TOWARDS CONFLICT-FREE SWITCHING IN MULTIHOP WIRELESS MESH NETWORKS

by

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ABSTRACT OF THE DISSERTATION

Towards Conflict-Free Switching in Multihop Wireless Mesh Networks

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In wireless mesh networks, an important open problem is that of efficiently supporting end-to-end real-time flows such as voice, video or aggregated infrastructure traffic. The overall performance achieved by conventional layered approaches (802.11 MAC combined with independent ad hoc routing protocols) is significantly lower than the underlying network capacity due to interferences and poor interactions between MAC and routing layers. In this Ph.D. thesis, we propose a "conflict-free switching" framework to handle this challenge through a combination of techniques at the medium access control (MAC) and network (routing) layers.

At first, we focus on the per-packet scheduling in MAC layer only and propose the D-LSMA MAC protocol as an enhancement of IEEE 802.11 MAC to solve the inefficiency of MAC problems in multi-hop wireless networks. Simulation results show that our D-LSMA protocol achieved 20-30% more throughput than the original IEEE 802.11 MAC.

In dense wireless mesh environments, the communication complexity to establish conflict-free scheduling becomes very high due to extended interference range. In this case, per-flow optimization mechanisms are better than per-packet MAC scheduling solutions. Hence, to reduce control overhead and improve end-to-end performance further, we propose a clean-slated IRMA (Integrated Routing/MAC Scheduling) design to integrate the routing and MAC into a single protocol layer and use joint optimization techniques to establish end-to-end path and TDMA schedules for flows across the network. This approach achieves non-conflicting allocation of channel resources based on global or local traffic flow specifications and network conflict graphs. Two different joint routing/scheduling algorithms are presented. The first method solves min-hop routing, then optimizes link scheduling based on routing results and real-time flow demands. The second approach attempts to optimize routing and scheduling decisions simultaneously, using available MAC bandwidth information to route around congested areas. Both centralized and distributed algorithms based on these methods are proposed and evaluated with detailed simulations. Results show significant 2-3x improvements in network throughput when compared with baseline 802.11-based mesh networks using independent routing protocols.

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To my parents who have been a constant source of emotional support.

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Dedication

Dedicated to my lovely wife, Yu.

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Chapter 1

Introduction

1.1 Motivation

1.1.1 Emerging Broadband Radios and Mesh Networking

In the last two decades, wireless communication is dominated by centralized wireless access solutions based on long-range low-speed radios, such as GSM/CDMA cellular systems and recently built 3rd Generation networks. Since those networks seek to provide ubiquitous mobility solutions to users, they usually prefer using radios which cover long distance but with limited link data rate. This makes it difficult and expensive to support broadband multimedia applications over those carriers. On the other hand, recent "Moore's Law" improvements in short-range radio cost-performance have led to the thrive of Wi-Fi networks, a wireless technology based on IEEE 802.11 standard [1]. It supports a free data service much faster than its cellular counterparts. The success of Wi-Fi leads to a lot of activities in the development of short-range, high-speed broadband radios [2][3][4], as shown in Table 1.1.

Technology	Link Speed (in Mbps)	BW (MHz)	Frequency Band
IEEE 802.11n	74-248	20 or 40	2.4GHz/5GHz
WiMedia	53-480	500	3.1 to 10.6GHz
mmWave	up to 2000	N/A	60GHz

Table 1.1: Emerging broadband radios

As can be seen from Table 1.1, in the near future, it is highly plausible to have radios supporting 200Mbps to 2Gbps data rate over the air, depending on the channel bandwidth and transmission range.

On the other hand, the lowering costs of wireless radio devices bring new form of wireless networks to life. By employing wireless relay routers to relay multi-hop traffic, high-bandwidth data transportation could now be supported by radio links only. Such an emerging innovation would shift the radio network from a traditional pure access-based "edge" network to a more general "wireless mesh backbone". The replacement of wired infrastructure would make the network deployment cheaper and more flexible.

In this Ph.D. thesis, we envision a high-speed wireless mesh network architecture which is made up of a group of wireless stations (nodes). Each mesh node is equipped with one or more high-speed broadband radios. A mesh of wireless routers will connect each other through those radio interfaces. Due to the limited transmission range of broadband radios, such network architecture may not a good choice to establish universal mobile networking. It, nonetheless, probably can be widely used in future for home networks and office networks. For instance, in home networking, this kind of network can provide wireless connectivity among all kinds of consumer electronics and computers. Multimedia content sharing applications among HDTV, DVD Player, iPod or game consoles may take place in people's home. For enterprise networking, mesh routers can form a wireless backbone without Ethernet cables and switches. Some *edge* routers may have additional interfaces to allow client devices to connect this backbone through a point-to-point cable, Wireless LAN, Bluetooth, cellular link or other available access technologies supported by the edge routers. A typical wireless mesh architecture is depicted in Figure 1.1.

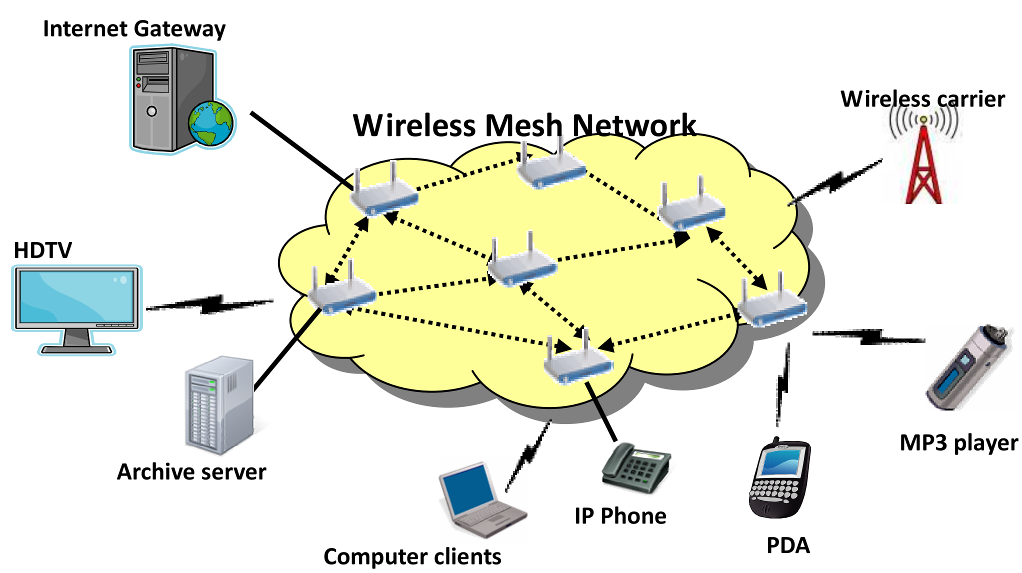

Figure 1.1: Wireless mesh network architecture

It is interesting to discuss what to do with all this bandwidth in high-speed wireless mesh networks. Conventional Internet applications usually do not need so much bandwidth. It seems that congestion will no longer be a problem in those networks. However, as long as bandwidth exists, there is no doubt that new bandwidth-consuming applications will emerge. Today's electronic devices tend to have huge storage capacity. For example, one of the Apple's newest products, iPhone, has a built-in 8GB flash memory. It would be very convenient for users if most of the data stored in this memory space could come and go across the wireless carrier. This would require a lot of bandwidth over the air. Moreover, some applications such as uncompressed video streaming, music and photo sharing, peer-to-peer gaming, even data transfer between DVD and HDTV can be purely "wireless", too. Also, in the office environment, the mesh backbone may support aggregated traffic from a bunch of clients which may run applications like voice/video conferencing, remote system backup. All above potential applications, when combined, are definitely able to deplete the network capacity of this next-generation, high-speed mesh network.

On the other hand, the capacity of wireless networks is usually significantly low when compared to their wired counterparts due to the existence of interference conflicts. It is often misleading to just use physical layer link speed directly as an estimate of the end-to-end network throughput. For example, the maximum link layer throughout for IEEE 802.11a radio is around 30Mbps although the PHY data rate is as high as 54Mbps. The end-to-end throughput for multi-hop flows are even worse [5]. If the higher layer network protocols are not carefully orchestrated, the network throughput may fall sharply when multiple broadband applications run simultaneously.

Before examining the design challenges in mesh networks, we want to point out that our definition of wireless mesh networks is more general than the one used in IEEE 802.11 based wireless mesh network[1] research. Both the respective application scenarios and research thrust of this mesh architecture are different from the related research activities in IEEE 802.11s standard group [7] too. 802.11 mesh networks use 802.11 standard as PHY and MAC protocol and adopts an opportunistic approach to seek solutions to utilize multiple Wi-Fi channels and extend Wi-Fi coverage. In our research, we discuss the general architecture and protocol design issues for mesh networking, especially for the single channel case. We do not assume IEEE 802.11 is used as a de-facto MAC protocol. On the contrary, the MAC

[1] A good review on the scope of wireless mesh network research can be found in [6].

protocol design for mesh networking itself is one of the issues we try to address in this thesis.

1.1.2 Protocol Design Challenges

The primary task of this kind of wireless mesh network is to achieve high throughput for end-to-end applications, including real-time bulk data transfers. Several challenges need to be overcome before this goal can be reached.

First, the co-channel interference must be suppressed both *effectively* and *efficiently*. The capacity of wireless networks is already lower than their wired counterparts due to the existence of interference conflicts. If link transmissions are not regulated correctly, the network performance would suffer further losses due to packet collisions resulted from interferers, e.g. "hidden terminals". Therefore, collision-free transmission scheduling is a necessity to ensure the network performance. On the other hand, too conservative scheduling (e.g. IEEE 802.11 CSMA/CA MAC) creates "exposed terminals" in the network and reduces the spatial reuse. It is a very challenging task to find good tradeoff between those two objectives.

Second, the end-to-end quality of service needs to be considered. Unlike best effort data, real-time flows and aggregated traffic between wireless routers need relatively deterministic bandwidths and bounded delays. Realizing that usually requires some combination of bandwidth reservation, scheduling and dynamic resource management. Traditionally, those schemes are implemented in communication protocols of layer 3 and above. However, this methodology cannot apply to this new problem because characteristics of radio resource are very different from that of static wireline links. The throughput of a wireless link can vary dramatically with different PHY and MAC configurations. Such traditional QoS techniques will only be effective if it can allocate resource in PHY and MAC layer directly. Therefore, a cross-layer approach or integrated protocol design for the whole protocol stack is often justified for this case.

The third challenge is to have reliable and robust coordination of the wireless routers. In a multihop wireless network, nodes that share bandwidth may not be able to talk with each other directly. This inability to communicate makes it difficult to coordinate medium access activities and ensure that every application flow gets the bandwidth it wants. Thus, the routers need self-organize a reliable communication structure for control and coordinate each other's behavior. This is a new challenging topic. Some prior work avoids the complexity of this issue by either ignoring it or resorting to offline optimization algorithms.

These issues all stem from key differences between wireless networks and their wireline counterparts, as identified above, which make the realization of our objective particularly challenging.

1.2 Thesis Overview

1.2.1 Conflict-Free Switching over Wireless Network

We deem the key to the solutions of above problems is to ensure conflict-free packet transmission in multi-hop wireless environment. Due to the limitation of current radio technology, if one link transmission is in conflict with other ongoing transmissions on the channel, it will result to a total packet loss. If link transmission failures are abundant because of interference conflicts, the precious channel resources are wasted and extra resources would be consumed for conducting retransmissions[2]. This not only produces negative impact on system throughput, but also makes it hardly possible to realize QoS for end-to-end flows. Therefore, *conflict-free channel access* is essential to a plausible systematic design for high-throughput wireless networks.

Moreover, we regard this as a two-tier problem. First, a scheduled channel access shall be free of collisions/conflicts. Second, when the first condition is satisfied, the network shall maximize the throughput by allowing as many concurrent accesses as possible. This means non-conflicting links shall not be unduly prohibited to access channel simultaneously. Here we use an example to manifest this idea. Eight wireless stations are placed in a topology depicted in Figure 1.2. Each station wants to communicate with its adjacent neighbors. We assume a radio's transmission may interfere with its 1-hop neighbors only. In (a) of Figure 1.2, two transmissions ($C \rightarrow B$ and $B \rightarrow A$) are scheduled at the same time. Because station B's radio cannot receive packets while transmitting, it is unable to receive station C's packet. Also, station G and E's transmissions will collide in station F. By preventing conflicting accesses, a conflict-free scheduling scenario can be obtained as shown in Figure 1.2(b). However, for the whole network, spatial reuse does not reach its maximal point until there are no more transmissions could coexist. This borderline scenario is called

[2]Hybrid ARQ scheme are proposed for 3G networks, but it is mainly used to combat varying physical channel conditions rather than collisions or transmission conflicts.

maximal scheduling and an example is shown in (c) of Figure 1.2. Even though, regarding the maximum number of coexisting transmissions, a better arrangement still exists. For this topology, at most 4 simultaneous link access can occur, as shown in Figure 1.2 (d). As seen from this example, link access solutions that reach or are close to either maximal or maximum scheduling results are far better than random or conservative access schemes.

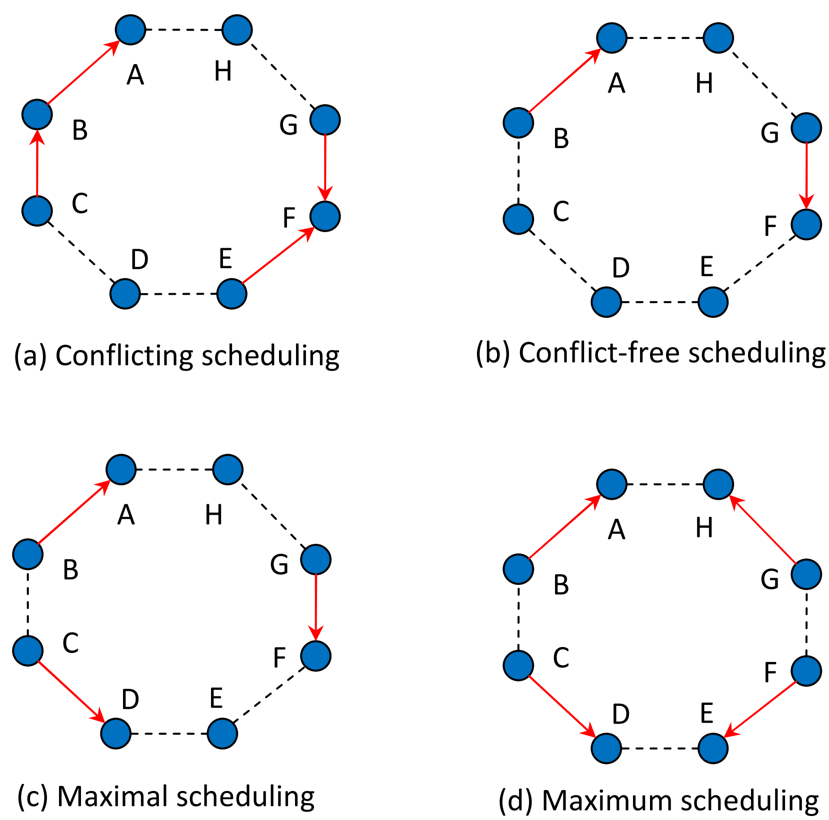

Figure 1.2: Conflict-free, maximal, and maximum schedules for wireless link access

Switching is a conventional technique to create conflict-free access to a shared resource. In this thesis, we propose to have a comprehensive switching design over the wireless network to seek both collision-free and throughput-optimal radio resource allocations. Once there exists such a protocol or mechanism to regulate link access both effectively and efficiently, it then can be used as a foundation for further extension to support QoS. Nevertheless, unlike previous switching algorithms used for telephony or ATM networks, the radio resource in a wireless network is shared by nodes across part of or even the whole network. The realization of conflict-free switching over a network requires both extensive communication and precise coordination, which turns out to be much more difficult than designing a single switching algorithm for telephone circuit switches or ATM switches.

In wireless networks, common radio resources can be shared in two dimensions: frequency and time. Hence, A switching design could divide certain resources into either time shares or frequency slices and then assign each of them to a certain *task unit*. The task unit here can be a single packet, a single-hop flow (equivalent to a bandwidth requirement for a link) or even a multihop end-to-end flow. Moreover, the physical interference constraints which restrict arbitrary switching in wireless networks can also be modeled mathematically in many different ways. Also, control signaling is needed to carry out packet or flow reservations. Certain issues arise regarding the design of control mechanism. For instance, control signaling and data messages can be mixed in the same single channel (as in IEEE 802.11 MAC) or separated physically, similar to TDMA schemes. And either centralized or distributed control protocols can be conceived. The design choices of above three aspects: *scheduling task unit*, *interference model* and *control mechanism* span a large design space for conflict-free switching protocol. It is obvious, nonetheless, that those choices can hardly be made independently. Not all the combinatory choices in this 3-dimensional space are good architectures for protocol implementation. Inappropriate combinations cannot mitigate interference, but cause severe performance degradation instead.

The scope of our research is currently limited to single-channel multihop wireless mesh networks where frequency allocation is unnecessary. Under this scope, we only consider the time-switching case in this thesis. We present two of our design choices for conflict-free switching solutions (D-LSMA and IRMA) and compare it with the basic IEEE 802.11 design. The performance evaluations are done from two aspects: theoretical analysis and protocol simulations. The theoretical throughput bounds can be obtained mathematically by formulate network optimizations under certain constrains based on network conflict graphs. In protocol evaluation, both performance and complexity metrics are evaluated. Through the analysis of those particular designs, we attempt to find answers to the following general questions:

1. Under different interference modeling, what's the appropriate choice for scheduling task unit, per-packet or per-flow scheduling?

2. What's the theoretical throughput bound for a particular design? How network throughput scales with increasing network size or traffic?

3. How heuristic protocol designs approximate the analytic performance bounds?

4. What's the overhead to realize interference-free switching for those schemes? What's the difference between centralized and distributed control?

1.2.2 Proposed Solutions

As the first part of our solution set, we give a per-packet scheduling solution in MAC layer. The proposed D-LSMA scheme is focused to optimize the MAC scheduling based on local information and attempt to solve both *hidden terminal* and *exposed terminal* problems together. It uses an extension of the IEEE 802.11 CSMA/CA procedure as the basis for a distributed link scheduling algorithm which results in dynamic TDMA-like bandwidth allocation among neighboring wireless nodes without the need for global synchronization. Unlike 802.11 MAC which is designed for conventional "star-topology"-like access networks, this MAC enhancement targets for multihop topology and shows satisfactory improvement of performance.

Then, we examine the general case for establishing efficient collision-free time-switching for flows. Flow-based scheduling conducts reservations based on end-to-end flow rates. Unlike packet-based scheduling, flow-based scheduling/switching would work better by reducing the intra-flow and inter-flow contentions, thereby yielding better end-to-end performance. It is natural to use TDMA MAC as a basis for this because it can guarantee a certain fixed data rate at a given link by satisfying the interference constraint.

In order to achieve this, we abandon the traditional layered approach and adopt a novel perspective to design routing and MAC protocols: Integrated Routing and MAC Scheduling (IRMA). With integrated MAC and routing, the relationship between path selection component and medium access control component has changed to a tight-coupled two-way interaction:

- Medium access schedule shall be determined and optimized based on the path-selection results.

- Route selection algorithms shall also consider the feasibility of MAC schedules.

The realization of the IRMA relies on a robust control plane to exchange certain global and local information. Basically, we assume a separation of data and control messages by introducing a Global Control Plane (GCP). To optimize conflict-free scheduled access for data traffic flows in the data plane, the nodes in the network exchange/broadcast necessary topology and traffic information in GCP. Control algorithms are employed in the control plane to optimize the path selection and MAC schedules jointly, based on those information.

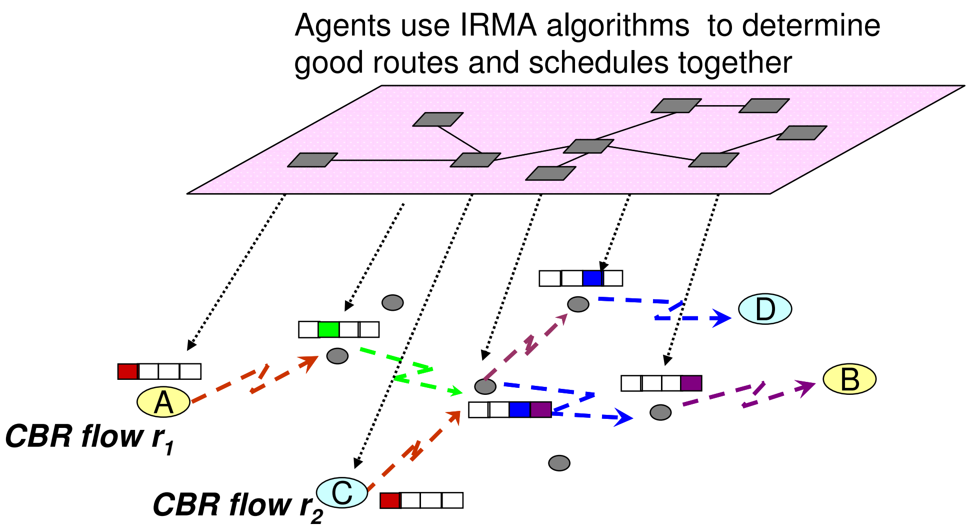

Figure 1.3: IRMA concept diagram

Figure 1.3 shows a diagram to explain the IRMA concept. Let us assume the aggregated traffic load of each router does not change frequently. For the two flows A to B and C to D over a mesh network, the routing tables and TDMA schedules could be jointly optimized for certain objectives. As shown as different colors of those wireless links, those per-hop transmissions can be scheduled at different time to completely avoid interference and maximize spatial reuse, which would improve the end-to-end throughput of the flows. The efficiency of the network can be greatly improved by this means. Suppose each node has a control agent. The control agents then could exchange information and determine the routing table and TDMA scheduling by running some algorithms over a "control plane". And after those new sets of parameters are determined and passed by the control agent to the "data plane" of the network, they will take effects to gear up the network with a better routing/MAC solution for every node.

The design of control algorithms is crucial to the overall performance of IRMA. We take a two-step approach to algorithm design. First, assuming the network traffic and topology information are exchanged sufficiently over the whole network, central algorithms are designed. By analyzing those central algorithms and comparing their performance with the network capacity obtained by LP (Linear Programming) analysis, we could understand the performance improvement margin of joint route-selection and scheduling mechanisms. Then, we relax the requirements for global knowledge and design heuristic, scalable, distributed IRMA algorithms.

1.3 Related Research and Our Contributions

The scope of this Ph.D. dissertation is limited to static, single-channel multihop wireless mesh networks that use compatible radio devices. Hence, radio transmissions are subjected to common co-channel interference, which may be modeled in a variety of methods. We also assume that there is no per-packet power adaptation and the transmit power is not adjustable for a very long time period. Under this scope, we first review the current related research in MAC, routing and cross-layer approaches respectively. Then, we will identify our distinctive contributions to this research field.

1.3.1 Overview of MAC Protocols in Wireless Networks

Medium access control (MAC) protocols in wireless networks should control access to the medium and share the channel between multiple source-destination pairs. Traditionally, MAC schemes are coarsely divided as two kinds: non-deterministic or deterministic approaches. In our thesis, based on the MAC functions and characteristics of multihop access, we further classify all MAC solutions in four fine categories: random access, contention-based access, scheduled access and dynamic reservation.

Random access MAC protocols started with the research on point-to-multipoint wireless communication systems among a dozen of islands [8]. Aloha and Slotted Aloha are two typical solutions in this category. Basically, in those schemes, a node accesses channel randomly without knowing whether a transmission is going to succeed or fail. Further research on this for satellite communication systems can be found in [9][10]. There is one recent work [11]which proposes to use probabilistic random Aloha access in multi-hop wireless networks. Generally, random access schemes are not scalable. When the network load (user number) increases, the probability of collision rises and channel throughput falls sharply. Some research on the stability and optimality of random access control in multi-hop networks are done recently [12] [13].

Contention-based access schemes are derived from CSMA(Carrier Sense Multiple Access) protocols [14]. With CSMA, nodes only access channel when carrier is sensed *idle*. Multiple nodes contend[3] for channel usage with a certain backoff mechanism such as the “basic access” method in IEEE 802.11 MAC. The major problem with those methods in multi-hop scenario is that an “idle” carrier sensing result is unable to ensure a “clean” channel, thereby often leading to hidden terminal problems and packet loss.

Unlike previous access schemes, the deterministic scheduled access schemes set up time-tables for individual nodes or links, such that the transmissions from the nodes or over the links are conflict-free in the “time” space of the channel. A deterministic schedule for all possible channel events is usually generated based on either pre-specified traffic profile, network topology or both. Once a schedule is determined, it can be used for a very long time as long as conditions do not change. For example, polling-based access are widely used for networks of “star” topology, where a master node can poll and guarantee each client’s access one by one with a fixed order. But it is very difficult to apply this in ad hoc and multi-hop networks. One interesting line of work is Time-Spread Multiple-Access (TSMA) [15][16], which creates topology independent collision-free MAC schedule. This is very attractive in mobile ad hoc networks although it often results in very low spatial reuse ratio. MAC solutions of this category are primarily focused on how to reach a good schedule with some mathematical optimization techniques. Most related studies for multihop wireless networks are about offline or centralized algorithms, which we are going to describe in detail in Section 1.3.3. There are very few interests in protocol development based on pre-deterministic scheduled access.

Different from above approaches, dynamic reservation MAC protocols are more promising and realistic approaches for solving multihop channel access problems. Basically, those protocols try to schedule conflict-free *reservations* for dynamic on-demand traffic. As reservations are supposed to be conflict-free, packet transmissions are less prone to collision loss. Also, they achieve better efficiency than fixed TDMA solutions because reservations are made based on actual traffic requirements. The reservations are usually made with

[3]Here, we distinguish contended access from random access by defining “contender” as nodes who can be aware of other contenders’ access activities by carrier sensing. This term may be abused in the rest of the thesis.

the help of control signaling. Collision-avoidance MAC solutions such as MACAW [17] and CSMA/CA [1] can be regarded as simple dynamic reservation schemes. For example, IEEE 802.11 MAC uses RTS/CTS handshake to reserve a future collision-free time interval to schedule a DATA frame and an acknowledgement. Essentially, this utilizes a contention-based access to book a contention-free time interval. Some CSMA/CA enhancements [18] [19] are proposed to solve exposed terminal problems. Those schemes do not need global synchronization because nodes are kept synchronized by neighboring channel events. Many dynamic reservation MAC protocols [20] [21] [22] [23] are build on a globally synchronized slot structure. They usually use dedicated slot/bandwidth for control signaling. For instance, Five Phase Reservation Protocol (FPRP) associates a fixed-size reservation slot with every information slot. Nodes compete for the channel access privilege of information slot in the respective reservation slot. In [21], a dedicated slot interval per frame is used to exchange the identifier of MAC contenders. And each contender uses a common ranking algorithm to determine the ownership of each slot.

For dynamic reservation schemes, some desirable features of the access protocol are to be able to reuse the resources as efficiently as possible, to avoid conflicts and collisions, to have minimum control overhead. Also, certain issues arise when the network is serving multihop flows and need to be taken care of. For example,

1. Self-interference between upstream node and downstream nodes existing in the traffic flow involving multiple hops [24].

2. Serious unfairness among the channel usage of different concurrent flows [25].

We are going to examine this line of research from optimization perspective in more detail after the literature review of routing protocols and cross-layer designs.

1.3.2 Routing Protocols and Cross-layer Approaches

To support multi-hop flows, a routing protocol is indispensable. There are numerous ad-hoc routing protocols proposed especially for mobile ad-hoc environment, such as DSDV [26], DSR [27], AODV [28]. Those protocols use either proactive or reactive signaling to discover and maintain the dynamic connectivity of the network, and adapt to topology changes resulting from node mobility or node failure.

As those routing protocols are mere network-layer solutions and do not consider the characteristics of wireless links (except the mobility) in the network, it turns out that the performance of the combination of those conventional protocols and typical contention access MACs such as IEEE 802.11 are very poor. The abstraction of wireless medium as a stable point-to-point link does not work well because the quality of a wireless link varies both temporally and spatially due to changing physical channel conditions and MAC states.

To enhance the overall performance of packet delivery over multi-hop wireless networks, several new cross-layer algorithms are proposed to take into account the underlying link characteristics while selecting paths from the source to the destination. ETX [29] metric is proposed to consider the measurement of link loss probability as the link metric. MTM [30] proposed to use the median transmission time to represent the link quality. In PARMA [31], the combination of packet transmission delay and access delay is used as link metric. For multi-channel multi-radio networks, an extension work of ETX metric, named WCETT [32] (Weighted Cumulative Expected Transmission Time) metric, proposed a path selection algorithm which takes link data rate, link loss rate and channel usage into account.

The limitations of those cross-layer routing protocols is that those schemes still rely on the MAC protocol which is designed regardless of the network layer and not optimized for end-to-end flows. As these modifications often target a specific parameter or mechanism instead of solving the fundamental inefficiency caused by MAC scheduling, they only provide limited overall improvements. Barrett et al. [33] characterize the interaction between routing and MAC in ad-hoc networks, and point out "optimizing the performance of individual layers is not likely to work beyond a certain point".

1.3.3 Conflict-free and Throughput-optimal Scheduling

Reservation-based medium access studies in link layer of wireless networks often resort to mathematical formulation of scheduling problems, under a variety of modeling of transmission conflicts[4]. The scheduling algorithms are of two basic types: node scheduling and link scheduling. In node scheduling, the reserved time interval can be used by the transmitting node to send a packet to any neighbor or broadcast a packet. Link scheduling requires a scheduled time interval is only used for a specific source-destination pairs. In this section,

[4] Please see Chapter 3 for more detail about interference models of transmission conflicts.

we classify the key research works on the optimization and realization of MAC scheduling in the following four categories based on the minimum task unit which the scheduling algorithm is supposed to handle.

Single-packet scheduling. Generally, this category includes scheduling algorithms or protocols which attempt to solve MAC scheduling problem per a single packet basis in a single hop or link. IEEE 802.11 MAC with RTS/CTS is a simple example of this kind. It uses RTS/CTS handshake to avoid collision based on a special 1-hop interference model. D-LSMA [19] and MACA-P [18] are two link scheduling algorithms which are back-compatible with IEEE 802.11, but with relaxed interference modeling. FRPR [20] and NAMA [21] schemes are two typical TDMA node scheduling algorithms based on 1-hop interference model. LAMA [21] is a per-packet TDMA link scheduling scheme under CDMA interference model. All above approaches are distributed algorithms because they are focused to solve a local access problem for a single packet.

Theoretically, optimization of per-packet scheduling can be modeled as either vertex- or edge- coloring problems[5] on network graphs given those graphs of network topology and transmission conflicts are known. Scheduling is equivalent to color a maximum set of nodes or edges without violating conflicts. A complexity analysis suggests optimal centralized policies are NP-hard to obtain for most of the interference models [34].

The performance of distributed packet scheduling schemes is often far from optimal. Usually, nodes only have a short time interval or even no time to exchange reservation signaling before making a decision. And once the channel access starts, there are no time left to optimize the decisions to allow more simultaneous access to reach *maximal or maximum matching*. For example, CSMA/CA scheme adopts a fixed RTS/CTS interval to inquire and decide whether a transmission is feasible or not. In NAMA [21], a slot contender may yield to a high-priority node, which, in turn, may have to yield to another high-priority node not conflicting with the original contender at all. All these problems compromise the performance of distributed scheduling. On the other hand, conflicts may not be completely eliminated due to limited and unreliable information exchange and race conditions [25]. In

[5]Vertex coloring problems corresponds to node scheduling, while edge coloring problems represent link scheduling. Moreover, edge coloring can be divided in two kinds: directional link coloring or bidirectional link coloring.

summary, those single-packet scheduling solutions have deficiency to satisfy either "conflict-free" or "throughput-optimal" conditions, or even both.

End-to-end packet scheduling. A multi-hop relayed packet need access channel multiple times, hop by hop. Algorithms in this category try to arrange the multiple sequential accesses for an end-to-end packet in a batch. So far, DCMA [24] is the only known protocol which facilitates the scheduling of all the transmission time for a data packet along multiple hops. It use a special ACK/RTS combo frame to set up cut-through reservations to expedite the packet forwarding.

Single-hop flow scheduling. The aggregated data transportation over a multi-hop network can be reduced to certain traffic amounts over individual hops or links. Regarding those single hop flows, finding the minimum length schedule which satisfies the flow rate demand is typically treated as k-colorability problem with vertexes or edges on a network graph. However, this is one of the classic set of NP-hard problems in graph theory [35]. Polynomial algorithms are known to achieve suboptimal solutions using randomized approaches or heuristics based on such graph attributes as the degree of the nodes. These include centralized [36] and distributed [37] node scheduling algorithms, and a variety of link coloring approaches [38] [39] [40] [41] [42]. Recently, those problems are revisited by [43] [44], based on more accurate and elaborate interference models. Although this topic is researched intensively, the answers to several non-trivial tough questions remain unclear. In regards of polynomial centralized algorithms, what's the comparative overhead to collect information and disseminate results for different interference models? Regarding distributed algorithms, the network need execute multiple rounds of scheduling before converge to a *tight* schedule. In each round, how does the network protocol suppress concurrency to avoid race condition? Or how does it, on the contrary, encourage concurrency to accelerate the algorithm? Is there a reliable way to notify all known or unknown (hidden) interferers about scheduling results at the end of each round and what's the complexity of that? Therefore, practical protocol designs based on those proposed algorithms are rarely seen.

Multi-hop flow scheduling. A traffic flow shall create equal traffic load in each hop along this path. The egress traffic amount from sources must be equal to the ingress traffic of sink nodes too. The observance of these constraints motivates further optimizations in scheduling. End-to-end flow scheduling algorithms are designed to solve the scheduling problems for each multi-hop flow rather than each single link. Those approaches often target to improve end-to-end network performance metrics. A seminal work [45] studied joint optimization of routing and link scheduling problem to improve end-to-end delay. Recently, global optimizations of scheduling and routing have been studied by [46][47], which describe methods for upper bounding the capacity/throughput of multi-hop network topologies with specified loads. However, these contributions are limited to performance bound calculations rather than construction of specific protocols. For example, in order to reach the optimality, each flow commodity needs to be routed through multiple paths. This is undesirable for a practical system design.

In regards of the above-mentioned problems with rate-based flow scheduling, we construct a systematic framework in this thesis to design and evaluate joint scheduling/routing protocols. It features a clean separation of data plane and control plane. Under this framework, we examine how centralized and distributed algorithms approximate optimal capacity bounds. We also identify the actual performance tradeoff regarding the control overhead, traffic dynamics. All these will provide unique contributions to this research arena.

1.3.4 Research Contributions

The distinctive contributions of this thesis could be described from two main aspects. First, we propose a novel "conflict-free switching" idea as a systematic approach to optimize the layer 2 and layer 3 protocol design and improve overall performance for multi-hop wireless mesh network. Regarding the performance-critical design choices for protocol implementation in this approach, we present our opinions as follows:

1. Both interference-free access and throughput-optimal scheduling are important design goals of wireless MAC protocols. Contention-based access or inappropriate reservation scheme (e.g. IEEE 802.11) produce poor end-to-end performance results for multihop wireless networks.

2. Various models of interference yield remarkably different performance results. Appropriate modeling in dense mesh environment shall go beyond simple 1-hop models. The signaling overhead for interference characterization and reservation are non-trivial and should be considered in protocol design.

3. To coordinate reservation activities and guarantee conflict-free switching, the data traffic and control signaling shall be separated. We implement an example *global*

control plane to provide a robust platform to exchange important control parameters across the different network entities and different layers.

4. Per-flow switching protocol is better than per-packet mechanism because it could 1) reuse reservation results for consistent traffic and require much less reservation overhead; 2) keep improving scheduling results by packing more non-conflicting transmissions in the same timeslot; 3) optimize routing and MAC scheduling jointly for extra performance gain.

Second, to validate the above ideas and realize "conflict-free switching", we conduct both numerical analysis of wireless mesh network capacity and exemplar mesh network protocol implementations.

1. We establish an analytical framework to obtain optimal resource allocations and throughput bounds for end-to-end traffic flows over single-channel wireless mesh networks, especially for single path routing case. We show that joint optimization of routing and scheduling show up to 300% performance gain in numerical results, comparing to conventional layered approaches.

2. We designed a per-packet link scheduling protocol, D-LSMA, as an 802.11 MAC enhancement. It can alleviate both hidden terminal and exposed terminal problems, help supporting single or multi-hop real-time flows in wireless ad-hoc networks.

3. We propose IRMA as a solution framework to realize flow-based conflict-free switching. IRMA solves medium access and path selection problems together with joint optimization. It tries to establish both collision-free link access and congestion-aware route selection. Ultimately, it can be extended to support QoS for end-to-end flows across the wireless networks. We design both centralized and distributed algorithms to realize the idea. Simulation results show that IRMA protocols can provide significant 2-3x improvements in network throughput when compared with baseline 802.11-based mesh networks using independent routing protocols.

The rest of the dissertation is organized as follows. In Chapter 2, we describe the D-LSMA protocol design and analyze its performance results. Then we discuss how interference modeling affects the designs of wireless protocols, especially for conflict-free MAC protocols, in Chapter 3. We present IRMA protocol, algorithms and corresponding evaluations in detail in Chapter 4. Finally, future working directions are given in Chapter 5.

Chapter 2

Distributed MAC Link Scheduling for Multi-hop Wireless Networks

In this chapter, we describe an innovative medium access control (MAC) protocol design for better QoS support in multi-hop mesh or ad hoc wireless networks, D-LSMA. The proposed D-LSMA (Distributed Link Scheduling Multiple Access) protocol uses an extension of the 802.11 CSMA/CA procedures as the basis for a distributed link scheduling algorithm which results in dynamic TDMA-like bandwidth allocation among neighboring wireless nodes without the need for global synchronization. In addition to supporting QoS, the proposed scheduling technique also solves the "exposed terminal" problem in ad-hoc 802.11, thus resulting in improved throughput in many scenarios. We believe, this IEEE 802.11 MAC extension is quite suitable for multi-hop WLAN and ad hoc networks to provide better support for end-to-end mobile applications.

2.1 Problems with IEEE 802.11 MAC

It has been pointed out by many researchers that the IEEE 802.11 MAC protocol does not handle interferences well, especially for the case of multihop wireless networks. In this section, we analyze several major shortcomings of CSMA/CA MAC when it is applied to serve multi-hop flows.

2.1.1 Contention

The basic CSMA scheme used in IEEE 802.11 MAC protocol requires each node contending for the channel access. Basically, each node needs to wait for a random backoff interval chosen from a backoff window. If the channel remains idle (detected by PCS (Physical Carrier Sensing)) during this interval, the node could access the channel.

Therefore, the MAC performance will degrade with the increasing number of contenders.

For a backlogged multihop flow, depending on the PCS range, a node has to contend for one or more upstream and downstream nodes. This often leads to reduced throughput and arbitrary delay in UDP flows and could have more severe consequences for TCP flows. Moreover, in regards of multiple flows in the whole network, this MAC creates unfairness. Short flows tend to have a leverage to achieve more throughput due to this effect.

2.1.2 Hidden Terminals vs. Exposed Terminals

Hidden node is a well-known problem in wireless communication. A sender can only sense the carrier around its transmitter, but is unable to sense whether the intended or unintended receiver is busy or not. Thus, the packet transmission could suffer loss because the receiver is not ready, as shown in the first example of Figure 2.1. Or the transmission may cause collision with another ongoing transmission, as shown by the 2nd example in Figure 2.1.

This problem is relieved by the so-called VCS (Virtual Carrier Sense) of 802.11 CSMA/CA protocol. A preceding request-to-send (RTS), clear-to-send (CTS) procedure with its "network allocation vector (NAV)" introduces the ability to schedule longer packets in a contention-free manner. This is done by distributing the NAV information to the vicinity of both the transmitter and the receiver. However, it is worthwhile to point out that the hidden terminal problems are not complete eliminated by the RTS/CTS solution. Essentially, the scheme just substitutes more harmful collisions of DATA messages with the losses of small size RTS frames. RTS or CTS frames are still subject to collisions caused by hidden terminals. A detailed analysis can be found in Appendix A.

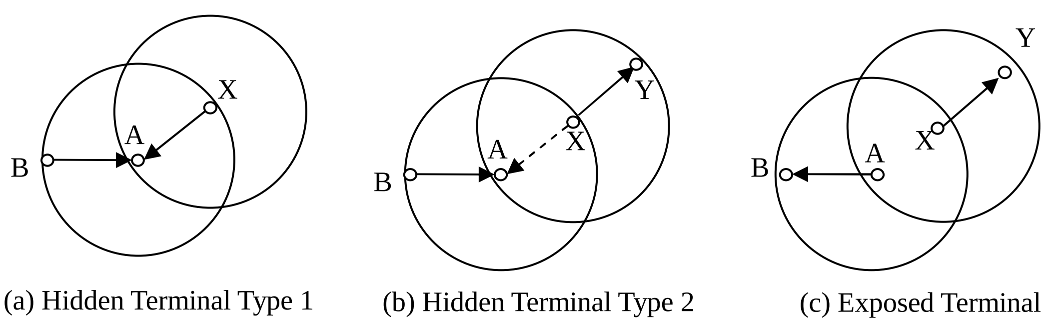

Figure 2.1: Hidden terminals and exposed terminals

Basically, the "virtual carrier sense" scheme is reservation-based per-packet time scheduling. This distributed algorithm intends to mark the time interval on the carrier as one of the three categories: 1) Free; 2) Reserved; 3) Prohibited. As depicted in Figure 2.2, an overheard RTS or CTS will set it as "prohibited" in NAV time duration, whereas a successful RTS/CTS exchange will put it in "reserved" state. After the time interval is consumed, the same procedure is applied for the next time interval.

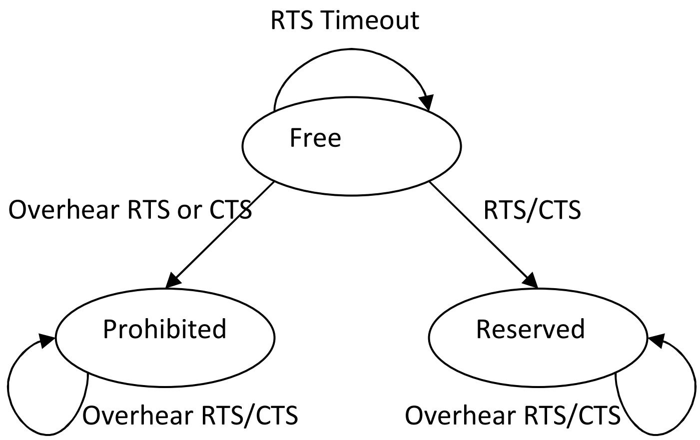

Figure 2.2: Scheduling with RTS/CTS in IEEE 802.11

A side effect of the RTS/CTS scheme in IEEE 802.11 MAC is the exposed terminal problem. This problem occurs when a node is prevented from sending packets to other nodes due to a neighboring transmitter. As shown in (c) of Figure 2.1, when A transmits to B, node X may also transmit to Y at the same time as long as B and Y are not affected by the other ongoing transmission respectively. However, in IEEE 802.11, node X restraints itself from transmitting because of the two-way $DATA+ACK$ packet exchange. The $DATA$ frame transmitted from X could potentially collide with an ACK from B. This is avoided specifically by exchanging RTS/CTS first. The existence of exposed terminals reduces the bandwidth utilization, especially in multihop networks.

2.2 D-LSMA Model

2.2.1 Link Scheduling Principle

The technical challenge of "link scheduling" in a multi-hop radio network is explored in [41]. The problem is that of constructing a TDM (Time Division Multiplexing) schedule for unicast communications in a multi-hop radio network. In this work, the multi-hop radio network is modeled as a *graph*. From a centralized perspective, this is equivalent to solving an "edge coloring" problem in directed graph. Note that this model assumes that if a node x cannot communicate with another node y, its transmission will not cause enough interference to cause a collision around y. The basic scheduling rule under this model is that *two links could be assigned the same TDM slot as long as they are not adjacent and there is no third link from the transmitters of one link to the receivers of another link.* In other words, a link transmission is successful as long as there is no other 1-hop neighbor of the receiver transmitting. Applying this rule would eliminate both hidden terminals and exposed terminals. In [41], each node may be assigned TDMA slots in the schedule table for each directional link to a neighbor node using a centralized algorithm with full knowledge of network topology. The D-LSMA, however, uses a distributed approach to form such a schedule. In order to set up link scheduling in a distributed manner, each potential time slot shall be marked by each node in one of five following states:

- *Free.* Open to make reservations on this period or use this time slice to send reservation requests.
- *Prohibited.* Neither further TX nor RX is allowed.
- *Transmit OK.* Node may transmit to nodes except to those in the "active transmitter list". This list is formed by recording the senders of RTS frame overheard in neighborhood.
- *Receive OK.* Node may receive packets but cannot send packets.
- *Reserved.* The node itself will be the sender or receiver to use this time slice.

To schedule correctly, procedures depicted in Figure 2.3 are applied to ensure that for each time slice, only conflict-free transmissions will be scheduled simultaneously. Comparing to Figure 2.2, there are two more states: "TX OK" and "RX OK", In those states, although the node has overheard an RTS or CTS, it is still free to arrange additional parallel transmissions and move to *reserved* state. Only when multiple captured control messages indicate that the time interval is completely booked by other conflicting neighbors and all opportunity windows are closed, the node then marks the time interval as "prohibited". This mechanism provides extra communication opportunities to be harnessed in a multi-hop radio networks.

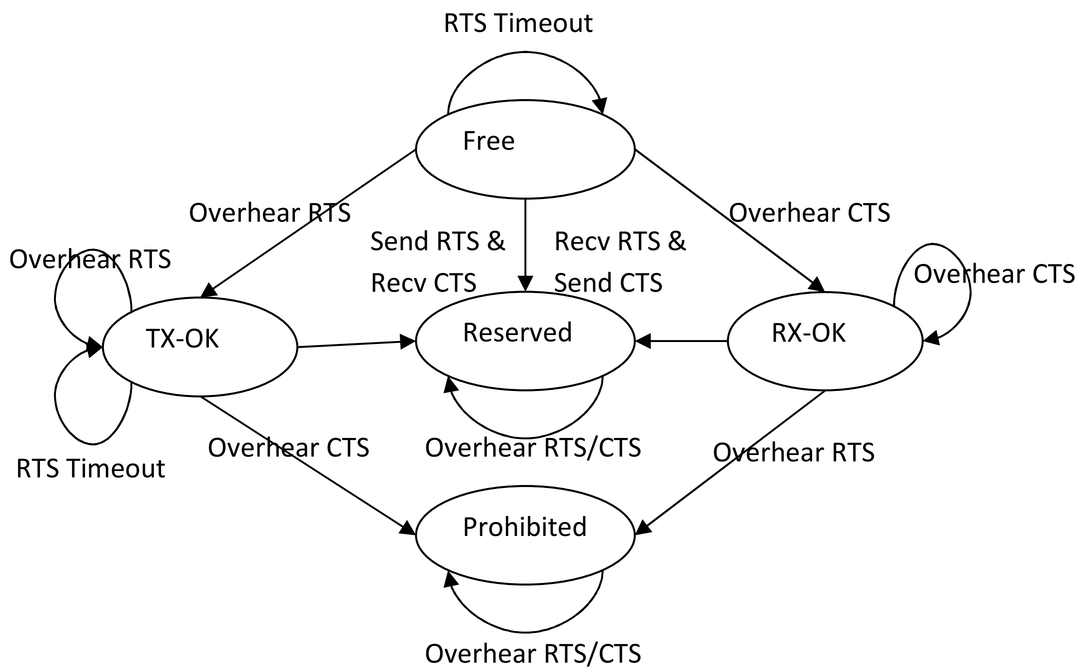

Figure 2.3: Scheduling procedures in D-LSMA

2.2.2 MAC Scheduler

In the proposed D-LSMA protocol, we generalize scheduling in 802.11 channels by introducing the concept of segregation between an "upper MAC" and "lower MAC". The lower MAC in D-LSMA is similar to that in the 802.11 standard with extensions to the control syntax necessary to support more general link scheduling policies as in Figure 2.3. The upper MAC can be thought of as an intelligent scheduler which monitors flows to neighboring nodes and makes decisions on "when to reserve?" and "how much to reserve?" depending on traffic volume and flow QoS requirements at that node. The upper MAC can incorporate algorithms that are aware of network topology and traffic load in order to maintain flow QoS. As shown in Figure 2.4, the upper MAC can be designed to support a mix of traffic types with separate packet queues and different scheduling policies. Note that this type of segregation by traffic type is an important feature in multi-hop ad-hoc networks where radio nodes have to handle both local and cross traffic with different service/bandwidth requirements.

In the rest of this chapter, we describe a specific realization of D-LSMA aimed at supporting QoS for real time traffic flows. It is noted here that the separation of scheduling from

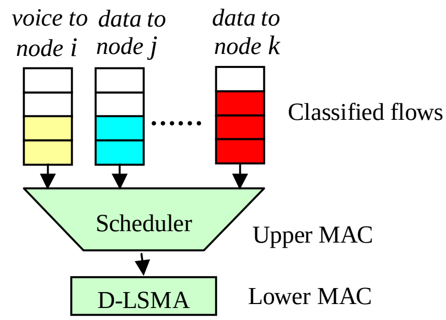

Figure 2.4: New MAC structure: scheduler + basic MAC

basic channel access means that the protocol described can be extended to other service objectives without changing the basic architecture.

2.3 D-LSMA MAC Protocol

The D-LSMA protocol is a distributed MAC protocol similar to IEEE 802.11 MAC. It uses standard 802.11 access protocol with DCF and RTS/CTS functions. However, to support distributed link scheduling, several important modifications are introduced.

2.3.1 Improved RTS/CTS procedure

When an RTS or CTS is overheard, a node not only collects the carried timing information, but the corresponding link information (sender and receiver identifier) as well. The information is used to determine if an overlapping transmission can be arranged or not. Also, to allow multiple transmissions to be reserved in parallel, the DATA message is separated from the previous atomic RTS/CTS/DATA procedure. An artificial control cap is inserted between the RTS/CTS exchange and the following DATA transmission. Within this control gap, more than one RTS/CTS exchange can occur before the DATA transmission.

2.3.2 Packet Classifier

When a time interval is marked in TX-OK state, it would be able to schedule a transmission to a certain destination except the neighbors already in the transmitter list. Thus, if the head of packet queue is in that list, the transmission chance will be wasted even if other packets in the queue are destined to nodes not in that list. To utilize the multi-user diversity in the multi-hop wireless networks, we propose to classify the packets into several different flows (queues) based on MAC destination address and flow specifications. The MAC scheduler then can decide which queue shall dispatch a packet, based on current MAC reservation status and QoS policy. If packets in more than one queue are eligible, the flows are served in a round-robin manner.

2.3.3 Suppression of Acknowledgement

To allow exposed terminals to transmit in parallel, it is necessary to avoid the ACK frame of one data transmission colliding with the DATA transmission in parallel. One possible solution is to schedule all ACK frames in a separate time interval [18]. In D-LSMA, our solution to this is simply suppressing the ACK frames. Omitting link-level retransmission is helpful for real-time applications because retransmissions generally increase delay variance for received packets and may not provide an improvement in throughput relative to end-to-end error control alternatives.

2.3.4 Flexible Reservation

Usually, an RTS/CTS exchange only reserves a time interval enough to transmit a single DATA message in IEEE 802.11 MAC. In D-LSMA, there is considerable flexibility in making reservation requests. Node may reserve in the same way as 802.11, or reserve back-to-back transmission for multiple packets in the same queue, or reserve periodic time slots for packets from same CBR flow. Allowing multiple reservations made in one RTS/CTS exchange could improve the protocol efficiency and help reduce the contention. The timeline of reservation procedure is depicted in Figure 2.5[1].

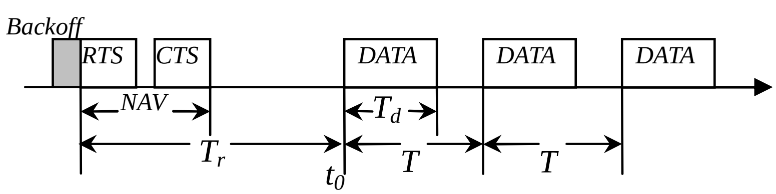

Figure 2.5: Timing relationships for reservation

As seen in the figure, the following parameters are involved:

[1]For simplicity, small time intervals like SIFS are not depicted.

- t_0. Starting time for a D-LSMA transmission procedure. In RTS frame, this is actually represented as an offset from the reservation time till t_0 time instant.
- T_d. Time needed for data transmission.
- N. Number of periodic time slices to reserve.
- T. Cycle time of a periodic packet flow if $N > 1$.
- T_r. Time between RTS reservation and reserved first data transmission.

A modified RTS frame which includes above parameters will be sent after contention with backoff procedure. NAV is adjusted to the duration only covering RTS/CTS exchange. By exchanging RTS/CTS, the sending node and receiving node will reach an agreement that the sender will use the time slice as $[t_0+iT, t_0+T_d+iT], i = 1, 2, \ldots, N-1$ for transmission with a successful reservation. The scheduler is responsible for choosing appropriate above parameters when the MAC obtains the channel after backoff and is ready to send an RTS message.

In the reservation, there is a time gap T_r between the current time and DATA transmission time t_0. In 802.11, by default, this gap is equal to the sum of transmission time of an RTS frame and a CTS frame. Here, the gap shall be large enough to allow multiple RTS/CTS exchanges occur. Usually, the nearest available feasible transmission time after a minimum T_r offset in the schedule table is chosen as t_0. Note that once an RTS frame fails, the D-LSMA MAC will generate a new RTS rather than retransmit the old RTS because the field indicating a relative offset to t_0 has to be recalculated. And if the remaining time in T_r is not long enough for a new RTS/CTS exchange, the node will abort reservation and wait for the next opportunity. The absolute value of t_0 has to be reselected by the scheduler when this node reserves again. In the preliminary simulation results given in the next section, the minimum value of reservation gap is set as $1.5ms$.

2.3.5 D-LSMA Example

Here is an example in Figure 2.6 which shows a network with 5 nodes, A, B, C, D and E. Nodes A and C have some traffic to B, while D has some traffic to C and E each. The procedure followed by the nodes to establish transmission schedules for periodic flows to neighbors is outlined below:

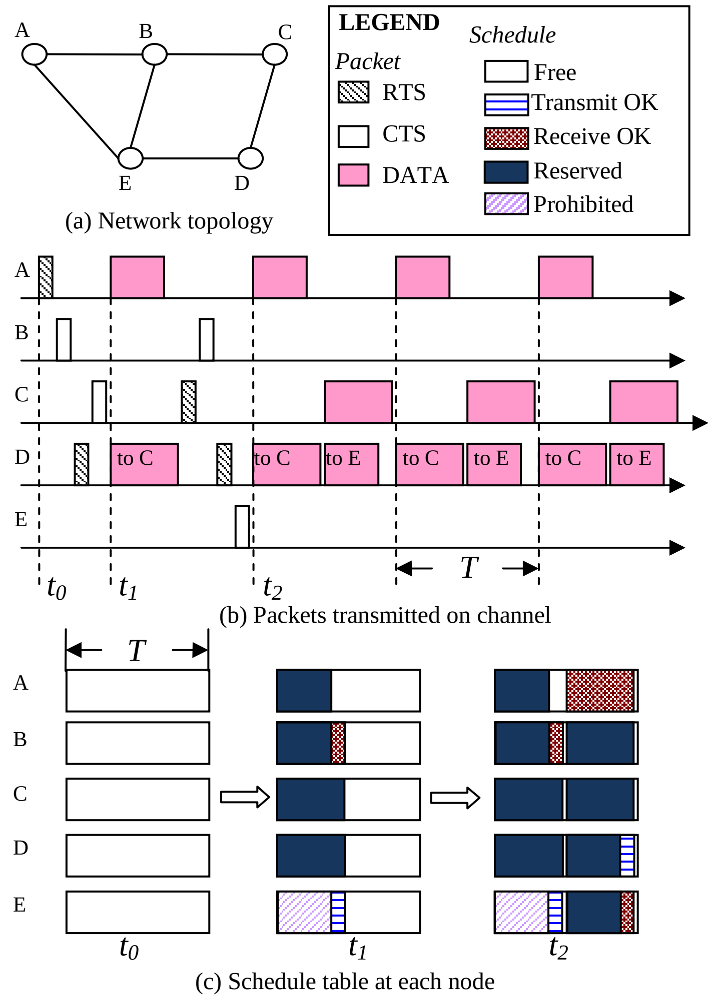

Figure 2.6: Diagram for a D-LSMA example

1. At the beginning (t_0), nodes A, C and D all want to make reservation requests for each of their traffic flows based on the desired bandwidth (or time slice referred to a known periodic interval, T). Since the nodes do not have information about other traffic in the network, the schedules of nodes are all empty.

2. Following 802.11 carrier sensing and backoff procedures, Node A and D obtains the carrier sequentially in the first control gap and reserve channel successfully with B and C respectively. So, at time t_1, the schedule tables of those nodes change as illustrated in part (c) of Figure 2.6.

3. Nodes A and D transmit their data packets according to the established schedule.

After that, nodes C and D want to reserve their respective flows again. In this case, node C gets the channel and sends the RTS first. Based on link scheduling rules, although node D hears node C's scheduled transmission to B, it finds that this does not affect its own transmission to E. Thus, D reserves a slice through RTS/CTS to E. The resulting schedule table at time t_2 is also shown in Figure 2.6. Once this schedule is established, the desired CBR flows are efficiently supported by the network.

The above example shows that D-LSMA scheme is able to arrange simultaneous transmissions, which cannot be done with IEEE 802.11 MAC. For example, Flow $A \rightarrow B$ and Flow $D \rightarrow C$ are scheduled to occur in overlapping time intervals. This obviously could double the system throughput. In the above example, D-LSMA forms an ideal schedule to arrange four single-hop flows ($A \rightarrow B, D \rightarrow C, C \rightarrow B$ and $D \rightarrow E$). This shows D-LSMA MAC mechanism can be extended to support *rate-based single-hop flow scheduling*. In our implementation and following performance evaluations, nevertheless, D-LSMA is still a *per-packet scheduling* solution. This is because the flow rate information is usually beyond the reach of a MAC scheme unless some cross-layer mechanisms are introduced, e.g. direct TCP control through the intelligent scheduler implemented in upper MAC.

2.3.6 Implementation Considerations

DATA Structrue for Scheduling. It is obvious that the simple NAV settings used in standard 802.11 cannot handle the complex mechanism shown in 2.3. In D-LSMA, each node maintains a schedule table which is made up of a list of non-overlapping consecutive time slices. Each slice is uniquely identified with its timing delimiters and state information. Auxiliary algorithms are designed to 1) determine what's the available time slice(s) satisfying a particular reservation demand; 2) check if the reservation request embedded in RTS frame is feasible in current schedule table; 3) update the schedule table according to new channel events, e.g. RTS.

Timing synchronization. In the 802.11 frame format, only relative timing information is included in the NAV field. In D-LSMA, packet transmission is also reserved to start at a future relative time in the RTS frame, although it does not immediately follow RTS/CTS. As each node only describes its reservation requests to its 1-hop neighbors, nodes that cannot hear each other do not need to have uniform timing descriptions. Thus, a local synchronization scheme is introduced to align neighboring nodes. Each node holds a "timing offset" table to integrate schedule information from different neighbors and map them into the schedule table. The propagation delay issue can be solved as same as in IEEE 802.11 MAC.

Handle imperfect scheduling information. With a distributed algorithm lack of centralized management, some messages will carry inaccurate scheduling information. For example, an RTS message without CTS response claims the usage of channel for a certain time interval which is eventually not to be occupied. Some messages may contradict to each other due to race conditions created by random access. All these, if not checked, could lead to packet collisions because of the schedules discrepancy of in a neighborhood. To handle this situation, we adopt a conservative policy based on the following rules:

- A CTS message is taken to be more trustworthy than an RTS message. Information carried in the CTS frame overrides that of a contradicting RTS frame.
- Fresh information from a node always overrides prior information provided by the same node.

The above rules could help to discover an implicit reject of RTS frame and eliminate schedule ambiguity. However, there is still no guarantee that a node is fully aware of all relevant channel events, because in-band control messages are still subject to collisions.

2.4 Performance Evaluation of D-LSMA and Other MAC enhancements

In this section, we present detailed performance results for the proposed D-LSMA access protocol using an *ns-2* simulator [48]. In our simulation model, the data rate is 1Mbps (basic rate) and the effective transmission range is 250 meters. Based on the assumption that interference could only affect 1-hop neighbors, the carrier sense range setting is adjusted to equal to 250 meters, too. This will allow nodes out of 250-meter range to reserve freely without held by physical carrier sensing. Please refer to Appendix B for details about the interference modeling of ns-2 simulator.

Each source generates constant CBR traffic flows. Note that all reported results are averages over 100-second simulations and all nodes are stationary during the simulation. All simulated data packets are preceded by an RTS/CTS exchange regardless of the size.

In each RTS frame, the reservation is made only for one single packet.

2.4.1 Performance Metrics

The following metrics are used to measure the performance of the proposed protocol:

- *End-to-end latency*, measured as the elapsed time between packet generation and successful reception at the destination.
- *Throughput*, defined as the end-to-end "goodput" for data packets delivered to the UDP layer.
- *Fairness*, as it relates to fair sharing of the bandwidth between different sources. Fairness is often measured with the *fairness index* defined in [49]: Given n different flow with normalized flow throughput $x_i, i = 1, 2, \ldots, n$, the fairness index k is defined as:

$$k = \frac{(\sum_{i=0}^{n} x_i)^2}{n \sum_{i=0}^{n} x_i^2}.$$

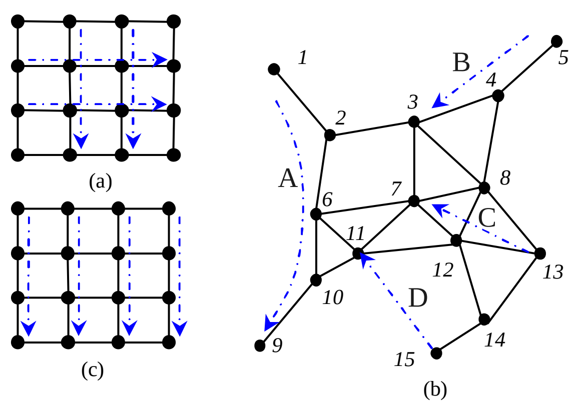

Figure 2.7: Simulation topologies for D-LSMA evaluation

2.4.2 Comparison with 802.11 MAC

A 4 by 4 grid illustrated in graph (a) of Figure 2.7 with the dimension of 1000 meters is used. Each node is separated from its neighbors with a distance equal to the maximum transmission range. Two traffic flows run along the rows and columns respectively, as shown. We measure the total throughput of these 4 flows. The packet size for CBR traffic is set as 1024 bytes, and the packet arrival rate is varied to increase offered load. Observed performance results are shown in Figure 2.8.

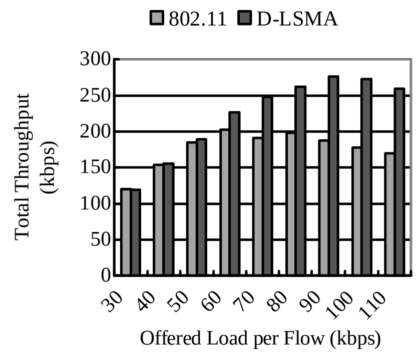

Figure 2.8: Throughput comparison for grid topology

From the figure, we can see that for 802.11 MAC, performance degrades when the offered load per flow is beyond 50 Kbps, the gross throughput saturates with the amount of 0.2 Mbps. The D-LSMA MAC has a maximum gross throughput about 0.27 Mbps, thus achieving a throughput gain for this scenario of about 35%. The better throughput performance of D-LSMA is mainly due to effective link scheduling policies allowing parallel transmissions. It is true that omitting ACK frames is also a factor in the throughput improvement, but is considered to be a relatively minor factor.

We also measure the end-to-end delay of those packets received successfully in this simulation scenario. Results are shown in Figure 2.9.

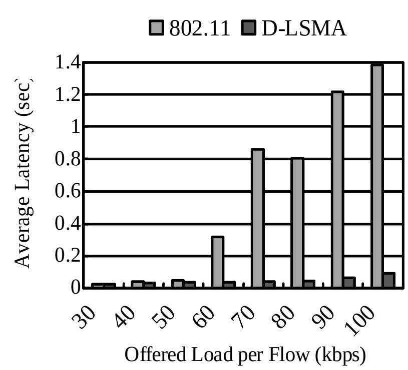

Figure 2.9: Latency comparison for grid topology

It can be seen that D-LSMA provides significantly better delay properties than 802.11

even under overload conditions. It is noted that the delay in 802.11 increases dramatically when the channel reaches its throughput limit, while the delay remains bounded and relatively small in D-LSMA. The reasons for this are reduced queuing delay under congestion due to removal of ACK's and more deterministic scheduling of CBR flows in D-LSMA.

Then, we consider a test scenario of 15 nodes randomly distributed in a 800×800 square meters area. The topology is depicted in graph (b) of Figure 2.7. Four pairs of transmitting and receiving nodes are randomly chosen. The flows are labeled from A to D in that graph. Fixed routing paths are pre-specified for each flow as in Table 2.1. Three protocol options are considered for this scenario: 802.11, MACA-P and D-LSMA. The simulation is conducted by supplying the same CBR packet rate for each flow. The packet size is 512 bytes.

Flow	Hop Count	Path
A	4	1-2-6-10-9
B	2	5-4-3
C	2	13-8-7
D	3	15-14-12-11

Table 2.1: Respective flows in random topology

Figure 2.10 shows the throughput and delay values of each flow for both 802.11 and D-LSMA when the data rate for each is 110 Kbps (equivalent to 27.5 packets per second).

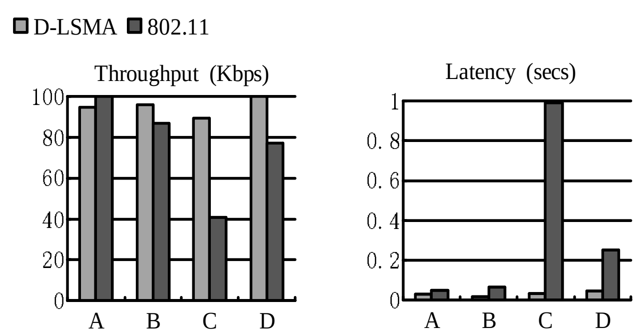

Figure 2.10: Comparing flows in random topology

It is obvious that the contention behaviors among different flows, especially between flow C and flow D cause throughput reduction and high end-to-end delay in 802.11. In D-LSMA, the performance is significantly improved both in terms of throughput-delay and fairness.

Note that in 802.11, flow C has the least throughput because both node 7 and node 8 of this flow have to contend with their 5 neighbors. But D-LSMA protocol provides extra chances for those nodes to send or receive packets, thereby improving the throughput of flows C and D. The end-to-end delays in D-LSMA are all maintained at a low level (< 0.037 second) as desired for CBR flows.

Figure 2.11 shows the throughput gain measured as the gross throughput of all flows for 802.11 MAC, MACA-P and D-LSMA. In this test scenario, D-LSMA appears to provide about 20-23% more throughput than IEEE 802.11 MAC when network goes into saturation with increasing offered load.

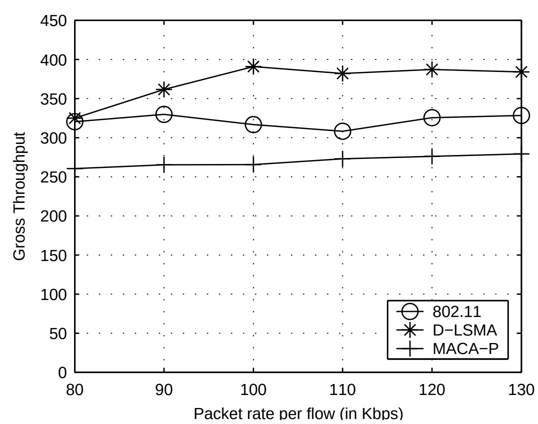

Figure 2.11: Throughput results for random topology

2.4.3 Comparison with MACA-P

In the above simulation, MACA-P protocol shows a saturated throughput less than that of 802.11. This is because if each node always tries to synchronize its schedule with neighborhood events, it may restrict its own capability to deliver packets in certain adversary circumstances [18]. Thus, certain flows get throttled while other flows take the advantage of synchronized parallelism in the MACA-P case.

2.4.4 Fairness

From the results shown in Figure 2.10, we can see that 802.11 MAC has a tendency to favor certain low contention flows and starve other heavy-contention flows. Figure 2.12

plots the changes of fairness index with increasing offered load for three MAC schemes. We can see that D-LSMA shows better fairness than the other two schemes. Because nodes with D-LSMA MAC have more efficient packet transmission schedules, flows in heavy contention neighborhoods can be better served. Moreover, in D-LSMA, as nodes with multiple flows will reserve on a round robin basis, the reservation tends to be fairer. Those factors lead to some improvement in fairness. Note that the fairness issue is closely related to scheduler design and can be further improved. Even for the simple scheduler used here, the improvement in fairness with D-LSMA is significant.

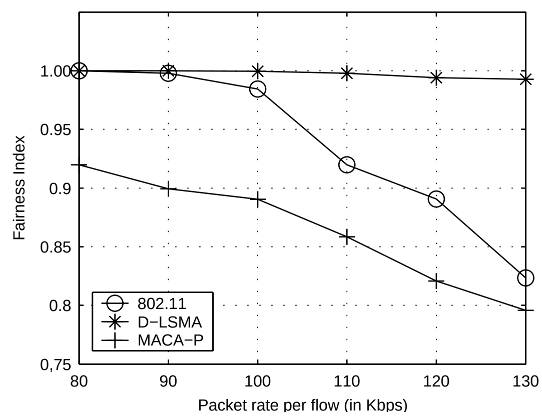

Figure 2.12: Comparing fairness index for random topology

2.4.5 Simulation with Asymmetric Traffic

The above simulations were carried out with equal flows. In order to see the performance with asymmetric traffic, which is more realistic in practice, we divided four flows into two distinctive groups. Flow A and C are grouped in group I, Flow B and D are in group II. Flows within each group have an equal portion of offered load, while the total load is divided in Group I and II with different distribution percentage ranging from 0-100 to 20-80 and 40-60 and 50-50. With overall offered load as a constant (480Kbps), we measured the total throughput of all flows with different portions from each group. Note that when Group I presents 100% of load, it is a typical "hidden terminal" scenario where two flows in Group I contend with each other. When Group II presents 100% of load, there are two separate multi-hop flows and there are no contentions between them. The results in Figure 2.13 show that throughput increases when contention is reduced as might be expected independent of the MAC protocol used. For all load distribution between Groups I and II, D-LSMA provides better throughput than 802.11 MAC. And especially when contention is heavy (i.e., in the left half of the figure), D-LSMA outperforms 802.11 MAC by a significant margin.

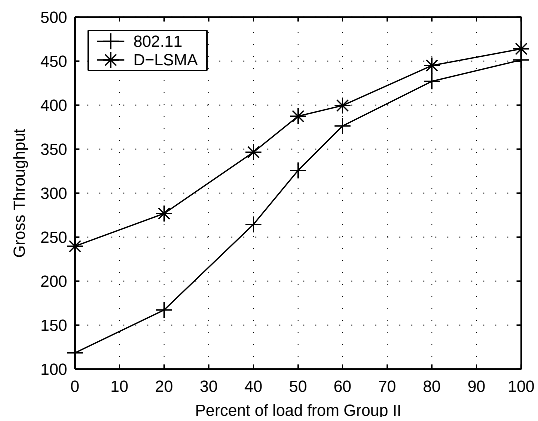

Figure 2.13: Comparing throughput with asymmetric traffic load

2.4.6 Comparison with DCMA

Finally, we provide a brief comparison of D-LSMA with the DCMA scheme. The same 4 by 4 grid topology in [24] has been simulated with D-LSMA. As depicted in graph (c) of Figure 2.7, four greedy nodes in first row send vertical streams of 1024 byte sized UDP packets to the nodes in last row. Flows are labeled as 1 to 4 from the leftmost column to the rightmost.

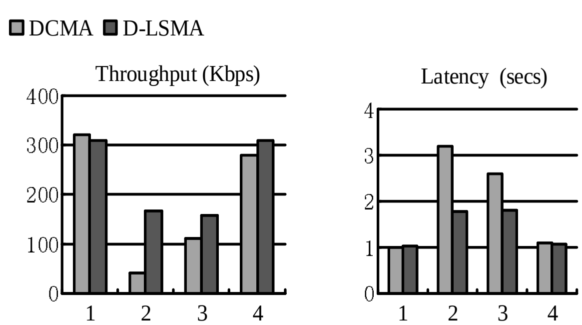

Figure 2.14: Comparing D-LSMA with DCMA

The performance comparison in Figure 2.14 shows that D-LSMA has higher throughput and lower delay in the two middle columns. Basically, this is due to the fact that nodes in D-LSMA scheme get extra chances to transmit even when carrier sense is busy, so middle nodes perform better and flows are not as starved as in DCMA. While DCMA introduces a cut-through method to reduce contention and expedites forwarding in the same flow, D-LSMA explores the packet forwarding opportunities from multi-flow diversity. Both these schemes indicate a potential for performance improvements in ad-hoc network MAC performance with suitable extensions to widely available 802.11 radios.

2.5 Conclusion of D-LSMA and Discussion

In summary, the performance of D-LSMA was evaluated using an *ns-2* simulation model and compared with 802.11 and DCMA. The results show that D-LSMA achieves throughput gains of up to 35% when compared with IEEE 802.11, while providing bounded delay and improved fairness. The performance was also found to be competitive with DCMA and MACA-P, two other recent proposals for improving 802.11 performance in multi-hop scenarios.

However, the general performance improvement of D-LSMA is not as high as expected. Intuitively, if "exposed terminal" problems are well avoided, the link transmission opportunities shall be improved by at least two-fold. A detailed analysis of simulation results shows that parallel transmission opportunities are not always utilized because of the collision of either RTS or CTS messages with other packets. This is hard to avoid when RTS/CTS signaling is mixed with heavy data traffic in the same channel. Some researchers found similar problem and called that as *masked node* problem [50] or *jammed node* problem [51]. Due to the same reason, the MACA-P scheme also behaves underperformed. Those observations suggest that the MAC schemes featuring minor modifications upon on CSMA/CA MAC only achieve a limited portion of expected throughput gains. The performance is not comparable to that of optimal link scheduling schemes yet.

The distributed LSMA design implements correct link scheduling algorithm, which is strictly based on a packet radio interference model. This practice, however, does not create expected performance gains due to its weaknesses in control mechanism. The contention nature of control signaling and the mixture of data and control in the same channel prevent timely and effective link scheduling. The per-packet scheduling nature is also a major obstacle to achieve optimal link scheduling. For example, for each packet, there is only a small time interval (control gap length) to arrange simultaneous link transmissions. If the gap is too small, there is no way to reach maximal link scheduling. If the gap is too big, too much channel resource is wasted in excessive waiting. All above considerations motivate us to come up with a more advanced design based on a clean separation of data and control plane.

Chapter 3

Impact of Interference in Wireless Protocol Design

3.1 Survey on Interference Models

In order to set up collision-free end-to-end transmission schedules, we first need to understand the interference model that is used to compute whether a packet collides or is successfully transmitted and received. We briefly discuss the several widely used interference models here.

3.1.1 CDMA Interference Model

This, also called as node exclusive model, is a very simple model of transmission conflicts, which is used in several studies [38] [45] [47]. In this model, to ensure conflict-free transmissions, it is only required that no two links that share a common node may be activated simultaneously. It assumes that suitable spread-spectrum modulation is adopted, so that there are no Type 2 "hidden terminal" problems depicted in Figure 2.1. This model is often used for radio network based on CDMA technology. Note that although IEEE 802.11b radio uses a DSSS (Direct-Sequence Spread Spectrum) PHY, it does not fit in this model. Because distinctive 802.11b clients do not use different orthogonal codes for communication, the scheme cannot ensure the successful recovery of a packet in the presence of strong co-channel interference noise. Strictly speaking, this model is not applicable to our study because it utilize extra bandwidth (spread spectrum) to mitigate the impact of interference, it is not very helpful to understand how much capacity can be really achieved on a given fixed channel bandwidth.

3.1.2 Packet Radio Interference Model

This model is very widely used in the studies on the so-called PRN (Packet Radio Networks) [36] [41] [40]. The network is represented as a directed graph G(V,E) where the nodes of the graph correspond to the radio nodes and the edge(i, j) denotes a radio link directed from the node i to the node j. Similarly, link scheduling corresponds to coloring the edges of the graph such that any pair of directed edges (a, b), (c, d) may be colored the same if and only if:

1. a, b, c, d are all mutually distinct, and
2. $(a, d) \notin E$ and $(c, b) \notin E$.

Compare to the previous model, Type 2 hidden terminals exist here and have to be avoided in collision-free scheduling. The link scheduling rule described here is exactly as same as the ones given in Section 2.2.1. In other words, our D-LSMA MAC scheme is designed based on this model.

3.1.3 Physical Model of Interference

In the *physical interference model* [52], a transmission is successful based on the signal-to-interference and noise ratio (SINR) at the receiver. Suppose a node i wants to transmit to a node j, we can calculate the SINR at the receiver j as:

$$SINR_{ij} = \frac{G_{ij} P_k}{NW + \sum_{k \neq i} G_{kj} P_k} \tag{3.1}$$

where P_i denotes the transmit power of the node i and G_{ij} is the link gain from the node i to the node j, which is mainly determined by the path loss of the wireless link. NW denotes the ambient noise and the second term in the denominator is the interference due to the other simultaneous transmissions in the network. The transmission is successful if $SINR_{ij} \geq SINR_{thresh}$, where $SINR_{thresh}$ is the necessary threshold for decoding the transmission successfully.

3.1.4 Protocol Model of Interference

In the protocol interference model [46] [53], Two distance-based range value are used: communication range R and interference range R'. Generally, $R' > R$ and as depicted in Figure 3.1, a transmission is successful if both of the following conditions are satisfied:

1. $d_{ij} \leq R_i$ (i.e. receiver j is in the transmission range of sender i)

2. Any node k, such that $d_{kj} \leq R'_k$, is not transmitting (i.e. a receiver is not in the interference range of any other sender except the current sender)

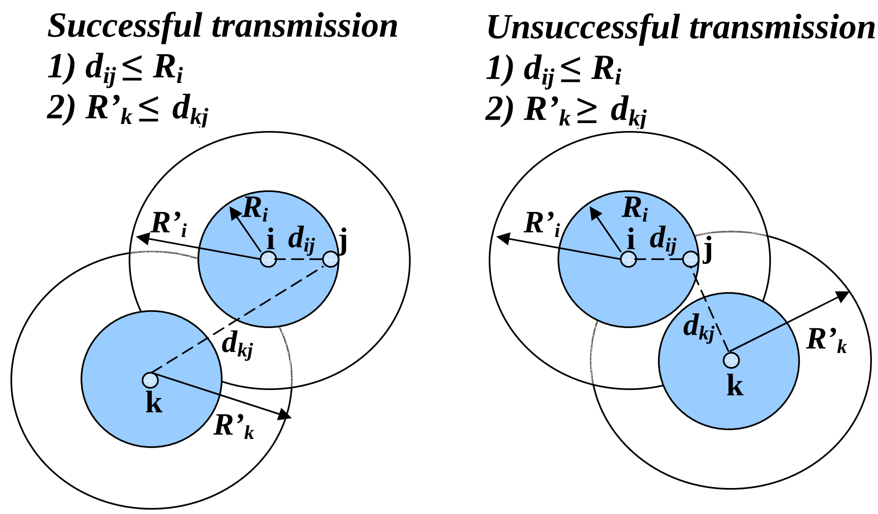

Figure 3.1: Protocol model of interference

Note that the transmission range and interference range could be different for different nodes, depending on their respective transmit power.

3.1.5 RTS/CTS Interference Model

This model [46] [43] is used in the IEEE 802.11 MAC protocol. Similar to RTS/CTS mechanism, this model requires that for every pair of transmitter and receiver, all nodes that are within the 1-hop communication range of either the transmitter or the receiver cannot transmit or receive. In other words, two link transmissions, from node a to b and from c to d, can coexist if and only if:

1. a, b, c, d are all mutually distinct, and
2. None of the following directional links $(a, d), (a, c), (b, d), (b, c), (c, a), (c, b), (d, a), (d, b)$ exists in E.

This is because the data transmission following RTS/CTS is a two-way frame exchange. Because of this two-way $DATA+ACK$ packet exchange, the $DATA$ frame transmitted from a could potentially collide with an ACK from d, if link (b,d) or (d,b) exists. Therefore, it requires that no links exist between any node pairs except (a,b) and (c,d).

It is a questionable assumption that the radio interference of an 802.11 transmission is regarded to be limited within 1-hop range. With the existence of spread spectrum techniques in IEEE 802.11, the MAC supports a very low data rate (1Mbps) on a large frequency bandwidth (20MHz). This is far lower than the 1bit/Hz norm in wireless communication. Therefore, the 802.11 frame may be decoded when SINR (signal-to-interference and noise ratio) is lower than normal threshold, say 10dB. In this case, the harm of radio interference is not significant when the victim is out of 1-hop range. But when modulation scheme is tuned to support much higher data rates (e.g. 11Mbps, 24Mbps, or even 54Mbps), the processing gain of spread spectrum diminished or replaced by OFDM PHY. IEEE 802.11 PHY then cannot combat co-channel interference effectively. For those cases, this RTS/CTS interference model may not be appropriate.

3.1.6 Impact of Interference Modeling

Basically, different models will generate different link conflict relationships. For instance, RTS/CTS model has much stricter constraints than the packet radio model. In the example topology shown in Figure 3.2, there is a 4 by 4 grid network.

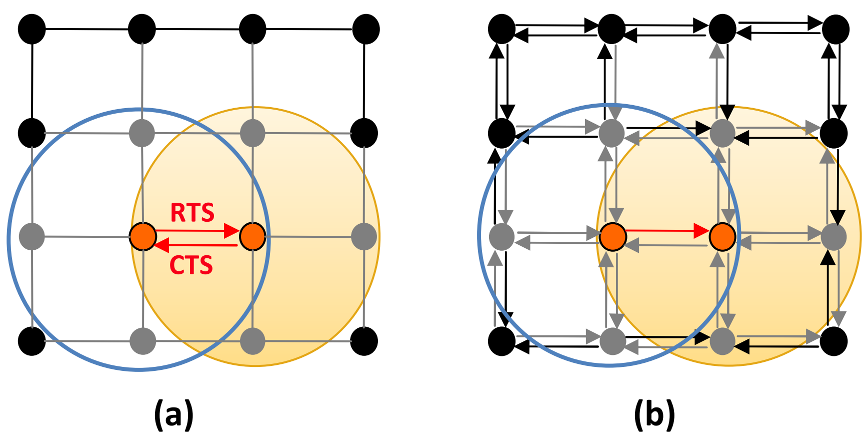

Figure 3.2: Interference effects of different interference models

Once an RTS/CTS handshake occurs, most of the links (shown as gray color in (a) of Figure 3.2) are forbidden to be active, according to the RTS/CTS interference model. However, to justify a conflict-free transmission in the same directional link where DATA frame is supposed to occur, packet-radio model only prohibits those links which violate the rules described in Section 3.1.2. As shown in (b) of the figure, some of the links banned by

RTS/CTS interference model are allowed in this case. This is one of the key reasons why D-LSMA protocol performs better than 802.11 MAC protocol.

Generally, for the same network graph, different link conflict graph will be created based on distinctive interference models. As collision-free scheduling problems are solved based on this link-conflict graph, varied scheduling results and system throughput will be obtained even for the same network by only changing interference model.

3.2 Appropriate Modeling of Interference

From a wide variety of interference models described above, it is very important to choose an appropriate one for realistic system design. The above-mentioned models can be divided in two classes. CDMA model, packet radio model and RTS/CTS model of interference are relatively simple. An interferer only creates interference affecting one or more nodes in its 1-hop neighborhood. Another sort of models, such as the physical model and the protocol model of interference, are more general and sophisticated. With more than 20 years of development of radio technology and engineering practice, it becomes more and more evident that just a few simple models can no longer reflect the reality of wireless communication systems. On the other hand, it is also very cumbersome to develop algorithms and protocols based on complex models. In this section, we present a simple hop-based interference model to bridge this gap. Then we detailed the connections and differences of these models to understand how good they are, in regards of the estimation of physical interference.

3.2.1 Relaxed K-hop Interference Model

The k-hop neighborhood protocol model of interference, specifies that each node's transmission will affect nodes as far as k-hops away, where 1-hop distance is equal to the usual communication range. k is called *interference index*. As k is common to all nodes, this also assumes the nodes use identical transmit power. K-hop interference model is a relaxed model of interference to approximate the protocol model. Comparing to the protocol model, the conditions to determine whether a link transmission from i to j is successful or not is changed as:

1. j is with the 1-hop range of sender i
2. any node within the k-hop neighborhood of j is not transmitting.

Note that this k-hop interference model [54] is different from the k-hop model used in [34] [55], which we call it "k-hop RTS/CTS model". That model requires that neither sender nor receiver of another interfering link is within the k-hop neighborhood of node i or node j [1]. As the neighborhood information can be derived from the network connectivity graph easily without measuring signal strength or node distance, this model is useful for a relatively simple practical design.

3.2.2 Conversion of Interference Models

The physical model of interference provides the most comprehensive view of reality among the models described in Section 3.1. It can even be extended to the CDMA network scenario by incorporating the spread spectrum processing gain factor into the channel gain matrix G_{kj}. The drawback of this model is that it requires complex computation and a complete knowledge of the channel gain matrix. Although a recent study [44] proposed a centralized computationally efficient scheduling algorithm, it is still unclear how to design distributed protocols based on this model. Hence, it would be very helpful to find ways to converse this model to other simpler interference models.

Here, we first show how to derive the corresponding protocol model from a physical model of interference, and then we extend the technique further to find a matching k-hop interference model.

The protocol model of interference uses two range values to characterize the interference relationship. It is obvious that what really matters is the ratios of the two ranges (communication range R vs. interference range R'). Here, we give a way to find this relationship from the parameters of the physical model. Assuming all nodes are identical and ignoring the ambient noise, Equation (3.1) can be simplified as:

$$SINR_{ij} = \frac{G_{ij}}{\sum_{k \neq i} G_{kj}} \tag{3.2}$$

Generally, in wireless communication,

$$G_{ij} \propto d_{ij}^{-\gamma} \tag{3.3}$$

[1]To be precise, the interference region of the k-hop interference model in [34] does not includes nodes that k hops away. So, strictly, it is equivalent to a "k-1"-hop interference region.

where d_{ij} is the distance from the node i to the node j and γ is the path loss index [56]. In the worst case d_{ij} is equal to R i.e. the receiver is at the edge of the transmission range. Substituting this in (3.2), the worst-case scenario requirement for R' is

$$R' \geq \sqrt[\gamma]{SINR_{thresh}}R \tag{3.4}$$

The above equation indicates clearly how far the protection shall reach to eliminate collisions caused by interference. With this method, we give some example mapping of SINR threshold to the interference range in the following table, assuming communication range is 250 meters. The distance unit for interference range in Table 3.1 is meter. The

$SINR_{thresh}$	$\gamma = 2$	$\gamma = 3$	$\gamma = 4$
5dB	445	367	333
10dB	791	539	445
15dB	1406	791	593
20dB	2500	1160	791

Table 3.1: Interference range vs. different physical interference parameters when R=250m

simplifications, nonetheless, does not come without a cost, two major discrepancy of the protocol model need to be pointed out.

First, the protocol model uses only pair-wise interference comparison to determine if two links conflict. Therefore, the accumulative effects of interference power as in Equation 3.1) is totally ignored. An example is given in Figure 3.3(a). In the network, the three transmissions, $1 \rightarrow 2$, $3 \rightarrow 4$ and $5 \rightarrow 6$ can be scheduled simultaneously according to the protocol interference model since all the receivers are in transmission range of their corresponding senders and out of the interference range of any other transmitter. However, at node 4, according to the physical interference model, the total interference from both the node 1 and the node 5 could make the $SINR_{34} < SINR_{thresh}$ and the transmission from 3 to 4 would fail.

Second, the protocol model tends to *overprotect*. This is because the interference range is usually set to protect potential receivers at the borderline of communication range because those link transmissions are most vulnerable to interference. However, if a receiver is much nearer, the required interference power to disrupt a successful reception of this receiver becomes much higher. Therefore, in this case, a transmission of an interferer within the interference range may not cause a conflict. This will be characterized correctly in the

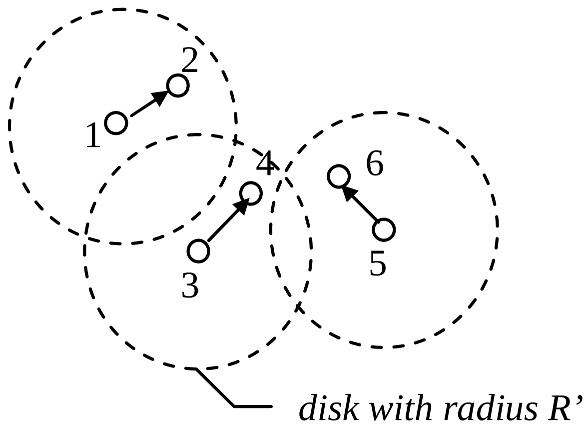

Figure 3.3: Artifact of the protocol interference model: accumulative interference

physical model, but not in the protocol model, as shown in Figure 3.4. Because $d_{ij} \leq R_i$ and $d_{kj} \leq R'_k$, the transmission from node k will conflict with the transmission from node i to node j. But if $d_{ij} << R_i$, the path loss from node i to node j will be significantly lower. So the interference signal generated by node k may not strong enough to corrupt the packet from i to j. This is a typical over-protection scenario produced by the protocol interference model.

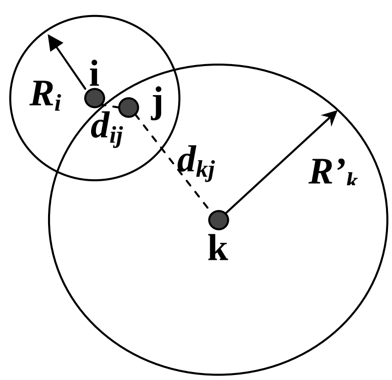

Figure 3.4: Artifact of the protocol interference model: over-protection

Those artifacts of the protocol model of interference will have impacts on the performance of protocols. Thus, extra precaution is necessary in protocol design. Even when conflict-free scheduling is supposed to work, it is better to prepare for unexpected link transmission loss. This can be detected by requesting acknowledgements to be sent back in data link layer, just as we do in the IRMA protocol design.

Next, we take a further step to determine the appropriate interference index, k, in the k-hop interference model, based on the above analysis, from the physical model or the protocol model. A node distance of k-hops means the distance is large than the sum distance of k-1 hops and less or equal to the distance of k jumps. Therefore, a receiver of a collision-free transmission shall be measured as k+1 hops away from any interferer. In order to be safe, we choose k as the first integer which satisfies $k > R'/R$. Hence,

$$\sqrt[\gamma]{SINR_{thresh}} + 1 > k \geq \sqrt[\gamma]{SINR_{thresh}} \tag{3.5}$$

We give some example mapping of SINR threshold to the interference index too, in Table 3.2.

$SINR_{thresh}$	$\gamma = 2$	$\gamma = 3$	$\gamma = 4$
5dB	2	2	2
10dB	4	3	2
15dB	6	4	3
20dB	11	5	4

Table 3.2: Example of the mapping between the interference index and SINR threshold

Note that equation (3.5) suggests that k should be at least 2 for any $SINR$ threshold larger than $0dB$. Hence, a very common assumption that interference only affects 1-hop neighborhood is actually an over-simplification. Thus, those simple interference models (Packet-radio model and RTS/CTS model) are too idealistic. Protocol designs only based on those interference models will probably be haunted by interference-induced performance reductions in the real wireless mesh network deployment.

For k-hop interference model, it seems that the k selected according to Equation 3.5 would be a safe choice, thereby corresponding scheduling policies shall avoid collisions completely. However, the k-hop interference model is just an approximated model too. There is over-simplification in the above relaxation process.

One potential problem caused by this simplification is shown in Figure 3.5. This is a chain network topology which is determined by communication range R. If the interference index k is 2, then as node 5 and node 1 are 3-hops away from node 2 and 4 respectively, the transmission: $1 \rightarrow 2$ and $5 \rightarrow 4$ could be scheduled at the same time. However, node separation by k hops may not be equivalent to a physical separation by $k \times R$. The actual distance from $1 \rightarrow 4$ and $2 \rightarrow 5$ might be smaller than $2R$ because the nodes 3 and 4 are in very close proximity. Therefore, it is still possible for the two transmissions to interfere with each other. Hence, link scheduling policies, although obeying the k-hop interference model rules, does not ensure 100% interference-free schedules. If we relax the equation (3.5) to choose a bigger k, the problem could be mitigated but the spatial reuse in the whole network will suffer.

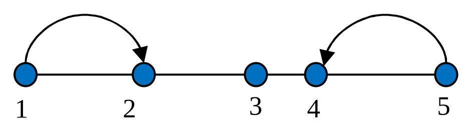

Figure 3.5: Example of deficiency of hop-based interference model

3.3 Complexity of Interference-Aware Protocol Design

The ultimate goal of interference-aware protocol is to eliminate the effect of interference. As an example, a link i to j denoted as e. For every e, $I(e)$ is the set of all transmissions (edges) conflicting with e. A transmission in link e is regarded to be interference-free only if the edge e and any edge $e' \subseteq I(e)$ are scheduled in different time slots. This looks quite straight-forward in an offline algorithm design. But for online protocol design, the communication complexity to enable this is non-negligible.

The communication overhead of interference-free scheduling comes from two main parts: interference characterization and interference avoidance. Next, we evaluate the communication complexity for each of them respectively.

3.3.1 Interference Characterization

Generally, interference characterization creates the network conflict graph of link transmissions for the whole network. Whenever the network topology changes, this conflict graph has to be updated. Form a distributed computing perspective, each node[2] discovers the neighborhood and builds its own set of interference relationship for future use.

In the following table, we list the estimated communication overhead of distributed interference characterization methods for each interference model. We use m to denote the node density (average number of 1-hop neighbors in a network topology). The overhead is represented by the average number of messages transported to collect necessary information about interference neighborhood per node. Note that a message passing to a node n hops

[2]Note that "link" is incapable of computing.

away is counted as an overhead of n.

Interference Model	Communication Complexity
CDMA model	0
Packet radio model	$O(1)$
RTS/CTS model	$O(1)$
K-hop model	$O(mk^2)$

Table 3.3: Comparison of communication complexity for interference characterization

With CDMA model, interference characterization is unnecessary because the node does not need any prior interference knowledge to avoid interference. As there exists only the primary conflict (Type I hidden terminal), no conflict will occur as long as only the sender and intended receiver are aware of the transmission. For both packet radio model and RTS/CTS model, 1-hop neighbors need to be discovered. This can be done by letting each node broadcast its node identifier once. Note that the time of those broadcasts need to be randomized to avoid collisions. Also, broadcasts can be conducted multiple times to ensure robustness. Generally, the per-node complexity of this operation is $O(1)$.

The overhead for k-hop interference model case is much higher. This is mainly because the interferer (sender of the edge in $I(e)$) could be out of the normal communication range and become *hidden* to the interfered victim. Thus, even though the victim can sense an interfering signal, it cannot decode it and recognize the identity of the interferer from the signal. Hence, a node needs to announce its identifier with a *k-hop broadcast* to reach all nodes vulnerable to its transmission. Given a uniform node density m, the number of nodes in k-hop neighborhood is of $O(mk^2)$. With controlled flooding, each node within $k-1$ hop neighborhood has to conduct one broadcast to realize a k-hop broadcast coverage. The number of necessary messages passing is $m(k-1)^2$. The complexity of this operation can be roughly estimated as $O(mk^2)$.

Neither the physical nor protocol interference model is listed in Table 3.3 because they require explicit knowledge of much more information, such as transmit power, link gain characteristics or the distances between nodes. Thus, it is not an easy task to characterize the interference for those interference models.

Here we present two solutions to overcome this obstacle and collect necessary data for collision-free scheduling. The first solution is to let each node equip with a GPS (Global Positioning System) radio. With GPS, a node can know its own location. Each node can flood its node identifier, location and transmit power to the whole network. Then every node can calculate the pair-wise node distances from node coordinates. By comparing those distance with the information of communication range and interference range (derived from transmit power and radio receiver sensitivity), the interference conflict relationship can be obtained. Note that this solution explicitly requires that relevant information to be exchanged beyond 1-hop neighborhood by a flooding protocol and dictates a GPS receiver. Obviously, this method is complex and requires a lot of computation and communication.

In the second solution, each node can use a dedicated control radio which can reach not only the normal communication range, but cover interference range as well. Those control signaling messages, which contain node identifier and transmit power, can be sent and received by the corresponding control radios. With this method, a node then can infer the node distance from both the receiving power measurements of those control packets and the transmit power information. After that, it is able to identify all "hidden" interferers by correlate node distances with node identifiers. Finally, the distance-based link conflict relationship can be derived. To avoid using a 2nd radio, we can also adapt the data radio to use enhanced source/channel coding or a more robust modulation scheme to put extra protection for control signaling from channel path loss. For example, a Wi-Fi radio could transmit data frames with both 11Mbps rate and 1Mbps rate. The data frames sent with 1Mbps channel rate can reach much further. With the help of this method, the control signaling can be decoded by all hidden interferers. This solution produces much less communication overhead, comparing to the previous one.

Basically, the total overhead of interference characterization depends on how frequent the interference conflicts need to be updated. As the topology seldom changes for a static wireless mesh infrastructure, this can be regarded as a one-time cost. It can even be done offline when the network is initially deployed and configured.

3.3.2 Interference Avoidance

The run-time interference avoidance procedure, on the other hand, means the scheduling results of one particular link (e.g. edge e from node i to j) needs to be known by all the source or/and destination nodes of links in $I(e)$ to avoid conflicts. This needs to be done by node i or j for each unit scheduling operation whenever e is involved.

In the following table, we list the estimated communication overhead of distributed interference avoidance mechanisms for each respective interference model. The communication overhead is defined as the average number of message passing to let a node i believe all sender of links in $I(e)$ has been notified successfully about its transmission and scheduling intention. Note that this communication complexity definition is unorthodox, and different from the conventional meaning of algorithm complexity [57].

Interference Model	Communication Complexity
CDMA model	$O(1)$
Packet radio model	$O(m)$
RTS/CTS model	$O(m)$
K-hop model	$O(mk^3)$

Table 3.4: Comparison of communication complexity for run time interference avoidance

We assume that both the sender and receiver of a link transmission have to agree with the arrangement before it is scheduled successfully. Hence, for CDMA model, a two-way handshake of $O(1)$ complexity is needed. For both packet radio model and RTS/CTS model, 1-hop neighbors need to be notified to prevent the establishment of any conflicting transmissions. This notification has to be reliable and cannot be done with just a simple unacknowledged broadcast. Because the receivers of this broadcast message may be interfered by another simultaneous broadcast, each neighboring receiver needs to send back an acknowledgement. Hence, the complexity for those models can be estimated as $O(m)$. For a similar reason, the overhead for k-hop interference model is equivalent to a reliable multicast in a k-hop neighborhood. Given a uniform node density m, the number of nodes in k-hop neighborhood is of $O(mk^2)$. To notify each one of them and get back a confirmation, $O(k)$ number of transmissions are needed. Hence, the number of required message passing for this scenario is of $O(mk^3)$.

3.3.3 Per-packet Scheduling vs. Per-flow Scheduling

As can be seen, to determine and more important, schedule links according to the accurate link conflict relationship, require a lot of computation and communication overhead. If this has to be done for every packet, it would cost a lot of link resource. For instance, if the k-hop based interference model is used, for each packet transmission scheduled, both the sender and the receiver have to deliver the signaling (e.g. RTS and CTS packets) "reliably" to nodes as far as k hops away. This is of $O(mk^3)$ complexity comparing to the $O(1)$ complexity of the unreliable collision avoidance scheme in IEEE 802.11 MAC[3]. It needs to be carefully considered whether it is worth or not scheduling packets with so much overhead. For a small size packet, the control overhead for scheduling the packet could be even bigger than transmitting the packet itself.

The control overhead problem can be mitigated by allowing a series of consecutive frames to be transmitted within one reservation, just as in the "TXOP (Transmit Opportunity)" scheme introduced in IEEE 802.11e. However, this requires the packet queue to be back-logged, which is not true in many practical scenarios.

Due to this reason, we prefer to conduct per-flow scheduling rather than per-packet scheduling in dense mesh environments. If a scheduling decision made for a certain time interval can be reused again and again, a lot of control overhead can be spared. Intuitively, if there are CBR (Constant Bit Rate) flows running over the wireless network, it is probable that the same pattern of channel usage and link scheduling would apply periodically. So there is no need to conduct per-packet scheduling. In this case, the overhead is largely determined by the number of flow sessions rather than the number of packets.

There are some other potential advantages for per-flow scheduling. MAC scheduling can be jointly optimized with route selection and other flow-based algorithms. In the next chapter, we will describe such a protocol design which is named IRMA (Integrated Routing and MAC Scheduling).

[3]It needs to be pointed out that the RTS/CTS collision avoidance scheme in IEEE 802.11 is proved to be not interference-free because it does not use O(m) message passing to have the schedule concurred by all relevant neighbors.

Chapter 4

IRMA: Integrated Routing/MAC Scheduling

Our previous analysis and another study [33] on multi-hop wireless networks both suggest that designing communication network protocols by optimizing the performance of individual routing and MAC layers usually does not work beyond a certain point. Thus, protocols in the entire stack shall be treated as a "single algorithmic construct" in order to improve the performance further. Here, we propose a fundamentally new design to realize high-performance collision-free switching mesh infrastructure, which is named IRMA (Integrated routing and MAC Scheduling). IRMA is a rate-based flow scheduling solution, targeting to improve the performance of end-to-end flow transportation. It solves the routing and MAC problems together in a single algorithm. The path and schedule solved for each flow is sustained by a well controlled and coordinated TDMA MAC.

In this chapter, we first use an example to explain the IRMA idea. Then we give a theoretical analysis on this integrated routing and scheduling approach. It could help to identify the achievable capacity gains of several different joint routing/scheduling methods. Then we will describe the realistic system model and a couple of online algorithms. Simulation and performance evaluation of those algorithms are shown in the last section.

4.1 Problem Definition and IRMA Approach

The conventional design of wireless mesh networks uses a layered implementation of MAC and routing protocols, for example, 802.11 MAC in combination with routing protocols, such as AODV[28], DSR[27] or DSDV[26]. In such a layered design, the routing protocol determines the next-hop for each destination with global topology information whereas MAC layer acts only on locally observed information for channel access. Because the 802.11 MAC was not originally designed for multi-hop scenarios, the carrier-sense mechanisms and distributed contention scheme are not good at handling interference in dense mesh environments. On the contrary, the use of CSMA and collision avoidance mechanisms can sometimes cause large overheads. This is shown with the help of an example.

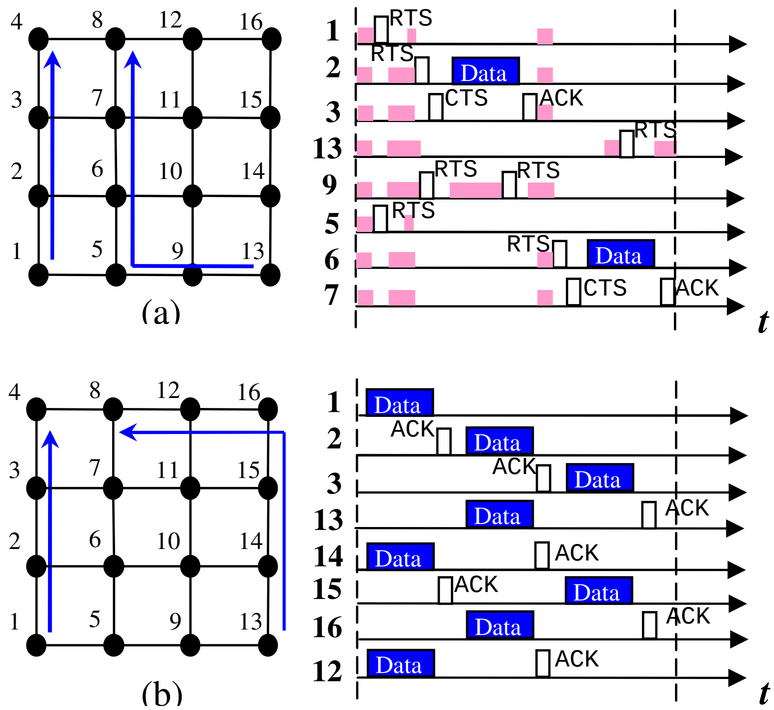

Figure 4.1: Example contrasting conventional routing/scheduling scheme and ideal scheme over a 4x4 grid

In our example, we simulate two multihop flows (1 to 4 and 13 to 8) running over the 4×4 mesh network shown in Figure 4.1. The shortest path routing protocol and 802.11 MAC are used. After analyzing the simulation trace, we depict a portion of the trace in the timing diagram of Figure 4.1(a). In this case, path 1-2-3-4 and 13-9-5-6-7-8 are selected. The timing diagram depicts MAC activities of each individual sender. Shaded areas denote 802.11 backoffs. As can be seen, a series of contention, collision and backoff activity is triggered because most senders (1, 2, 3, 5, 6 and 7) involved in these two paths are in the same interfering neighborhood. Finally, only 2 MAC transmissions are sent successfully (2 to 3, 5 to 6) during the observation period. It is also worth noting that when node 9 tries to access channel, its RTS to node 5 get no response because 5 is silenced by node 2's RTS frame. This also causes node 13 to remain silent because node 9's RTS announced false busy information about the channel in its NAV (Network Allocation Vector) field. A further investigation on the behavior of 802.11 MAC shows that when network is saturated, the average failure probability of an RTS frame is almost 68%. This shows that the RTS/CTS scheme is a very ineffective method for dealing with interference in a dense multi-hop environment. This is mainly due to 1) the interference range is much larger than the communication range, as pointed out in Section 3.1. Thus, the unprotected RTS frame is vulnerable to hidden nodes. 2) Unacknowledged RTS frames send false alarm to the neighborhood, preventing them to acknowledge other feasible RTS attempts.

These performance problems, however, can be largely overcome using a fundamentally different system design approach in which end-to-end path routing is linked to MAC scheduling under control of a global optimization algorithm. Suppose the flow from 13 to 8 uses an alternative path of same length as indicated in (b) of Figure 4.1. Thus, path 1-2-3-4 and 13-14-15-16-12-8 are chosen for two respective flows. This reduces the mutual interference between two flows. Also, by carefully scheduling non-conflicting MAC transmissions in overlapping time intervals, all 8 link transmissions can be arranged in 3 non-overlapping time slots without interfering each other. Thus, in the same observation period, this scheme shows a 4-fold performance improvement over the conventional *CSMA/CA+Routing* approach.

The dramatic difference demonstrated in the example gives us two key hints: 1) Instead of random MAC contention, transmissions should be scheduled with global information about the end-to-end path selections and ensuing interference relations. 2) Also, path selection in routing should consider MAC conflicts and interference-induced bandwidth reductions in addition to normal distance factors, i.e. paths with equal or longer lengths may be a better choice in some cases.

However, realization of the concepts outlined above requires a tight-coupling between the MAC and routing layers in the network. This cannot be handled easily by loosely-coupled cross-layer approaches as in [58][31]. Thus, we propose integrate routing and MAC in the mesh network protocol stack as a single layer and treat both functions as a single controllable algorithmic construct for optimization. At each mesh node, this new layer, which is called IRMA layer, is responsible for selecting an optimal combination of path and MAC schedule for the flow according to available local or global information.

First, we analyze this approach by formulating it as a joint routing/scheduling optimization problem.

4.2 LP Formulation for Joint Routing/Scheduling

In this section, we first formulate the integrated MAC-Routing optimization to maximize the aggregate throughput of all end-to-end sessions over the whole network. Our LP formulation is similar to the one described in [46], but we consider two separate cases: 1) route is known and 2) route is unknown. Moreover, the formulation in [46] does not consider fairness as a factor, therefore the optimal solution found could starve some flows to maximize the overall throughput. Here, we enhance the LP formulation with the parameter, q, that controls the trade-off between throughput and fairness.

4.2.1 LP Formulation for Link Scheduling with Known Path

First, consider a wireless network with a group of nodes in a plane, which forms a network graph $G(V, E)$ given a communication range R. The capacity of each directional link e is upper bounded by the link bandwidth $b(e)$. There are M end-to-end flows in the network. Each pair of source and destination (s_i, d_i) generates a flow with rate $r_i, i = 1, 2, \ldots, M$. There are M link sequences $L_1, L_2, \ldots, L_M$, each corresponding to a path from a source to a destination with path lengths $p_1, p_2, \ldots, p_M$ respectively. Thus, each L_i is composed of p_i hops. We define an edge set $L \subseteq E$, which contains all edges used by those paths. Assume each path segment l_{ij} to have a flow rate variable f_{ij}, where $j = 1, 2, \ldots, p_i - 1$. The problem is formulated as:

$$Maximize \sum_{i=1}^{M} f_{i1}$$

Subject to three set of constraints:

1. $f_{ij} = f_{i,j+1}$, for $i = 1, 2, \ldots, M, j = 1, 2, \ldots, p_i - 1$
2. $r_i \geq f_{i1} \geq qr_i$, for $i = 1, 2, \ldots, M$.
3. $\sum_i \sum_j c_{ij} f_{ij} = f(e) \leq b(e)$, where $c_{ij} = 1$ if path segment l_{ij} coincides link edge $e \in L$, otherwise 0.

The first set of constraints is needed to guarantee flow conservation at each intermediate node. The second set of constraints are used to ensure each flow has at least q $(0 < q < 1)$ fraction of its offered load served. The parameter, q, allows a tradeoff between throughput and fairness. The third set of constraints considers that the total flow amounts supported by the link edge, denoted as $f(e)$, cannot exceed the edge capacity.

We denote the above formulation as the *basic problem.* The basic problem is similar to the formulation of a wired network when the path of each flow is known. Then, the interference constraints derived from the radio interference model need to be augmented to the "basic problem" to extend the problem for wireless networks. A procedure similar to the one used in [46] is used. The work is briefly summarized here for the sake of clarity.

To account for wireless interference in the optimization problem, a *conflict graph* G' is used, where the vertexes of the conflict graph are the edges in the original graph. Based on an n-hop neighborhood interference model, there exists an edge between two vertices' of G' that interfere with each other. A *clique* in a conflict graph is a set of edges which conflict with each other. The cliques can be found by searching G'. Each edge e could belong to one or more cliques and the total usage of the links in each clique is at most 1. Therefore, if the clique set found in G' is defined as $X_k, k = 1, 2 \ldots, K$, the interference constraints can be written as:

$$\sum_{e \in X_k} \frac{f(e)}{b(e)} \leq 1, k = 1, 2 \ldots, K, e \in L$$

Substituting the third constraint set of the basic problem with this stronger set of constraints, the LP formulation can be used to find a reasonable *upper bound* of the scheduling problem with wireless interference.

To find the optimal schedule, however, more strict constraints need to be reinforced, because the edges involved in the transmission scheduling solution also have to be schedulable. To realize this, all edges utilized in the same time slot have to belong to the same *independent set* of G', where any edge in this set does not conflict with any other edges. If the collection of all independent sets is defined as $Y_k, k = 1, 2 \ldots, K'$ and suppose each independent set only becomes active for a portion, λ_k, of a TDMA frame, we have the following new constraints:

1. $\sum_k \lambda_k \leq 1, k = 1, 2 \ldots, K'$

2. $\frac{f(e)}{b(e)} \leq \sum_{e \in Y_k} \lambda_k$, for each e $\in L$

Adding above constraints to the basic problem would complete the LP formulation of the optimal scheduling problem with known path. From the above solution, the link rates of each path segments can be derived and an optimal TDM schedule can be constructed to approximate those link rate allocations. However, the problem of finding maximal independent set is NP-hard. In practice, only a limit number of independent sets are found and the corresponding LP solution only yields a *lower bound* of the problem.

In this thesis, with different mesh topologies, we apply the above method to find reasonably good upper and lower bounds by conducting a certain large number of iterations. If the upper bound and lower bound converges, then the converged value is regarded as the analytical throughput of the LP solution. Otherwise, the upper bound is used.

4.2.2 LP Formulation for Integrated Routing and Link Scheduling

As the route selection can itself be optimized for load-balancing and congestion control purpose, as shown by the example in Figure 4.1, it is desirable to optimize routing and MAC scheduling jointly. In this case, since the paths for any given flow are unknown, the LP problem becomes more complicated. Because any edge $e \in E$ might support one or more flows possibly, the set of flow rate variables in the LP problem will be extended to every possible $f(i, e)$. In addition, there are usually two implications based on different routing strategies:

1. Multi-path routing: Traffic is split over multiple paths to reach the destination node. This would results in out-of-order packets reception in the destination and other complexities for practical implementation.

2. Single-path routing: Traffic in a flow always follows the same unique path from the source to destination. Many existing routing algorithms [28] [27] [26] are confined to single path routing.

According to [46], in order to limit path selection to single path routing for each flow $< s_i, d_i >$, there exists some new constraints:

1. $f(i, e) \leq b(e)z(i, e)$, where $z(i, e) \in \{0, 1\}, e \in E$

2. $\sum_{e \in S(v)} z(i, e) \leq 1$, where $S(v)$ contains all edges originating at node v.

$\{z(i, e)\}$ is a set of binary variables introduced to the LP formulation to reinforce the single-path requirements. Compared to the LP problem in the previous case where path is known, this formulation leads to an MIP (Mixed Integer Programming) problem which is hard to solve.

To estimate the benefits of optimal single-path routing, we use a heuristic algorithm to approximate the LP optimal solution in this thesis. First, we solve the above problem without any single-path routing constraints. This avoids the usage of integer variables and provides a multi-path routing solution with varying traffic rates in each path. Then, we perform the path decomposition [59] on the optimal rate variables to identify a set of end-to-end paths which each carries a fraction of the traffic. Among the set of paths for a certain flow, the one with the maximum fraction routed through it can be viewed as the most preferred by the LP. This path is expected to yield a higher end-to-end rate in the objective function than others. Thus, we pick it as an approximated optimal path solution.

4.2.3 Major Findings from Theoretical Analysis

We solve the above several LP formulations with a couple of typical mesh topologies. For the case where the routing path is known in the LP formulation, we choose to use minimum-hop path for each source destination pairs and assume each link has the same bandwidth. We have following major observations from the analysis:

1. The capacity (aggregated end-to-end throughput) of wireless mesh network increase slowly when network grows. But the capacity decreases with increasing number of end-to-end flows.

2. The throughput bounds obtained from LP analysis are much higher than the simulation results of existing protocols, as shown later in 4.6.

3. Possible optimal routing paths can be found to yield better throughput than minimum-hop paths. This indicates that by carefully selecting path and MAC schedules together, a detour path which encountering less interference is probably better than the shortest one.

4. Solving the LP problems is NP-hard and needs global knowledge about network topology, conflict graph and traffic rate profile as the input parameters.

4.2.4 Mesh Network Capacity and Scalability

Using this optimization framework, we studied how system capacity (achievable end-to-end throughput) will scale with increasing number of nodes and traffic flows. We consider networks of 10, 20, 40, 60 nodes respectively. For each specific network size, a set of 5 random topologies is generated. In each topology, a couple of concurrent end-to-end CBR sessions are created. The traffic session number varies from 3 to 15. The link bandwidth for every link in those networks is set as 1 unit bandwidth. For each network topology, achievable throughput bound is calculated with joint routing/scheduling optimization (multi-path routing allowed) and the fairness-throughput tradeoff radio q is set to 1, which means the network is required to sustain the same flow rate amount for all the flows. The results shown in Figure 4.2 are all averaged over performances of those 5 different random topologies.

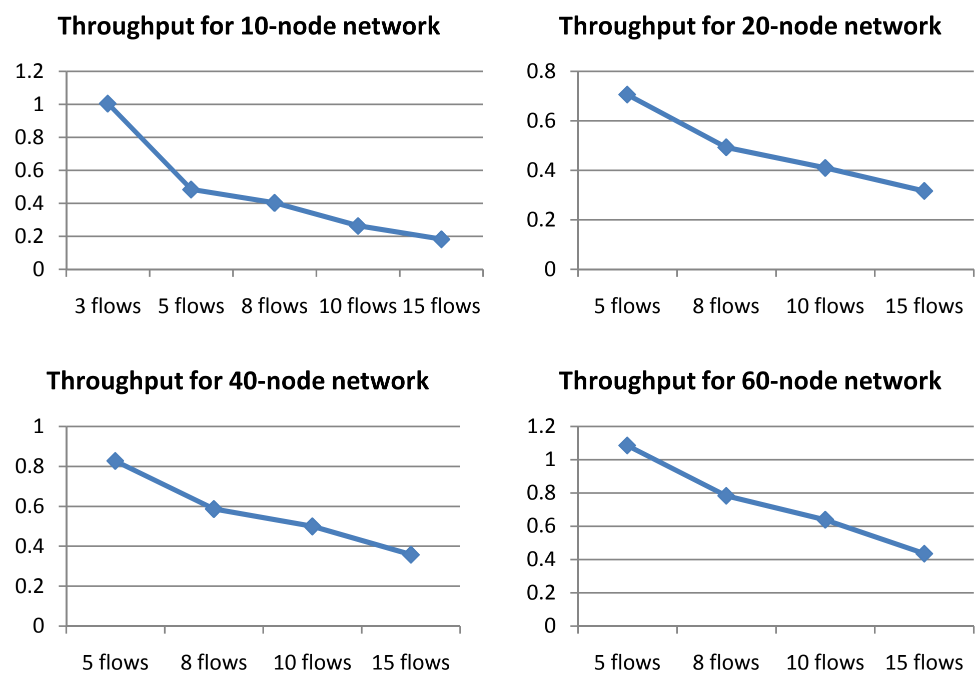

Figure 4.2: Throughput of varying number of flows

As can be seen, no matter what mesh network size is, the overall maximal network throughput declines with increasing number of traffic flows. This is because, with more and more random flows, there is less room to allow load balancing and congestion-avoiding detours. Thus, for end-to-end flow scheduling, it would be better to have only a limited number of simultaneous flows.

It is also very useful to know how this achievable network capacity scales with network size. In the following experiment, we assume when more nodes join a network, its coverage is expanded while both the communication ranges of its radios and average node density are kept same[1]. We compare the average network capacity for 10-, 20-, 40-, 60-node network and plot it in Figure 4.3. From the left figure, we can see that the aggregated network throughput increases slowly with increasing number of nodes in the network. However, the right plot shows that the normalized per-node throughput decreases actually. For example, the average per-node throughput for a network of 60 nodes is only half of that of a 10-node network. This result conforms to another study on the asymptotic wireless network capacity [52] which claims that for a multi-hop wireless network, the uniform per node throughput capacity with interference-free protocols is of $O(\frac{1}{\sqrt{n \log n}})$, where n is the network size.

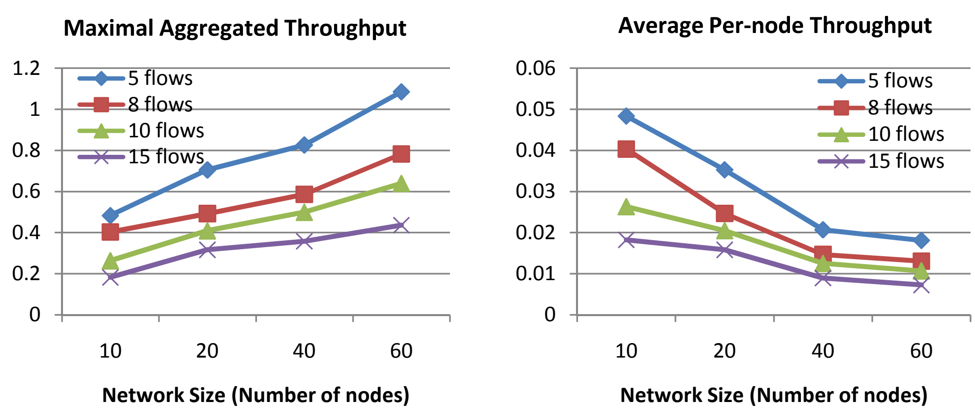

Figure 4.3: Achievable throughput bounds vs. network size

The above analysis clearly indicates that in order to have superior end-to-end performance, both the network size and number of concurrent traffic sessions shall be controlled within a moderate amount. The flat mesh architecture is fundamentally not scalable as pointed in [52]. For practical single-radio single channel mesh network deployment, it is important to choose an appropriate small or medium network size. If a very large network is necessary, an alternative hierarchy architecture, such as SOHAN [60] which uses wired connections to relay certain traffic, is a good choice.

[1]This can also be interpreted as an equivalent case where the network covers the same footprint, but radio communication range shrinks correspondingly by reducing transmit power.

4.2.5 Performance Gains of Joint Routing/Scheduling

We manifest the performance gaps between theoretical throughput bounds obtained by LP optimizations to a practical system design simulated with ns-2, where the 802.11 MAC is used in conjunction with a common ad-hoc routing protocol. In this comparison, we use a set of five 40-node random mesh topologies. In each topology, 5 randomly chosen source-sink pairs are used to generate end-to-end CBR sessions. The link bandwidth for all links in the network is of 1Mbps. We compare 4 different schemes in this experiment.

- Scheme 1: DSDV routing protocol with IEEE 802.11 MAC.
- Scheme 2: Optimal MAC scheduling along the routing paths discovered by DSDV routing protocol.
- Scheme 3: Integrated optimal scheduling with single-path routing solved with the approximation rounding method.
- Scheme 4: Integrated routing/scheduling and multipath routing is allowed.

To make a fair comparison, we set the fairness-throughput tradeoff radio q in LP optimization to 0.8. The measured throughput in ns-2 simulations are also required to achieve at least 80% of the offered load. Hence, the main difference of the 1st and 2nd schemes is that the LP solution is achieved by interference-free optimal MAC scheduling while the IEEE 802.11 protocol in simulation relies on RTS/CTS to avoid interference. Also, the only change between the 2nd scheme 2 and the 3rd scheme is that the latter prefer single optimal paths rather than the shortest paths. For the last scheme, the constraints enforcing single-path routing is removed to allow optimal multipath routing solutions. The results of aggregated throughput value (normalized with 1Mbps link bandwidth) of all flows for those topologies are contrasted in Table 4.1.

As we can see, in all five scenarios, schemes with optimal MAC scheduling provide much better throughput (typically 2$\times$ to 4$\times$) than the 802.11 MAC-based designs. To be more specific, the optimal scheduling scheme itself, while use same path sets discovered by DSDV, could deliver 110%-221% more end-to-end throughput. If alternative single path is allowed, the average throughput would be improved to equivalent to 3.44 times of the baseline schemes. Finally, the optimal joint routing/scheduling scheme without single path constraints presents performance gains of 246%-412%, depending on different topologies.

Topology	DSDV 802.11	Min-hop routing w/ scheduling	Single-path routing w/ scheduling	Multipath routing w/ Scheduling
1	0.189	0.475	0.601	0.8395
2	0.184	0.591	0.680	0.882494
3	0.194	0.511	0.785	0.854615
4	0.192	0.584	0.692	0.984713
5	0.19	0.399	0.511	0.657795

Table 4.1: Comparison of optimal throughput bounds vs. DSDV+802.11 MAC simulations

Comparing to the schemes using min-hop paths, the LP solutions using optimal single-path routing could provide 15%-54% more throughput, as shown in the numerical results of Table 4.1. This is not surprising because the first optimization problem using min-hop path routing can be regarded as a special case for the second optimization problem, with additional fixed path selection constraints. When those constraints are relaxed, a set of paths which generate lower inter-flow interference than the default min-hop paths can be chosen to transport more data end-to-end. Also, for a similar reason, the LP solutions of multi-path routing scheme show 9%-42% more throughput than that of single-path routing schemes. This is because that when traffic load is distributed to multiple routing paths, it could create a more balanced and optimal utilization of network capacity. For the sake of practical system design, single path routing algorithms are much less complex and bear less overhead than multi-path routing schemes. So, we mainly focus on design heuristic algorithms to approximate the performance bounds obtained by optimization of single-path routing and scheduling.

Hence, for future possible flat mesh deployment such as in home networks or office networks, it is very attractive to apply the joint routing and MAC optimization described above to obtain the expected 200%-400% performance gains. But it is also noted that the methodology used in this LP analysis is just a means to conduct offline IRMA optimization to maximize the network throughput. It is not appropriate for a system design because a couple of practical issues remain unsolved. For example:

1. Is it possible to obtain all the inputs required by the LP modeling real-time? If yes, how long it will take? If no, what's the impact to the performance by using an alternative, less accurate information or modeling?

2. Instead of solving NP-hard problems, is there any good heuristic polynomial approximation algorithms?

3. What's the signaling overhead to realize IRMA? Is it scalable with the network size and traffic demands?

Next, we are trying to investigate the realization of IRMA systems and find ways to approach those ideal throughput provided by joint routing/scheduling.

4.3 IRMA Framework

4.3.1 System Assumptions and Model

In this section, we briefly introduce our system model. We consider a homogeneous wireless mesh network. Each node in the network only has one radio interface and shares a common channel. In the future, we plan to extend our model to multiple channels and multiple radios. Each radio has the same transmission power, P_{tx}, to cover the same transmission range and we also assume the network is globally synchronized.

Note that our system model would be considered for a wireless backbone in a mesh network deployment with a relatively static infrastructure. Each mesh node are supposed to carry traffic from several mobile or wired clients and we only consider *aggregated* traffic requests in our algorithm. Client mobility, arrival and departure of clients manifest as changes in the traffic demand from the respective aggregation mesh routers. As those aggregated traffic demands shall not change frequently, it can be simplified as a series of CBR sessions each of which has a reasonably long duration to a certain destination node. We account for these changes of CBR sessions by sending traffic demand request messages dynamically.

4.3.2 Control Plane

To realize IRMA, it is necessary to have a robust online mechanism to collect necessary input information and disseminate the desired MAC/routing parameters, similar to the LP formulations in Section 4.2. However, unlike solving the LP problem offline, this requires real-time coordination and information exchange among the networking nodes. We separate those control processes in a *control plane*, in contrast to the *data plane* where per-packet data deliveries occur. The primary challenge in control plane design is that control parameters need to be transported over the network before the algorithms in IRMA layer can be applied. One of the following methods may be used: 1) to use legacy MAC and routing protocols to bootstrap IRMA optimization. 2) to utilize a new reliable out-of-band signaling mechanism for this purpose, e.g. using a dedicated control radio. The control plane conducts the following tasks:

1. Discover and exchange local or global topology and resource information. This assists the initial bootstrapping and discovery phase when new nodes join the network.

2. Interference characterization. Equivalent to finding edges in the network conflict graph G', each node needs to identify whether its link transmission conflicts with others due to interference. A node need probe beyond its 1-hop neighborhood because the source of interference could be out of its communication range.

3. Obtain traffic flow specifications and run IRMA algorithms to optimize link schedules and path selections.

There are two protocol modes in IRMA system: centralized and distributed. The control algorithms employed in the centralized protocol is run in a centralized or distributed manner. After the discovery in both the data plane and the control plane, the traffic and topology information can be exchanged in the GCP either using a routing protocol or by other flooding mechanisms. After receiving this information from the nodes, then the algorithm determines the routed paths and TDMA slot assignments for each source-destination pair. The problems associated with carrier-sense based random access, such as hidden node, exposed nodes, are eliminated by arranging conflicting transmissions in different time slots. Spatial reuse in the whole network can also be maximized by scheduling a maximum number of compatible transmissions simultaneously in the same timeslot.

The IRMA control algorithms in the GCP depend on the signaling messages to exchange essential information, such as topology information, traffic updates and schedules. As an example, we present the format for the traffic update message used in the centralized IRMA protocol in Figure 4.4. This is sent out by the mesh nodes to notify a traffic event.

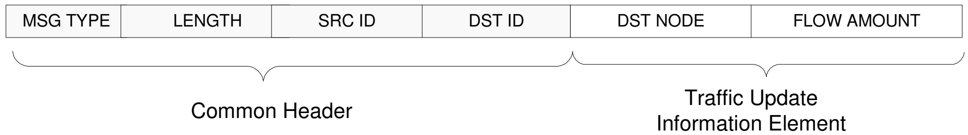

Figure 4.4: Format of a typical control signaling

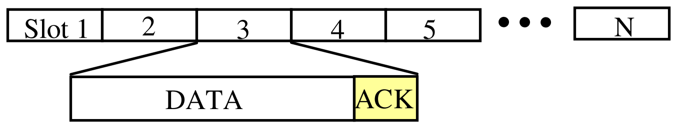

Figure 4.5: TDMA frame structure

4.3.3 Slot and Frame Structure

In IRMA design, the channel is divided into a number of timeslots so that more than one conflicting link transmission can shared the channel as in dynamic TDMA. The duration of the time slot is set to contain one fixed-size packet transmission, depending on the PHY layer data rate. Each slot also accommodates the time required for an ACK frame to acknowledge receipt of the data frame. As shown in Figure 4.5, a fixed part at the end of each time slot is used for this purpose. With this particular design, the collision probability for ACK frames will be minimized if their respective DATA transmissions do not collide [16]. The absence of an ACK frame indicates that the DATA frame is not received successfully by the recipient and need to be retransmitted. Although IRMA protocol is designed to establish conflict-free access, the introduction of ACK frames helps to improve robustness. It will be particularly useful in any one of the following cases:

- Due to the discrepancy between the protocol model and physical model of interference, collisions may not be entirely eliminated by the scheduling algorithm and packet loss may still occur in real environment.
- Occasional link errors due to varying wireless channel conditions.
- Schedules set-up by distributed algorithms may not be perfect, the existence of ACK frames help to identify transmission conflicts so that the sender can inform the IRMA algorithm to adjust slot assignments.

The bandwidth allocation for each link in a periodic TDMA schedule is measured by the number of assigned slots out of every N slots, where N is the number of slots in a TDMA *frame*. For instance, assigning one slot per frame is equivalent to allocating an exact 1/N of the channel bandwidth. With this slot and frame structure, we simplify the optimal scheduling problem with an approximated fix-length TDMA schedule filling problem.

The global synchronization required by TDMA MAC can be implemented either by having a GPS signal fed into each nodes of the network or selecting a central entity with accurate clock to distribute precise timing over the global control plane. For the latter case, a protocol like IEEE 1588 [61] can be applied. Recently, another method to synchronize all nodes in multihop wireless networks with an AM signal is presented [23]. Therefore, we deem the time synchronization issue is not a major technical obstacle for the realization of IRMA.

As mentioned in Section 4.2, IRMA optimization problems defined earlier are usually NP-hard. Moreover, the numerical methods require an LP solver and numerous iterations. Thus, we focus on designing fast, heuristic optimization algorithms to approximate globally optimal solutions instead of applying those optimizations directly. Corresponding to the two LP optimizations featuring single-path routing described before in Section 4.2, we consider two alternative integrated routing/MAC approaches: 1) *Link Scheduling with Min Hop Routing* and 2) *Link Scheduling with Bandwidth-Aware Routing*.

4.4 Centralized IRMA Algorithms

In centralized mode, a central entity with access to the control plane is assumed for the system model. This may not always be practical for large networks, but we study this case to obtain an upper bound on achievable protocol performance. After the initial boot-up and discovery, we assume there is one central master node collecting the following information.

- Connectivity matrix of the network topology
- Interference characterization
- Source - destination pairs and their respective traffic demands.

We account for the variations of those parameters by periodically sending handshake messages among neighbors and reporting messages from mesh nodes to the master node. Note that when there are no traffic demands, there is no need for optimization, too. Based on those inputs which at least contains new traffic profile, centralized algorithms will be executed to determine the routes and TDMA schedules for each source-sink pair involved. Then the per-link solution is reconfigured and divided into per-node information sets and disseminated to each affected node in the network. After that, IRMA parameters will take effective and tune the network to support the specified traffic demand efficiently.

4.4.1 Centralized Link Scheduling-Minimum Hop Routing

The procedure to solve optimal link scheduling under min-hop routing in Section 4.2.1 involves NP-hard problems. So it is not proper to run in online in one of the nodes because there is no guarantee that optimal solution will be found in less than exponential time. Instead, we use a greedy algorithm named CIRMA-MH (Centralized Link Scheduling with Min-Hop Routing) to get a sub-optimal solution. In this greedy algorithm, the shortest path for each flow is found with hop count metric. Then, for each flow, schedules for its per-hop transmissions are made based on its respective traffic demands one by one. The algorithm is presented as Algorithm 1.

Algorithm 1 CIRMA-MH

Require: topology $G(V, E)$, flow $F = \{F_i\}$, conflict graph G'
Ensure: link schedule and min-hop paths for F

```
arrange flows in {F_i} with random order
for each F_i do
    compute the shortest path L_i with hop metric
    A_i = 0
end for
while F is not empty do
    for each F_i do
        if A_i < r_i then
            for each e in L_i do
                try: schedule e to first available slot k such that P_k ∩ (e ∪ I(e)) = φ
            end for
            A_i = A_i + B_0
        else
            remove F_i from F
        end if
    end for
end while
```

The objective of this algorithm is to determine the appropriate link schedule for allocating each path segment of each flow with a bandwidth $A_i (A_i \geq r_i)$. This is done by augmenting the allocation from 0 with a step-size of $B_0 = B/N$, which is the minimum bandwidth unit can be allocated in a N-length TDMA frame. Here we assume the links in the network all have the same bandwidth B. P_k is used to denote all path segments (links) which are scheduled in slot k, where $k = 1, 2, \ldots, N$. The algorithm schedules an edge e, in the first available time slot such that the slot neither has the edge e scheduled nor has any edge that belongs to $I(e)$, where $I(e)$ is the set of potential interfering edges of e derived from G', the conflict graph. In our simulations, we found that this simple greedy algorithm is typically able to achieve 90% of the optimal value of the LP solution.

4.4.2 Centralized Link Scheduling-Bandwidth Aware Routing

A common shortcoming of the distance-based routing algorithm is that it could create congested areas if many paths cross the same neighborhood. Our solution is to include available bandwidth into an integrated metric, instead of using hop counts alone.

In the proposed CIRMA-BR algorithm, the local information about the potential MAC bandwidth is measured by the number of eligible slots in the TDMA frame. The integrated metric of a link e: $w(e)$ is augmented by bandwidth metric, which is the number of *ineligible* slots in a given TDMA frame. Then, when the algorithm selects a path with the minimum sum of metrics, both the hop counts and available bandwidth will be factored in. The pseudo code of this centralized algorithm is given as Algorithm 2.

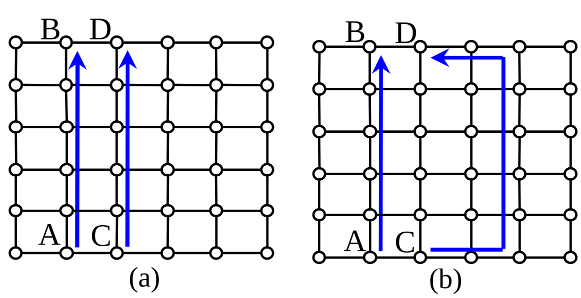

Figure 4.6: Different routes produced by CIRMA-MH and CIRMA-BR in a 6×6 grid for two vertical flows

With this heuristic algorithm, a path with more available bandwidth will be preferred over a short congested path. Here we use an example to show that how CIRMA-BR routing

Algorithm 2 CIRMA-BR

Require: topology $G(V, E)$, flow $F = \{F_i\}$, conflict graph G'
Ensure: link schedule and a single-path route for each $\{F_i\}$

arrange flows in $\{F_i\}$ with random order
set $w(e)$ for each e as default hop metric
for each F_i **do**
  compute the shortest path L_i with $w(e)$ metric
  while $A_i < r_i$ **do**
    for each e in L_i **do**
      schedule e to first available slot k such that $P_k \cap (e \cup I(e)) = \phi$
    end for
    $A_i = A_i + B_0$
  end while
  for each $e \in E$ **do**
    $w(e) = 1$
    for $m = 1, 2, \ldots, N$ **do**
      if $P_m \cap (e \cup I(e)) \neq \phi$ **then**
        $w(e) = w(e) + 1$
      end if
    end for
  end for
end for

could select better routes with the help of bandwidth information. In Figure 4.6, two end-to-end flows $A \rightarrow B$ and $C \rightarrow D$ needs to be scheduled. In (a), the CIRMA-MH algorithm selects two adjacent min-hop paths causing strong mutual interference. In (b), an alternative path is found by the CIRMA-BR algorithm for flow $C \rightarrow D$ to route around the congested area. This is because the CIRMA-BR algorithm relies on the updated available bandwidth measurement considering all already scheduled flows. Thus, it can select the detour route for $C \rightarrow D$ after $A \rightarrow B$ is scheduled. This reduces the interference and generates more end-to-end throughput.

4.5 Distributed IRMA Algorithms

Distributed algorithms are preferable to centralized ones as the mesh network grows in scale. This is because the overhead of collecting control information would tend to grow rapidly with the number of nodes, while distributed methods with local exchange of control information are likely to be more practical. For this reason, we next examine algorithms for decentralized routing/scheduling. In this mode, each node needs to figure out the “best” schedule and route for its traffic in a distributed manner, with local information exchange only. As route selection often requires determining the feasibility of schedule in that route first, it is quite desirable to have a fast heuristic algorithm to solve link scheduling problems. Therefore, the distributed control mechanism in DIRMA protocol shall be adaptive to flow rate demand variations, fast to converge and correct in interference avoidance. First, we present the protocol which realizes distributed link scheduling with min-hop routing.

4.5.1 Distributed Link Scheduling with Min-Hop Routing

As same as its centralized counterparts, the DIRMA-MH algorithm assumes the routing path is known as the min-hop path. The objective of the algorithm is to find schedules for a certain number of active links (path segments) *distributively*.

In centralized algorithms, link schedules are usually determined by a series of sequential slot-allocation decisions made with a certain order of nodes, links or flows. In distributed algorithms, those TDMA slot contenders obtain slot assignments in a concurrent manner, which may lead to slot conflicts. Previous studies propose to use either priority ranks[40][21] or contention [43] to lock the resource for unique access within the interference neighborhood. However, a successful *lock-and-schedule* action requires 1) exchange of identification/priority information before scheduling to ensure that only one contender is selected; 2) announcing the schedule decision to all other conflicting contenders. Both conditions are not easy to satisfy because wireless broadcast is generally unreliable and those operations often require more than a simple 1-hop broadcast. For example, a potential hidden node is usually out of the direct reach of a sender.

Due to above considerations, we propose a novel "schedule first, correct later" approach to resolve it. The main idea is to set up as many as possible reservations concurrently. Once link collisions are detected later, erroneous slot assignments are revoked and new reservation procedure will be triggered. This process is done recursively until no more collisions are found or all slots are exhausted.

The greedy algorithm uses $SREQ$(slot request), $SAPP$(slot approve), $SREJ$(slot reject), $SCAN$(slot cancel) and $SUPD$(slot update) messages to help nodes negotiate slot reservations.

As an example in Figure4.7, node A sends $SREQ$ message to B, the $SREQ$ message contains the intended "slot id", e.g. x for reservation. Node B checks its schedule for

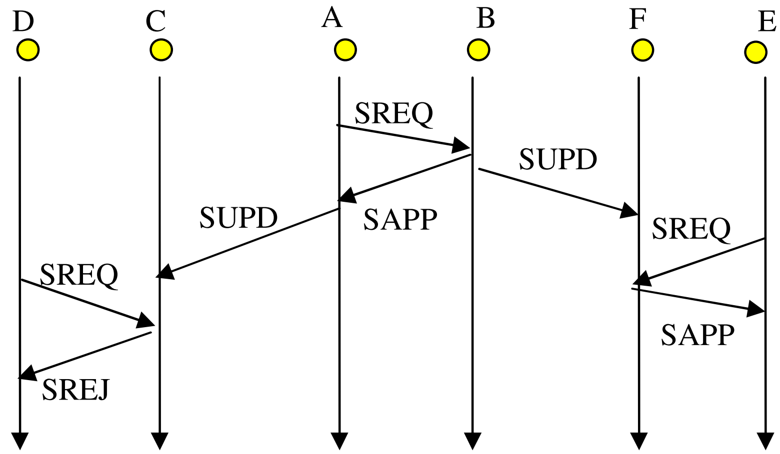

Figure 4.7: An example of distributed reservation process

slot x. If a transmission from A to B scheduled in slot x doesn't conflict any existing activities indicated in its schedule, it will send back a *SAPP* message. Once the reservation is accepted, both A and B will trigger a *SUPD* to let their neighbors know this schedule change occurred in slot x. Later, when C sends a *SREQ* to D request the usage of slot x, D will send *SREJ* to C because D's schedule shows that it is impossible to let link transmission C to D coexists with other current arrangements. In this way, *hidden node* problems are successfully avoided. On the other hand, E will determine that it is feasible to schedule a transmission from E to F after the schedule constraints are applied. Therefore, E will send *SREQ* to F, and F will confirm the reservation with a *SAPP* message. Hence, *exposed node* problems are also overcome.

Concurrent reservations, nonetheless, may cause incompatible schedules. For example, if node F sends *SREQ* to E before E hears *SUPD* from B, two conflicting links will be scheduled in the same slot. This can be detected either by a schedule sanity check or a collision monitor associated with the sender. Once the schedule error is detected, a *SCAN* message will be sent to the counterpart of the link to revoke the problematic reservation. To avoid deadlock due to schedule errors, nodes use an exponential backoff after an incorrect reservation. Moreover, besides triggered schedule updates, *SUPD* messages are broadcasted periodically to all potential interferers to synchronize the local schedule.

Each TDM slot can be used to support multiple parallel link transmissions for different node pairs. For each link, there exists a slot state which can be regarded as controlled by a state machine, as shown in Figure 4.8.

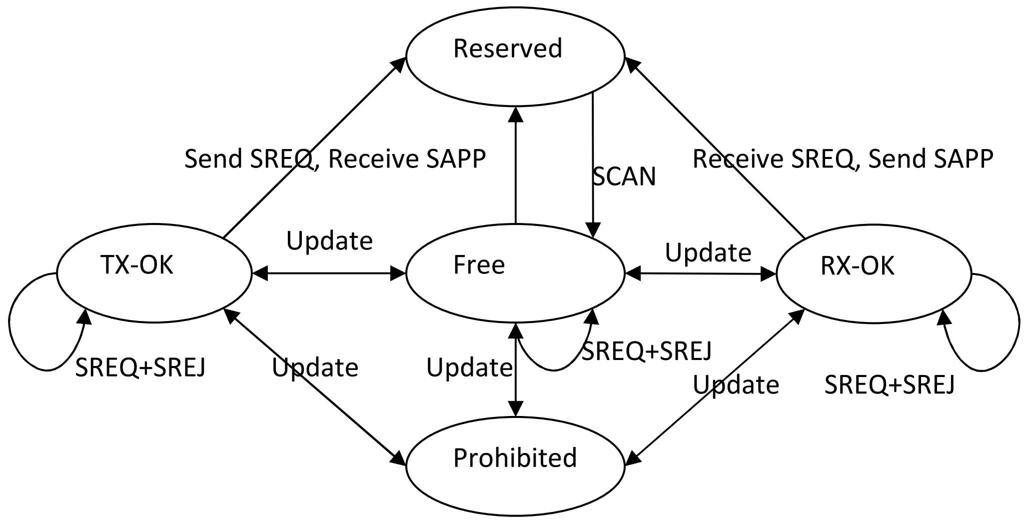

Figure 4.8: Slot state transition diagram for DIRMA Algorithms

For a certain link, the slot state is affected by other neighboring/interfering links which also use this same slot. That usage information is carried in SUPD messages. The information are combined and then analyzed with link scheduling rules. The result is stored and then used to determine the corresponding state of the slot for this link. It can be in one of those states: “Free”, “TX-OK”, “RX-OK’ and “Prohibited”. Similar to the D-LSMA design, “TX-OK” and “RX-OK” are states that link is only partially affected by other reservations in this slot. It is still possible to use this slot (transfer to “Reserved” state) after a successful SREQ/SAPP handshake. Also, the reservation could be dropped and the slot state transfer to “free” state before it is updated with the stored *slot usage* information. This is normally triggered by SCAN events once the traffic session ends.

The execution of the state machine is done by the end nodes of this link. This procedure only covers how to establish the interference-free link scheduling in one slot for one particular link. The complete DIRMA-MH algorithm of a node (e.g. node a) is given as Algorithm 3.

Since the traffic demand is only known by the source of the flow, we require the upstream node to propagate the traffic profile to the chosen down-stream node to trigger its own algorithm. This hop-by-hop process will reach the destination with a successful end-to-end schedule along the path.

Algorithm 3 DIRMA-MH

Require: local topology of node a: G_a, local conflict graph G'_a and schedule S_a, a flow F_i with demand r

Ensure: next-hop b in shortest path and slot assignments for $a \rightarrow b$

find b with distributed shortest-path algorithm
send traffic update message to b
while slot demand $r > 0$ **do**
    find an eligible slot x in S_a based on G'_a
    send $SREQ$ from a to b
    if receive $SAPP$ **then**
        decrement r
        update x's status in S_a and send $SUPD$
    else if receive $SREJ$ **then**
        update x's status in S_a and continue
    end if
    if collision detected **then**
        cancel local schedule and send $SCAN$
    end if
end while

4.5.2 Distributed Link Scheduling- Bandwidth Aware Routing

This distributed algorithm tries to conduct bandwidth-aware path selection to route around congested or interfered areas. The main idea is to consider both the distance factor and interference/congestion factor in path selection. For example, in Figure 4.9, node A is supposed to use node B as the next-hop for a certain flow if min-hop routing is used. However, the shortest path from A to B is affected by interference from another ongoing flow (implied by shaded region). As the neighborhood of link AB is interfered, the effective bandwidth of link AB is reduced. Our proposed algorithm considers a couple of next-hop candidates (B, C and D) instead of just node B. By checking and weighing the conditions of each candidate. As B and D are affected more by interference, a good next-hop, node C, is determined locally to route around the interfered area. This path from A to C should both avoid interference and maintain a plausible direction towards the sink. The pseudo code of the DIRMA-BR algorithm for a involved node a is given as Algorithm 4.

In order to ensure the quality of candidates, we add the restriction that a node j can be admitted to the candidate pool W only when it satisfies the following conditions:

1. It's a neighbor of both a and b (min-hop next-hop).

2. According to node j's schedule, it has enough bandwidth to arrange both $a \rightarrow j$ and

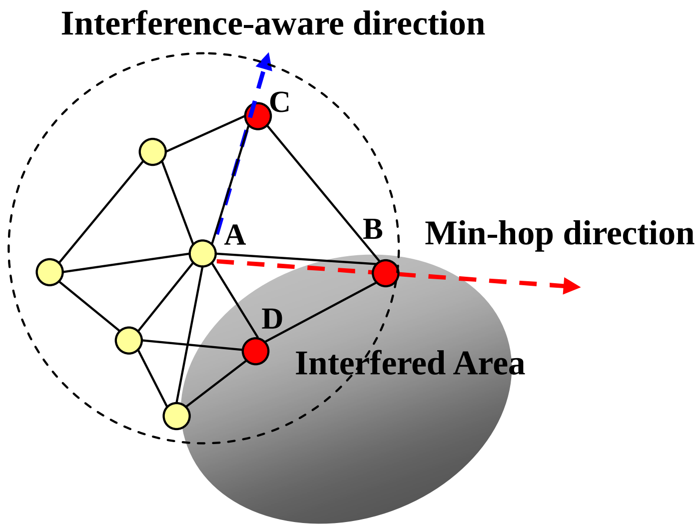

Figure 4.9: An example of DIRMA-BR mechanism

$j \rightarrow j$'s next hop.

After the candidate pool W is generated, it is sorted by the combined metric of both the distance to sink and the consumed bandwidth indicated by schedule S_a. The candidate with the smallest metric will be selected first to start the reservation procedure used in DIRMA-MH algorithm. This will be done recursively until the demand is satisfied or the pool W is exhausted. Once the node a finishes the above algorithm, it will send a traffic update message to the node $\acute{a}$ and triggers DIRMA-BR procedure in the node $\acute{a}$. When there are multiple flows in the network, the above distributed procedure will be executed concurrently.

4.6 Performance Evaluation

In this section, we present the *ns-2* simulation results of the above integrated MAC/routing design. In ns-2 simulator, a sender can communicate with a receiver as far as 250 meters away if interference-free. All radios use the same transmit power. We add some slight changes in the default ns-2 model of interference to reflect more accurate interference description[2]. In this modified model, if the difference of received signal strength of two colliding packet transmissions around the same receiver is less than 10dB, then both packets got dropped due to collision. In the Global Control Plane, the IRMA protocols characterize

[2]Please refer to Appendix B for details about the interference modeling of ns-2 simulator.

Algorithm 4 DIRMA-BR

Require: local topology info: G_a, G'_a, local schedules S_a and a flow F_i from s to d with demand r

Ensure: next-hop $\acute{a}$ and new schedule S'_a where slot demand for $a \rightarrow \acute{a}$ is satisfied

find $b \Leftarrow$ next-hop node with min-hop metric
define node set $W = \{j | d_{aj} \leq R \cup d_{bj} \leq R, j \neq a\}$
for node $j \in W$ **do**
    inquiry node j about M_{j1}, M_{j2}
    $M_{j1} \Leftarrow$ distance from j to d
    $M_{j2} \Leftarrow j$'s total used bandwidth including the prospective reservation
    if $M_{j2} > N$ **then**
        remove j from set W
    else
        $M_j \Leftarrow M_{j1} + M_{j2}$
    end if
end for
sort W with ascending metric M.
while W is not empty **do**
    pick a node in W as next-hop, try Algorithm 3 (reservation).
    if reservation fails, remove node from W.
end while
send traffic update message to next-hop $\acute{a}$

the interference with the protocol interference model in which R is equal to 250m and R' is equal to 445m. This two range parameters are derived based on the interference model conversion methods described in Section 3.2.2 based on 10dB SINR threshold and a path loss index of 4.

For IRMA protocols, a TDMA frame has 40 slots. The size of each slot allows a transmission of a packet up to 1000-bytes payload. The size of each slot allows a transmission of a packet up to 1000-bytes payload. In the IRMA protocol implementation, without loss of generality, we introduce a control channel as Global Control Plane. The data rate for the control channel is set to 100kbps. The PHY link bandwidth for the normal data channel is set at 1Mbps. All important simulation parameters are summarized in Table 4.2.

The *throughput* of the system is obtained in the following manner: each flow in the network generates CBR traffic with an offered load r. The throughput measurement is valid only if all flows can transmit a fraction q of load r successfully. We keep increasing offered load until the network saturates. Then the sum of maximum valid measurements for each flow is taken as the *aggregated throughput* given the uniform load of those source-destination pairs. By default, q is set to 0.8.

Topology size	1000x1000 m^2
Number of nodes	40
TX range	250m
Carrier sense range	550m
Channel data rate	1Mbps
Control Channel rate	100kbps
SINR threshold	10 dB
Propagation Model	TwoRayGround
MAC slot duration	8.4 msec
Slots per frame	40

Table 4.2: Ns-2 simulation parameters

4.6.1 Throughput Comparison with Capacity Bounds

In the first experiment, we examine how our centralized heuristic algorithms approximate the capacity bounds obtained by LP methods, which are already described before in Section4.2.5. We compare the performance of CIRMA-MH algorithms with the capacity upper bounds (Bound 1) obtained by solving cross-layer optimization problem with known shortest paths. We compare the performance of CIRMA-BR algorithm with the capacity bound (Bound 2) obtained by solving another optimization problem with any single path routes, too.

A set of five 40-node random topologies ($1000 \times 1000m^2$) is used. In each topology, 5 randomly chosen source-destination pairs are selected to generate end-to-end CBR sessions with flow rates specified as a parameter. The number of hops in the shortest paths for each individual flow varies in the range of 1 to 8, with an average number of 3.22. All flows run for the same duration of 120 seconds.

As shown in Figure 4.10, the CIRMA-MH algorithm's throughput results amount to 57-96% of the values of LP Solution 1 and CIRMA-BR algorithm achieves about 67-93% of LP Solution 2. This indicates that our greedy algorithms approximate the optimal solutions very well.

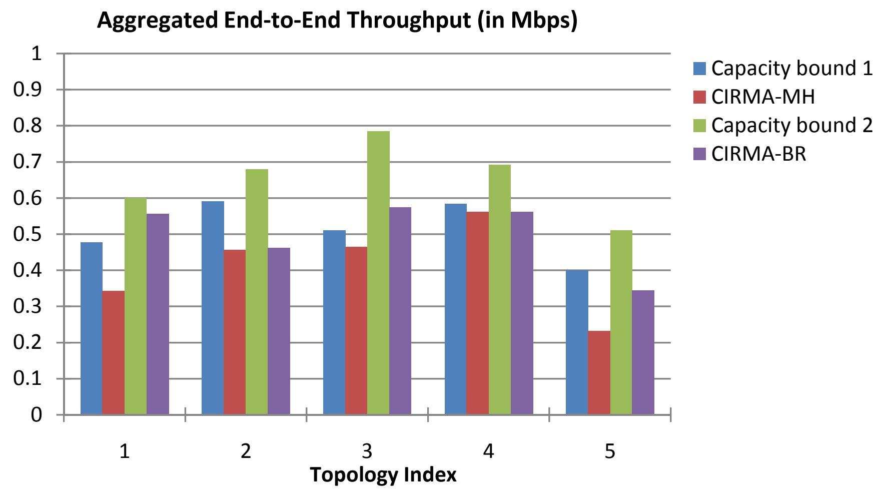

Figure 4.10: Performance of heuristic algorithms with capacity bounds

4.6.2 Performance Comparison of IRMA Algorithms

In the following experiment, we compare the performance of four IRMA algorithms (CIRMA-MH, CIRMA-BR, DIRMA-MH and DIRMA-BR) with two baseline scenarios[3] (AODV and DSDV routing protocol plus IEEE 802.11 MAC with RTS/CTS). We use the same set of 40-node random topologies with 3, 5, and 8 randomly generated end-to-end CBR flows respectively. The throughput results shown in Figure4.11 is aggregated over all end-to-end flows presented in a scenario and averaged over a set of 5 random topologies. The error bars in each column show the standard deviation of maximum throughput corresponding to each scheme. It can be seen that all 4 IRMA-MH algorithms yield a sustainable throughput much higher than the baseline scenarios. Compared to AODV baseline scheme, this gain is as high as 83%, 90% and 114%, for 3, 5 and 8 flow scenarios respectively. This gain is even up to 183% when compared with DSDV baseline scheme.

It is also worthwhile to note that both BR algorithms behave better than MH algorithms in most of the cases. In average, the CIRMA-BR yields 22.4% more throughput than CIRMA-MH while the DIRMA-BR performance is 2.37% better than DIRMA-MH algorithm. Note that the DIRMA-BR algorithm has a mixed result shown in the above simulation experiment. Sometimes, it even performs worse than the DIRMA-MH algorithm. This is because the routing decision in DIRMA-BR itself comes from a combination

[3]For baseline scenarios, the control channel is not used. All control messages and data packets are mixed in the 1Mbps data channel.

of static and dynamic metrics. The dynamic part is based upon very volatile local information, MAC schedules in DIRMA-BR scheme. Slot reservations, in DIRMA-BR protocol are much more frequently made and discarded when a mesh router examine the feasibility of a pool of next-hop router candidates one by one. This may give temporary and potentially wrong MAC bandwidth information about the neighborhood and result poor route selection for the DIRMA-BR algorithms.

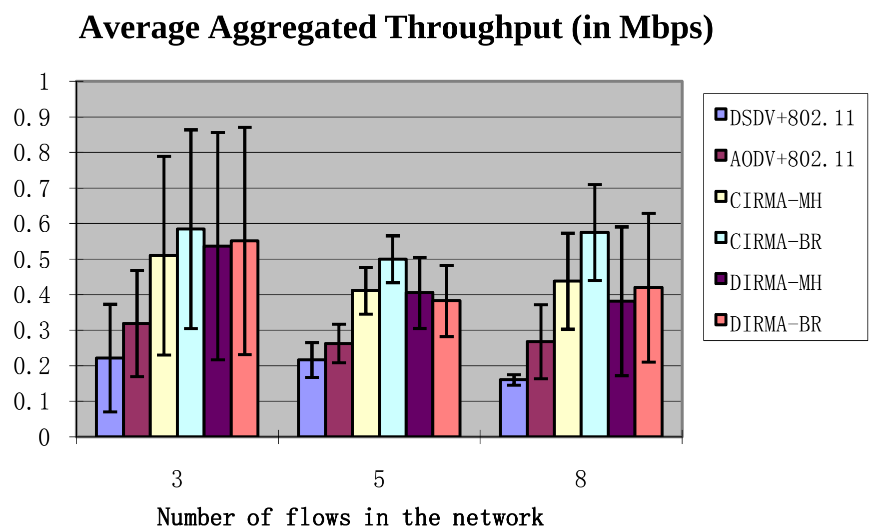

Figure 4.11: Performance comparison for IRMA protocols and baseline approaches

It is also observed that the distributed algorithms sometimes perform a little better than the centralized algorithms. This is due to the discrepancy between the protocol interference model and the physical model as mentioned in Section 3.2.2. Our distributed algorithms seek TDMA slot arrangements aggressively without full awareness of the schedules of other links. This might results in better solutions than centralized schemes, while links occupying the same slot are physically feasible but may be regarded as ineligible by the protocol interference model.

4.6.3 Control Overhead on the Control Plane

In this experiment, we estimate the control overhead in IRMA schemes and compare it with the signaling overhead of the conventional designs with an example scenario. For the conventional schemes, the overhead includes both of the routing messages and the 802.11 RTS/CTS frame exchanges which are used to avoid collision. For IRMA schemes, the

Scheme name	Overhead (in bps)	Normalized Overhead
CIRMA-MH	18646	1.499%
DSDV + 802.11	55117	6.1962%
AODV + 802.11	67558	7.0517%

Table 4.3: Control overhead comparison for IRMA and conventional approaches

overhead consists of all control packets exchanged in the control plane. To make a fair comparison, all signaling overheads are measured in layer 2.

We conduct the simulations on a 4×4 grid topology. Ten traffic sessions of random source-destination pairs are started at random time instants. The duration of the traffic sessions is exponentially distributed with an average of 30 seconds. The total simulation time is 80 seconds and the first traffic session starts at t=20 seconds. We conduct the same simulation procedure with 10 different traffic scenarios and average results over the 10 simulations. We report both the signaling overhead measurement (in bps) and the normalized overhead (ratio of control traffic in bytes to the actual data delivered end-to-end in bytes) for each scheme in Table 4.3.

First, note that the overall control overhead in IRMA scheme is a very small fraction (1.8%) of the control channel bandwidth. The results also indicate that the control overhead of IRMA scheme is much smaller than baseline schemes. It is mainly due to the fact that IRMA scheme uses much less signaling to arrange collision-free MAC scheduling than the per-packet RTS/CTS signaling used in IEEE 802.11 MAC protocol. This can be more clearly seen from the Figure 4.12.

In this figure, we plot the change of signaling overhead in a timeline for one of the simulation experiments. Conventional MAC protocols like IEEE 802.11 spent significant overhead to conduct per-packet reservation (RTS/CTS). The "DSDV+802.11" scheme has periodic routing overhead. Both CIRMA-MH scheme and AODV+802.11 scheme have a couple of spikes associated with the beginning of a new traffic session. The curve of the IRMA scheme also shows several spikes associated with the end of traffic session. The CIRMA-MH scheme has some heavy signaling load[4] prior to the traffic sessions that is related to bootstrapping, neighbor discovery and interference characterization, too. From

[4] In the illustration, there are several cases that instantaneous control signaling throughput is shown larger than the control channel bandwidth (100kbps). This is because the time interval bins used to classify the occurrence of control traffic has a width of 0.5 seconds. If more narrow bins are used, this artifact would be eliminated. This explanation also applies for Figure 4.14.

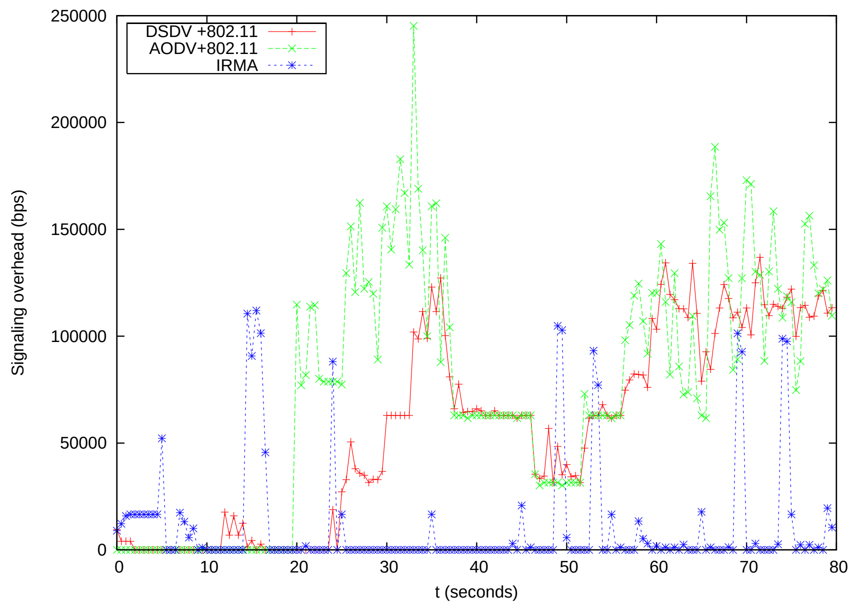

Figure 4.12: Measurements of signaling overhead

these simulation results, we can see the integrated routing/scheduling scheme would not only improve the end-to-end throughput, but also reduce the signaling overhead in protocols for static wireless mesh networks, comparing to the two conventional approaches.

Next, we conduct a couple of simulation experiments to compare the signaling overhead of centralized IRMA protocols and distributed IRMA protocols. The duration of each experiment is 145 seconds while the first traffic will not start till t=25 seconds. After that, various number of traffic sessions will start at random time. The duration of those traffic sessions is exponentially distributed with an average of 30 seconds. For each traffic session, a traffic demand equivalent to one slot out of the 40-slot frame is generated. The simulation is done with both CIRMA-MH and DIRMA-MH protocols for mesh networks of different sizes. For each network size, five random topologies are tested and the average results are shown in Figure 4.13.

As we can see, the signaling overhead of CIRMA scheme is higher than DIRMA schemes. This difference becomes more remarkable with more nodes in the network. Basically, centralized IRMA schemes need to let each node in the network communicate with a master node. When the network becomes large, this kind of communication would require more number of relay hops in general. Therefore, the overhead will increase dramatically in the

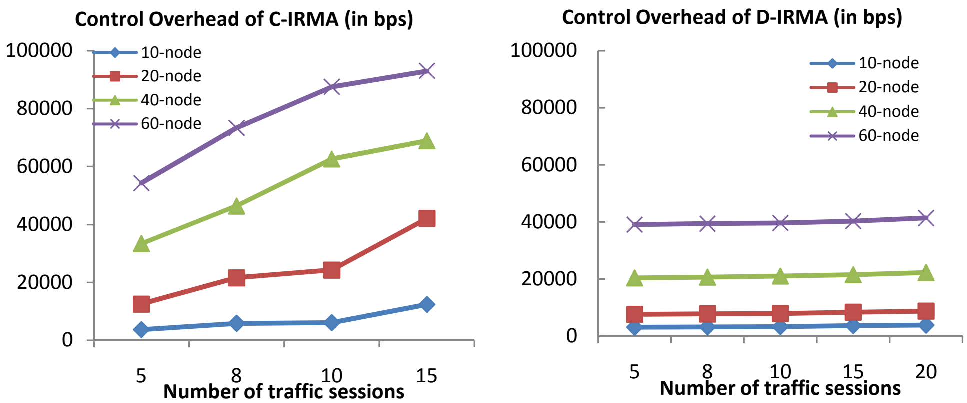

Figure 4.13: Overhead comparison for IRMA protocols

CIRMA protocol. Given that all those message deliveries are from or to one single master node, a bottleneck would be formed around the master node when network grows to a certain degree. This would eventually affect the network functions. On the other hand, the distributed IRMA protocol handles routing and scheduling with local information exchanges, thereby creating much less communication overhead. For the same topology and traffic profile, CIRMA-MH protocols produce 102%, 209%, 149% and 92% more control overhead than DIRMA-MH protocol in 10-, 20-, 40-, 60-node topologies respectively. Also, the overhead in DIRMA-MH protocol increase much slower than CIRMA-MH protocols too. We contrast the variation of signaling overhead in timeline for both two protocols in Figure 4.14. This is measured for a 40-node mesh topology with 10 random traffic sessions.

Usually, bootstrap, control plane discovery/routing and interference characterization occur in the first 25 seconds. During this phase, CIRMA protocol need allow the central master node to collect all global topology and interference information for the whole network, while DIRMA protocol only need local exchanges. So, as shown in the figure, CIRMA-MH protocol almost saturate the 100kbps control channel during this period while the DIRMA protocol only produces 20kbps in average overhead. After traffic starts, a significant part of CIRMA control overhead is traffic-dependent. A new set of routing/scheduling parameters is delivered to the network whenever a traffic flow starts or ends. For DIRMA protocol, the MAC schedule update messages (SUPD) which are broadcasted periodically, constitutes most of the overhead here. It helps to establish the interference awareness among the neighborhood, so that only very a few additional messages are needed to establish/release slot reservations when a new traffic session starts/ends. In summary, DIRMA protocols

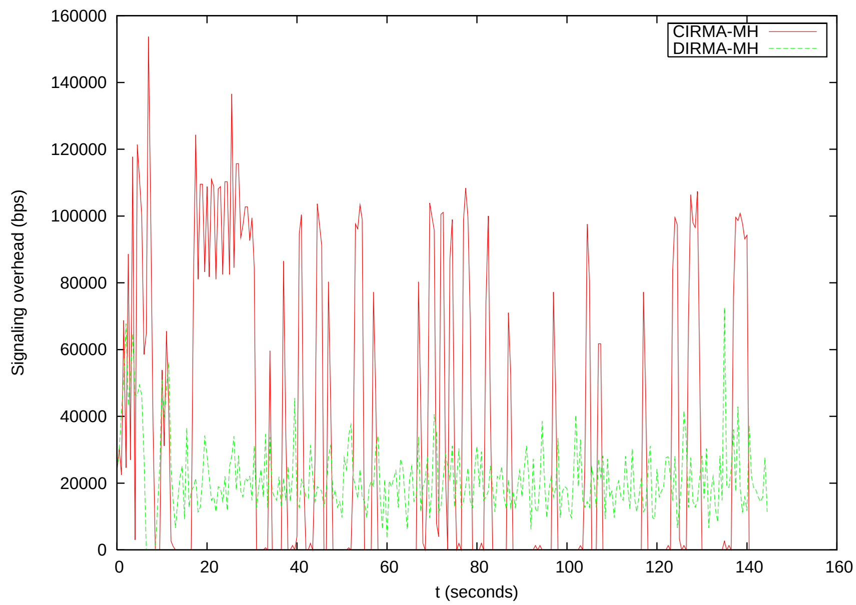

Figure 4.14: Signaling overhead timeline for centralized and distributed IRMA protocols

use much less control messages in the control plane and more suitable to support larger networks and more frequent traffic variations.

Chapter 5
Future Work

In the future, we first plan to extend our proposed research methodology for multi-channel wireless mesh networks, where resource allocation optimizations occur in both frequency and time domains. In this thesis, we discussed mainly on the protocol design for single channel wireless mesh networks. But the available frequency spectrum of this single channel can be split into multiple adjacent channels. If channel assignment is fixed, then the whole network can be decoupled as several individual networks working in orthogonal frequencies. And each of them could be solved with our proposed IRMA approach. But if dynamic channel assignment is introduced, or each node is allowed to have more than one radio, this would turn out to be a joint Routing/TDMA/FDMA optimization problem. Some prior theoretical investigation of this issue has already exist [62] [53]. The research could be done with a similar agenda in two phases: 1) numerical analysis on the potential performance gains; 2) If the gains exist, design heuristic algorithms to realize such gains and evaluate the complexity for protocol implementation with the global control plane.

Also, the IRMA protocol works well with long-lived CBR flows. The performance gain will diminish with the introduction of short-live bursty data traffic. It is quite a challenging task to have a system design which could accommodate both two kinds of traffic optimally. One ongoing research is trying to design dynamic CSMA/TDMA MAC. The dynamic MAC can work in two modes: CSMA/CA and TDMA. When traffic flow is bursty and network is not heavily loaded, CSMA/CA mode is turned on. However, when traffic is heavily backlogged or certain characteristics of the traffic flow can be predicted to last for a relatively long time, TMDA scheduling is switched on to replace random access MAC. To provide this kind of agility, advanced cognitive radio technologies are needed. Currently, in WINLAB, we are exploring to use GNU Radio [63] to realize this scheme.

Another piece of remaining work is to conduct a proof-of-concept experiment to validate the centralized IRMA approach in ORBIT testbed [64]. For this kind of validation test, we plan to form a 20-node multi-hop mesh network topology on the testbed and have 3-4 concurrent multihop flow sessions running on it. Then, both the conventional approach and the IRMA approach will be evaluated to see if the IRMA scheme can provide the significant performance improvement margin as indicated from ns-2 simulations.

Appendix A

Hidden Terminal Problem and Virtual Carrier Sensing

The virtual carrier sensing scheme is introduced to IEEE 802.11 MAC to avoid hidden terminal problems. The basic idea is to exchange RTS/CTS frames first before sending out a DATA frame. Every node hearing RTS or CTS will set its carrier as busy correspondingly. Here, we prove that with the use of RTS/CTS frame, a DATA frame cannot collide with another DATA frame unless it collides with a control frame first. Thus, hidden terminal problems still exist in another form although the chance for a direct collision between data frame is reduced.

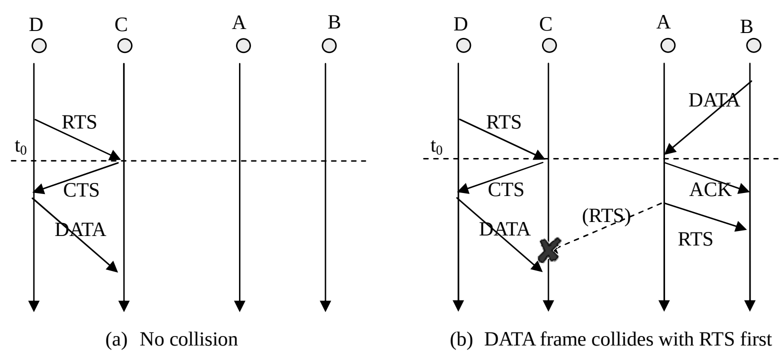

Figure A.1: Collision avoidance with RTS/CTS

Proof: As shown in Figure A.1, we consider two possible data transmissions, D to C and A to B. The necessary condition for a DATA frame collision is that there must be one DATA frame appear in the channel (e.g. a transmission from D to C). To make this happen, at least one RTS/CTS exchange has to succeed before the DATA frame. According to the 1-hop interference model, when node C received an RTS frame successfully at time t_0, it means none of its 1-hop neighbors (e.g. A) transmits any frame during that RTS period. It also means none of its neighbors (e.g. A) receives a CTS frame. If A receives a CTS frame, it must transmit an RTS frame before that. That transmission will overlap with D's RTS because CTS frame (14 byte) is shorter than RTS frame (20 byte). Thus, A was not receiving CTS before time t_0. So, there are only two possibilities: 1) Node A has been idle. 2) Node A has been receiving a DATA frame before time t_0.

For the former case, C's neighbor (e.g. Node A) will be aware of Node C's ensuing CTS and will not cause collision of following DATA frame. For the latter case, Node A has to wait at least the duration of one ACK frame before sending an RTS request. This RTS request will definitely conflict with the DATA frame first before a possible later DATA-DATA frame collision.

Therefore, we can see that even under the common 1-hop interference model, collision is still a very serious problem. Under physical model of interference, the effectiveness of RTS/CTS is even more doubtful [65].

Appendix B

Interference Modeling in Network Simulator 2

Network Simulator 2 (ns-2, in short) is a very popular network simulation tool and is widely used in networking research, especially for wireless networking. Here we describe the default interference model in ns-2 first.

B.1 IEEE 802.11 Interference Modeling in ns-2

To model a wireless network, one of the fundamental tasks is to determine whether a radio transmission, packet or frame, will be decoded and received correctly in the receiver, with or without the presence of interference. In ns-2, there is no per-bit calculation of signal-to-noise ratio or bit-error rate concept. All calculations are conducted in a packet basis.

If there is no interference (simultaneous or overlapping transmissions), the receiving power (signal strength) of an incoming packet is compared to a fixed threshold. If it is larger than the threshold, then the packet is error-free. Otherwise, the packet shall be regarded as damaged and shall be discarded by the receiver. The receiving power is derived from the transmit power of that packet according to a path-loss model. In each model, parameter such as antenna heights, antenna gains, distance between transmitter and receiver will be considered. "TwoRayGround" is the most common model used in wireless communication simulation in ns-2. If all nodes in the network are assumed to be identical, then a fixed communication range can be used to determine network connectivity. This is, by default 250 meters.

Modeling the case with the presence of interference is a little more complicated. In ns-2, this is actually implemented for a particular MAC, IEEE 802.11 standard. Suppose there are one valid transmission and one interfering transmission colliding around a receiver. The interfering transmission is relevant only after it is carrier sensed. This means, its power at this receiver shall be larger than a *carrier sense threshold* to be regarded as a potential interfering source. Then, depending on the arrival order of those two transmissions, there are two different outcomes. If the power of second transmission is l0dB larger than the first one, then both two transmissions will be dropped. Otherwise, the first transmission is *captured* and decodable. Hence, an valid packet transmission survives only if the valid transmission appears in the carrier first and bears a signal power 10 times larger than an interfering transmission, as shown in Figure B.1.

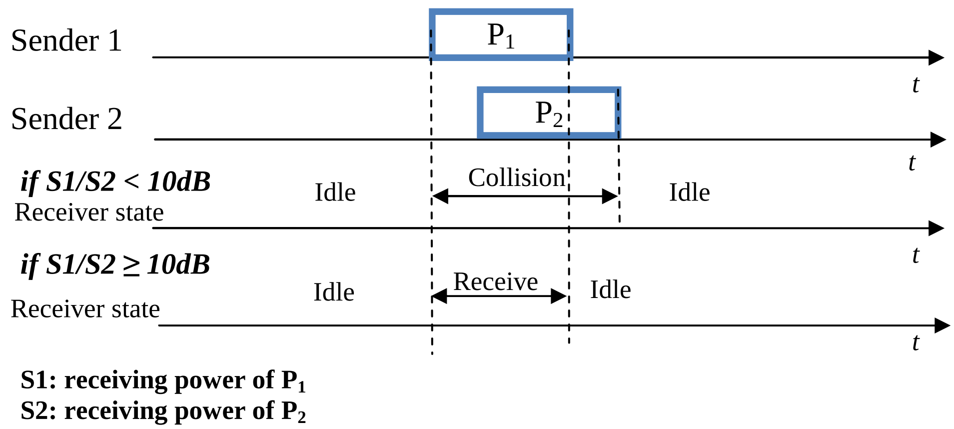

Figure B.1: Collision model in ns-2

This model is similar to the physical model of interference. But it contains a lot of simplifications. For instance, the model does not consider the aggregated interference effects. It also ignores the length of overlapping duration of those two transmissions. Even though there is only one microsecond overlapping for those two packet transmissions, it is still considered as collision.

It is also noted that this default model does not match the RTS/CTS interference model described in Section 3.1.5, either. Under the above modeling, even after a successful RTS/CTS handshake, the collision-free transmission of ensuing DATA frame is not warranted. This is due to the fact that some potential interferers may locate out of both the 250-meter communication range of the receiver and carrier sense range of the transmitter.

B.2 Ns-2 Modeling for D-LSMA Simulation

The D-LSMA design is based on the packet radio interference model. In this model, the radio does not leak any effective interference out of its normal transmission range. Thus, we modify the default carrier sensing threshold to let it to be equal to the receiving strength threshold. Therefore, a transmitter out of 1-hop will not be sensed at all. Also, for a particular receiver, if there is more than one neighbor transmitting at the same time, all transmissions shall be dropped by this receiver. We remove the 10dB requirement so that a collision occurs whenever there are two or more overlapping transmissions detected in the 1-hop neighborhood.

B.3 Ns-2 Modeling for IRMA Simulation

IRMA protocol assumes a general protocol model of interference. To emulate that in ns-2, both communication range and interference range need to be defined. By keeping the default ns-2 receiving signal strength threshold, the 1-hop communication range is still 250 meters. The protocol model requires that any interfering packet transmissions, which are originated from a node within the interference range of the receiver, shall cause collision. To realize this, we still keep the default 10dB threshold, but change it to a more general rule: if the power (signal strength) difference is less than 10dB, both packets will be discarded. Otherwise, only the packet with stronger signal shall be correctly captured by the receiver. The 10dB SINR threshold corresponds to an equivalent interference range of 445 meters. Note that this modified model is a mixture of physical model and protocol model. It will cause the *over-protection* artifact described in Section 3.2.2.

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