(1) = \mu \tag{A.16}$$

$$f_0''(x) = \sum_j j(j-1) p_j x^{j-2} \qquad f_0''(1) = \sum_j j(j-1) p_j \tag{A.17}$$

$$f_1'(x) = \frac{1}{\mu} \sum_j j(j-1) p_j x^{j-2} \qquad f_1'(1) = \frac{1}{\mu} \sum_j j(j-1) p_j \tag{A.18}$$

$$g_0'''(x) = \sum_k k(k-1)(k-2) q_k x^{k-3} \qquad g_0'''(1) = \sum_k k(k-1)(k-2) q_k \tag{A.19}$$

$$g_1'(x) = \frac{1}{\nu} \sum_k k(k-1) q_k x^{k-2} \qquad g_1'(1) = \frac{1}{\nu} \sum_k k(k-1) q_k \tag{A.20}$$

$$G_1'(x) = f_1'(g_1(x)) g_1'(x) \qquad G_1'(1) = f_1'(1) g_1'(1) \tag{A.21}$$

$$G_0''(x) = f''(g_1(x))[g_1'(x)]^2 + f_0'(g_1(x)) g_1''(x) \quad G_0''(1) = f''(1)[g_1'(1)]^2 + \mu g_1''(1) \tag{A.22}$$

With these derivatives evaluated for $x = 1$, the calculation of the average path length and the clustering coefficient are reduced to a summation of products of the empirical given probabilities p_j and q_k with the degree distribution.

Barrat et al. (2004) defined a weighted clustering coefficient c_i^w that accounts for the different weights by arguing that a stronger tie between two nodes leads to a higher cohesion compared to one weak tie.

$$c_i^w = \frac{1}{s_i(k_i - 1)} \sum_{j,h} \frac{w_{ij} + w_{ih}}{2} a_{ij} a_{ih} a_{jh} \tag{A.23}$$

[1] A detailed derivation is given in Newman et al. (2001) and in papers applying these formulas as Conyon and Muldoon (2006); Huang et al. (2007); Uzzi et al. (2007)).

For each triplet in the neighborhood of the focal node i the average weight of its ties, rather than the tie existence is counted. The sum over all triplets is normalized by the strength s_i, the sum over all weights, and the number of possible triplets, which guarantees that the weighted clustering coefficient is between zero and one. For constant weights, including all weights set to one, equation A.23 is equivalent to the clustering coefficient as defined by Watts and Strogatz (1998). The weighted global clustering coefficient C^w is the mean over all individual c_i^w. Similarly, $C(k)$ is the average clustering coefficient of all nodes with degree k.

Opsahl and Panzarasa (2009) defined a generalized clustering coefficient as an extension of the transitivity[2] . Similar to Barrat et al. (2004), for the local clustering coefficient, they account for the weights of the ties to calculate triplet values, which are either the arithmetic or geometric mean, the minimum or maximum of the ties, within the triplet. The generalized clustering coefficient is then

$$C_w^{generalized} = \frac{\text{total value of triangles}}{\text{total value of triplets}} = \frac{\sum_{\text{triangles}} w}{\sum_{\text{triplets}} w} \tag{A.24}$$

Weighted average nearest neighbor degree.

The average nearest neighbor degree is defined as the average over the degree of the nearest, i.e. directly connected, neighbors. The network is called *assortative* if the degree of nodes is positively correlated with the degree of their nearest neighbors, and disassoratative, if the correlation is negative (Newman 2002). Newman (2003a) found that social networks are in most cases assortative, while technical and biological networks are mainly disassortative. For instance board directors, who are members of many boards, are more likely connected to directors who are also serving on many boards. Barrat et al. (2004) extended the average nearest neighbor degree to weighted networks by introducing the weighted average over all nearest neighbors and normalizing

[2] In their terminology it is the standardized clustering coefficient.

it by the strength of the node.

$$k_{nn,i}^{w} = \frac{1}{s_i} \sum_{j=1}^{N} a_{ij} w_{ij} k_j \tag{A.25}$$

For identical weights to all neighbors, $k_{nn,i}^{w}$ is identical to the unweighted average. In the case of a larger propensity to connect to high degree neighbor for high weights, the weighted average nearest neighbor degree will be larger than the unweighted average. The comparison between these two allows examination of differences in the assortativity behavior in dependence of the weight of the interaction. For instance Barrat et al. (2004), in their analysis of a scientific co-authorship network, found a stronger assortativity behavior for the weighted average nearest neighbor.

A.3 Two-mode networks

Two-mode networks were brought to the attention of organizational scientist nearly 50 years ago, in a seminal paper by Breiger (1974) on the duality of people and groups. Despite this long history and multiple two-mode networks, such as individuals and groups in organizations and organizational affiliation networks, the analytical methods for two-mode networks still lag behind those of one-mode networks (Wasserman and Faust 1994). Several attempts have been made to put more attention to the analysis of two-mode networks — prominent examples is the work by Borgatti and Everett (1997) and Faust (1997) and recently by Latapy et al. (2008) as well as the use of two-mode networks in foodwebs (for a recent review refer to Bascompte and Jordano (2007)). As the centrality measures as suggested by Borgatti and Everett are already well established, I focus here on clustering coefficient in two-mode networks, nestedness and two-mode random networks.

A.3.1 Clustering coefficient

While the global clustering coefficient defined by Newman et al. (2001) allows a correct comparison for the small world analysis of projected two-mode networks, the weighted local clustering coefficient has still drawbacks for projected networks. The primary interest in the local clustering coefficient is the question of closure: in how far do existing ties of node i to node node j and k lead to the formation of a tie between the nodes j and k. In the projection of the two-mode, however, the tie formation is not independent and triangles will be formed simultaneously due to joint membership. This is reflected by the property of equation A.23 that it is identical to the unweighted clustering coefficient for equal weights of the ties, a characteristic of the projection of the membership of a single board. Furthermore, the definition of clustering coefficient (equation A.4) cannot be extended to two-mode networks as the connection of direct neighbors, both of the same type, is prohibited, and triangles cannot exist. Latapy et al. (2008) proposed an extension of the local clustering coefficient to two-mode networks on a more abstract definition of overlapping neighborhoods, the directly connected nodes, for two nodes i and j of the same type. The overlap is the fraction of joint neighbors in their both neighborhoods:

$$\text{overlap}(i, j) = \frac{|N(i) \cap N(j)|}{|N(i) \cup N(j)|}, \tag{A.26}$$

where the numerator gives the number of shared neighbors and the denominator the number of nodes in the combined neighborhoods. For two directors, this is the ratio of their shared boards to the boards either one of them serves. In case both directors serve only their shared board the overlap will be one; however, if one of the directors sits on ten boards, the overlap will be 0.1. To account for different sized neighborhoods one can normalize the overlap by either the size of the smallest or largest of the two neighborhoods:

$$\text{overlap}_{min}(i,j) = \frac{|N(i) \cap N(j)|}{\min(|N(i)|, |N(j)|)} \tag{A.27}$$

$$\text{overlap}_{max}(i,j) = \frac{|N(i) \cap N(j)|}{\max(|N(i)|, |N(j)|)}, \tag{A.28}$$

The two-mode local clustering coefficient for node i is then the average of its non-zero overlaps:

$$c_i^{two-mode} = \frac{\sum_{j \in N(i,2)} \text{overlap}(i,j)}{|N(i,2)|}, \tag{A.29}$$

where $N(i,2)$ is the neighborhood of node i with distance of two, i.e. nodes of the same type that are connected via a joint node of the other type. Overlap can be any of the three defined above in equations A.26 to A.28. The local two-mode clustering coefficient can be aggregated to a clustering coefficient for each type of nodes and for the complete network. In analogy to the transitivity, which provides the fraction of triangles over all triplets, the two-mode version was defined (Latapy et al. 2008; Robins and Alexander 2004) as

$$\text{transitivity}^{two-mode} = \frac{2N_{\text{fully connected quadruplets}}}{N_{\text{quadruplets with at least three ties}}} \tag{A.30}$$

Nestedness

While the two-mode local clustering coefficient is an extension of the one-mode concept of closure to two-mode networks, the nestedness property is a two-mode network property (Saavedra et al. 2009; Ulrich et al. 2009). Nestedness is an important property of biological two-mode networks as habitat communities (Atmar and Patterson 1993) or pollinator-plant systems (Bascompte et al. 2003) that are "... highly nested; that is, the more specialist species interact only with proper subsets of those species interacting with the more generalists." (Bascompte et al. 2003, page 9383). Specialists are nodes with a low degree, while generalists are nodes with a high degree. In a nested network of directors and boards, for instance, directors who serve only on one board (specialists) tend to be member of a board (subset of boards) with directors serving many boards (generalists). As a consequence of nestedness, generalists of one type of nodes are connected with generalists of the other type, while specialists are more likely connected to generalists. Nested networks are ordered systems. This can be best illustrated by the ordering of the incidence matrix of the two-mode network along the degree of both types of networks. In a perfectly nested network, only ties in the upper left triangle would exist, constrained by the isocline line that indicates the boundary of expected versus unexpected ties (Bascompte et al. 2003; Ulrich et al. 2009). A widely used measure of nestedness is the nestedness temperature, where a temperature is assigned based on the normalized sum of squared relative distances of unexpected absences or existence of ties (Atmar and Patterson 1993). A temperature of zero describes a perfectly nested network, while a temperature of 100 describes a completely unordered network. A more recent measure is "NODF" (nestedness metric based on overlap and decreasing fill), that is based on the overlap of row and column of the incidence matrix with decreasing degree (Almeida-Neto et al. 2008). The NODF measure also provides separate values for columns and rows, which allows to test these separately for nestedness. NODF takes values between 0 and 100, where 100 indicates full nestedness (an opposite behavior to the nestedness temperatue).

Random networks

Random networks were introduced by Erdõs and Rényi (1959) and became widely used with the small world study of Watts and Strogatz (1998) and following network analysis by comparison of the real network parameters with those of a random network that has the same number of nodes and ties. While such a random network keeps the same density and hence probability to form a tie, it is not the only possible random network. A random network which also reproduces the degree distribution provides more constraints on the random network. For two-mode networks, the choice of the right benchmark random network is even more difficult: the least constraint one has the same number of nodes of type 1, number of nodes of type 2 and number of ties (fixed density FD). As a two-mode network has two degree distribution, one can keep the degree distribution of row nodes (fixed row FR) or of column nodes (FC), the probability of tie formation based on the average row and column marginal of a given cell ("PRC") or both degree distributions (fixed row fixed column FRFC). The choice of the appropriate random network, which defines the null model the real network is compared to, is crucial, but not obvious (Gotelli and Ulrich 2012; Ulrich et al. 2009).

Appendix B

A nestedness measure for individual nodes

Here I introduce the nestedness measure for individual nodes, which is based on the nestedness based on overlap and decreasing fill (NODF) measure (Almeida-Neto et al. 2008) and the clustering coefficient for bipartite networks (Latapy et al. 2008). The concept of nestedness was developed in ecology for bipartite networks of communities as islands and species populating them (Atmar and Patterson 1993). In a nested structure the species of islands with lower species richness (specialists) tend to be proper subsets of the species found in the species richer islands. More generally for a bipartite network nodes with few links (specialists), interact with proper subsets of interaction partners of generalists (highly connected nodes). In a matrix network presentation of the bipartite network, where the rows and columns are ordered along decreasing degree (number of ties), a nested network is characterized by a concentration of ties in the upper left corner as in fig 3.2.

Almeida-Neto et al. (2008) derived their NODF measure with a combination of paired overlap (PO) of ties based on the condition of decreasing fill (DF). They started with a matrix representation of a network with m rows and n columns, where an entry of one in element a_{jk} indicates a tie between the nodes j and k, otherwise it is zero. Each row and column represent one node in the bipartite network. The evaluation is based on the comparison of pairs of two rows or columns and then added over all pairs. The percentage of paired overlap PO_{ij} counts the ones each pair has at the same location, i.e. the tie to the same node, compared to the row or column with the lower degree in the pair. It measures the level to which the specialist node complies to the nestedness of it ties in the ties of the generalists has. The reference to the node with lower degree implies that pair i and j is identical to the pair of j and i, leading in total to $n(n-1)/2$ pairs for the rows and $m(m-1)/1$ pairs for the columns. The decreasing fill implies that the overlap is zero in case of equal degree for both nodes. This leads to the nestedness measure NODF for the whole network

$$NODF = \frac{\sum N_{paired}}{(n(n-1)/2) + (m(m-1)/2)} \tag{B.1}$$

The NODF measure maps the definition of nestedness and measures the percentage of commonly connected nodes from the perspective of the specialist. It can be calculated separately for rows and columns that represent the two types of nodes.

The procedure used by Almeida-Neto et al. (2008) can be translated further into network language for bipartite networks. The set of nodes to which a focal node i is directly connected to is called neighborhood (of distance one) N_i, where the focal node is not part of its neighborhood. The degree of a node is the size of its neighborhood, $|N|$, i.e. the number of elements the neighborhood contains. The paired overlap PO_{ij} as defined above is then the intersection of the two neighborhood sets $N(i)$ and $N(j)$ divided by the size of the neighborhood with the smaller degree.

$$PO_{ij} = \frac{N_i \cap N_j}{min(N(i), N(j))} \quad . \tag{B.2}$$

This definition of the paired overlap is exactly the same as the *min-clustering* between two nodes in a bipartite network defined by Latapy et al. (2008) and given in equation A.27. They obtained the node-specific clustering coefficient as the average of the pairwise min-clustering coefficient over all non-empty pairs. Similarly I am looking for an appropriate summation over the pairwise overlap to a node-specific nestedness with two conditions that must be met: First, the node-specific nestedness measure must be comparable and second, the sum over the node-specific nestedness measure is identical to the NODF measure.

A naive summation over all pairs that include a specific node does not comply to the first condition. The node-specific nestedness for the most generalist will be always zero as there is no node with a higher degree, while it will be always larger than zero for the node with the lowest degree. The problem in this naive summation is that it covers only the specialist perspective and hence sums a varying number of pairs for each node or how much overlap the specialist node *sends* to the generalist. The specialist perspective describes how many of its ties are overlapping with the more generalist node in the pair compared to the total number of its ties. One way to overcome this is the introduction of the generalist perspective, which measures the *received* percentage overlap from the specialist. In this perspective the most generalist node receives overlap from all others, while the most specialist does not receive any overlap. The difference is shown in figure B.1, where the square matrix represents the PO_{ij} matrix (neighborhood overlap divided by pairwise minimum degree) of one type of node. For demonstration purposes the matrix is ordered with the degree of the nodes with the highest degree on the top and left and the assumption that the degree is strictly decreasing. The NODF procedure adds all the grey elements. The simple summation over all pairs of node i involving all nodes with higher degree is indicated by the red arrow (specialist perspective), while the receiving overlap in the generalist is indicated by the blue arrow. The individual overlap takes both perspectives into account.

The overall overlap is then defined the following:

$$overlap(i) = \sum_{degree(j)>degree(i)} PO_{ij} + \sum_{degree(j)<degree(i)} PO_{ji} \quad . \tag{B.3}$$

It complies to the first condition as all nodes will receive the same number of summations, however with a varying mix of sending and receiving overlap. It also complies to

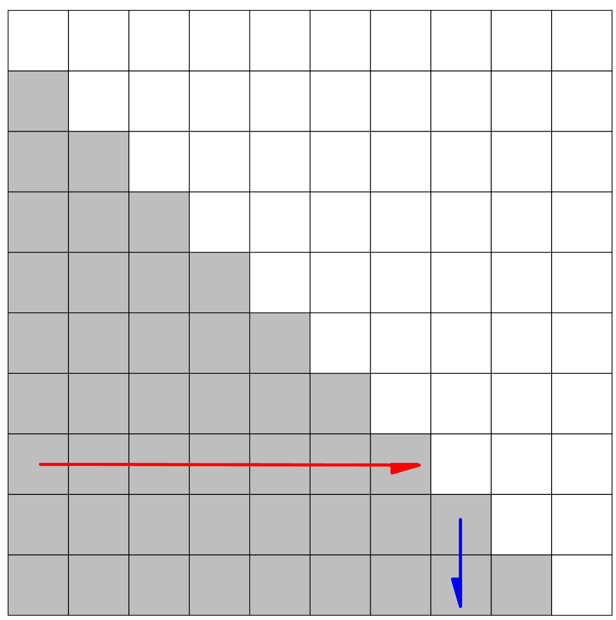

Figure B.1: Overlap matrix standardized by pairwise minimum degree with summation over pairs of sending overlap (red arrow) and receiving overlap (blue arrow).

the second condition with a summation over all nodes Adding the generalist perspective leads to summation of the overlap elements twice rather than once in the NODF measure. Hence the normalization needs to be changed accordingly

$$NODF = \frac{\sum_i overlap(i)}{n(n-1) + m(m-1)} \tag{B.4}$$

While equation B.4 reproduces the NODF measure based on individual overlaps, it requires the contribution of both types of nodes. In the next step it is accounted for that nodes not only overlap as visualized in figure B.1, but that they also facilitate overlap. For instance organizations that are involved in one or more innovations contribute to the innovation part of the nestedness by the contribution of these innovations (and the same applies for innovations and organizations). This *facilitated* part of nestedness is added to the overlap part with other organizations.

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Education	
1961	Born 24^{th} of June in Ebermannstadt, Germany
1980	Graduation from Gymnasium Fränkische Schweiz in Ebermannstadt, Germany
1986	Diploma in physics from Friedrich-Alexander-Universität in Erlangen, Germany
1990	PhD in astronomy from Ludwig-Maximilians-Universität in Muncih, Germany
2004	Executive MBA from Rutgers New Jersey State University in Beijing, China
from 2007	PhD in Management at Rutgers New Jersey State University in Newark, NJ, US
Work Experience	
1990 to 2007	Several managerial positions at Siemens, telecommunicatons industry, in Germany and China
Awards	
2010	Best Reviewer Award, AOM meeting Montreal, International Management division
2011	Dissertation Research Award, Technology Magagement Research Center, Rutgers
Publications	
2011	Contractor F, Woodley J and Piepenbrink A. 2011. How Tight an Embrace? Choosing the Optimal Degree of Partner Interaction in Alliances Based on Risk, Technology Characteristics, and Agreement Provisions, Global Strategy Journal 1 (1/2): 67-85.