DISTRIBUTED SPECTRUM COORDINATION FOR MULTI-RADIO PLATFORM CO-EXISTENCE: AN EXPERIMENTAL STUDY ON THE ORBIT TESTBED

BY SHANMUGA SUNDARAM ANANDARAMAN

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and approved by

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ABSTRACT OF THE THESIS

Distributed Spectrum Coordination for Multi-Radio Platform Co-Existence: An Experimental Study on the Orbit Testbed

By SHANMUGA SUNDARAM ANANDARAMAN

Thesis Director:
D. Raychaudhuri

This thesis presents an experimental investigation of algorithms for protocol-assisted spectrum coordination of multi-radio platforms in a dense radio environment. With increasing proliferation of new wireless technologies and radio standards such as 802.11b/g, Bluetooth, Zigbee, UWB, WiMax etc, multi-radio devices such as laptop computers, cell phones and PDA's will need to co-exist in shared unlicensed frequency bands.

The common spectrum coordination channel (CSCC) protocol has previously been proposed as a method for nearby devices to exchange spectrum usage and traffic information necessary to execute decentralized co-existence algorithms. This work focuses on the application of CSCC to dense deployments of multi-radio platforms with both 802.11 WLAN and Bluetooth in a typical office/SOHO type environment. Distributed spectrum coordination algorithms listen to these CSCC announcements from radios within range, and back off their transmission parameters to avoid contributing excessive interference. We have developed a set of distributed coordination algorithms, with the objective of achieving efficient co-existence between interfering radios while maintaining acceptable QOS (Quality of Service) at every node.

Specific coordination algorithms considered include Bluetooth defer-transfer (Bo), Simple Source Rate adaptation (Rt), distance based SIR link budget rate adaptation (SIR-BT). Each of these algorithms is defined and evaluated using dual-radio nodes on the 400-node ORBIT radio grid. System performance parameters obtained from the experiments are throughput, file transmission delay (for TCP) and quality of data/audio/video streams (for UDP).

Experimental results are given for a number of device densities and topologies. Significant degradation in throughput and application performance is observed without spectrum coordination. The proposed CSCC-based coordination algorithms are shown to provide significant performance gains, both in terms of system throughput and application level parameters. Overall, for the scenarios considered, the proposed coordination algorithms provide ~50-100% improvement in system throughput when compared to the case with no coordination.

Acknowledgement

The thesis illustrated in this document involves more than a year of hard work with many a help from ORBIT team, Winlab faculty and many of my friends in EE and CS at Winlab, Rutgers University. Thanks and Acknowledgement would be a very small literary tribute to all the people involved in this journey and for all their precious time and inputs. I want to attribute the project's success to People, but for whom, this project could not have been a reality and people whom I consider as a great privilege and joy to have worked with.

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I would fail in my duty, if I don't thank Mrs. Lynn Ruggiero of Department of EE for being very understanding and clearly highlighting all the administrative requirements of the department whenever I knocked her doors for help.

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Also I am obliged to the entire Rutgers EE and Rigsa (Rutgers Indian association) community and my roommates in particular, for making my stay, a joyful and a memorable experience. Never for once have I felt isolated or lonely, in this alien land and it is all due to your continuous pampering and irrefutable joyous company.

I am taking with me all these wonderful moments for life and thanks to all those whom I have mentioned here and whom my absence-minded brain forgot to acknowledge, for being with me and making this happen in the first place. Thanks…

Shanmuga S Anandaraman
17th June 2008

Dedication

To

my mother, Mrs. Suganya Anandaraman, for her invaluable love and affection,

my grand mother Mrs. Santhammal Seshasayanam for her blessings and good wishes and

my love of life, Miss Sandhya Gopinath, for her constant motivation to keep me going

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Abbreviations

CSCC Common Spectrum Coordination Channel

SOHO Small Office/Home Office

ORBIT Open Access Research Testbed for Next-Generation Wireless Networks at Winlab

BT Bluetooth

BT-Bo Bluetooth-Backoff defer transfer scheme

BT-Rt Bluetooth-Rate adapt scheme

SIR-BT Signal to Interference Ratio based Bluetooth adapt scheme with link budget SIR threshold 10

SIR-BT x Signal to Interference Ratio based Bluetooth adapt scheme with link budget SIR threshold x

Chapter 1

Introduction

Multi-radio portable computing platforms such as laptops and PDA's with 3-4 different radios (e.g. WiFi, WiMax, UWB, Bluetooth, Zigbee) are expected to become the norm in few years. One example is that of today's growing cellular phones, which is embedded with Bluetooth, GPRS and Wi-Fi. With proliferation of new radio standards and technologies, greater are the chances of multiple radios operating simultaneously in same or adjacent frequencies e.g., ISM 2.4 GHz. Such scenarios could lead to inter-radio interference and degradation in radio performances.

1.1 Multi-Radio Coexistence Problem

In general the multi-radio coexistence problem can be classified as arising from two scenarios: in-platform and adjacent platform. Adjacent platform indicates the case where devices are not located in the same platform but are close enough that they interfere with each other. In-platfrom on the other hand indicates the case where multiple radios are in the same physical unit in which mutual interference can be caused by conduction as well as radiation. The adjacent platform case is referred to as inter-node interference and in-platform is referred to as intra-node interference in our work. In general, degradation due to intra-node interference can be more severe than the inter-node, but as the multiple radios are located in the same platform, there are easier ways to address them. At the same time, in the absence of any common interface or communication channel between the heterogeneous radios located in adjacent platforms, it becomes difficult to address the inter-node problem than the intra-node. Also the severity of interference not only depends on the distance of proximity but also on the density, namely number of possible interfering radios in the particular area of interest. Office rooms, conference halls and business conventions with dense distribution of multi-radio devices result in denser spectrum usage environment with as many as ~10's of radios per square meter operating in a variety of licensed and unlicensed bands. The technical challenge associated with such emerging multi-radio scenarios is that of defining a framework for distributed coordination between both adjacent platform radios and in-platform radios such that high spectrum efficiency could be achieved with good application level performance at each radio.

1.2 Existing Solution and Our Approach:

In the past a lot of research has gone in to address the coexistence problem. Table 1 group the list of existing techniques broadly under Physical and MAC layer approaches.

Table 1 List of Multi-Radio Interference Mitigation Techniques

Technique		Issues
PHY	• Spectrum masking • Antenna isolation • Shielding • filtering • Beam-forming(BF) • Interference Cancellation	• Static • Sacrifice performance e.g,(filter reduces sensitivity) • Added cost and size
MAC	• Dynamic **frequency** selection (DFS) • Transmission **power** Control (TPC) • **Time** Sharing (TS)	• Suboptimal without air-interface support • Control overhead

When we consider the PHY solutions listed in Table 1, all these have to be designed on a case by case basis and is static in approach. They usually involve additional hardware requirement and are also limited by the overall device size. Many of the PHY solutions are embedded in hardware and therefore are not easy to modify. They could even negatively impact the performance when the device works in a single-radio situation. Thus in denser environments with new radio technologies, physical layer approach would not be suitable. The added cost and size to achieve these PHY solutions make it cumbersome and less attractive too.

On the other hand, there are a number of MAC approaches, which are dynamic and provide reactive interference mitigation. All the approaches at MAC level is fundamentally based on dynamic need based adaptation/scheduling of one or more of these parameters: frequency, power and time. For example, AFH (adaptive frequency hopping defined in IEEE 802.15.2 [3] avoids WiFi radio interference by choosing those frequencies that do not lie in the band of active WiFi receiver. The intrinsic assumption of these dynamic frequency selection (DFS) algorithms is "Availability of in-active, collision free frequencies". But in scenarios with high radio density and wide band interference, choice of operating frequency might not be always available to the DFS radios.

In the case of TPC (transmission power control), a radio is forced to operate at its lowest transmit power depending on link budget measurement or calculation which as a result would lead to less interference with proximity nodes [1]. TPC would be ideal if all the clients are located very close and radios have the leverage to transmit at lower power levels. Although TPC is a generic approach, transmission power is a critical parameter for both the range of a system and the interference it contributes. Hence TPC cannot be used in isolation to enable coexistence solution.

In time sharing approaches the basic idea is to schedule multiple radios in time domain so that they do not overlap with each other. To achieve ideal time scheduling, a higher overhead needs to be tolerated and since there is no information from other radios located in adjacent platforms, time sharing is restricted to address only in-platfrom interference.

Overall, MAC approaches are more dynamic and perform better than the PHY schemes but do not provide a general solution for all kinds of dense multi-radio scenarios. The main issue with MAC solutions is, there is no single MAC for all the standards such as Bluetooth, WiFi, WiMAx etc. Hence as proposed in [1] there is a need for a generic media independent multi-radio coexistence and coordination layer integrating coexistence techniques and providing a unified and scalable multi-radio coexistence support. Therefore in order to address the multi-radio problem of inter and intra node interference generically, we have implemented a MICE like, distributed spectrum control and coordination for multi-radios that use CSCC (Common Spectrum Coordination Channel) etiquette protocol of our previous work [2]. Our approach is not tied to any particular radio or hardware and hence is an extendable software platform to design and evaluate any new coexistence algorithm that for various multi-radio scenarios. As a proof of concept, this thesis involves distributed co-existence protocol design, development of source-rate adaptive algorithms along with in-depth experimental validation of realistic multiple two-radio scenarios on the ORBIT 400 node Testbed for efficient WiFi(802.11g)-Bluetooth(802.15) co-existence.

1.3 Thesis Organization:

The remaining thesis is organized as follows. Chapter 2 surveys related and previous work on this problem and elaborates on typical multi-radio scenarios and CSCC protocol. In chapter 3, we discuss our proposed distributed spectrum coordination design and implementation. In chapter 4, we delve into the details of our experimental setup, implementation details, scenarios evaluated and corresponding results. We also summarize our work and mention future research items in Chapter 6.

Chapter 2

Multi-Radio Scenarios and CSCC Protocol

2.1 Related Work

Research in this area has so far been more on a case by case basis specific to a particular physical layer. Multi-radio problems have been extensively researched separately for specific radio cases like Bluetooth-WiFi, WiFi-WiMax, Bluetooth-Cellular UMTS etc. Examples of these studies include the coexistence of IEEE 802.11b with Bluetooth [4-8], the coexistence of IEEE 802.11b with WiMax operating in the same unlicensed band [9,10] and coexistence of Bluetooth and cellular UMTS [11]. Similarly the approach of adaptive source encoding, power control, packet scheduling, adaptive buffering have all been studied in a number of previous works[12-16] but only with the objective of improving video/audio streaming quality by adapting to the varying wireless parameters without awareness about the interferer. For these scenarios, single-radio devices are assumed to be randomly distributed in the same physical area and since multi-radio devices use different physical layer technologies; they would not able to decode each others' frames. Such unawareness translates to uncoordinated transmissions and large frame losses due to adjacent platform inter-node interference, when transmissions overlap both in time and frequency domains. In most of these adaptation schemes, little emphasis is given to improve the overall network performance or to provide a generic radio-independent solution for the multi-radio problem. Intel's communication technology lab has been recently working [1,17] to solve the issue of multi-radio coexistence from a generic point of view and some interesting works include a suggestion for a media independent multi-radio coexistence service layer(MICE) in their work in [1].

2.2 Multi-Radio Scenarios

In our study, we characterize typical usage scenarios in multi-radio co-existence environments by identifying representative habitats such as *home*, *small/home office* (SOHO), and *large* *enterprise*. These habitats consist of an appropriate floor-plan on which we consider the platforms with various radio technologies to reflect their role in occupant's lives by their quantity, real-world physical placement and offered traffic.

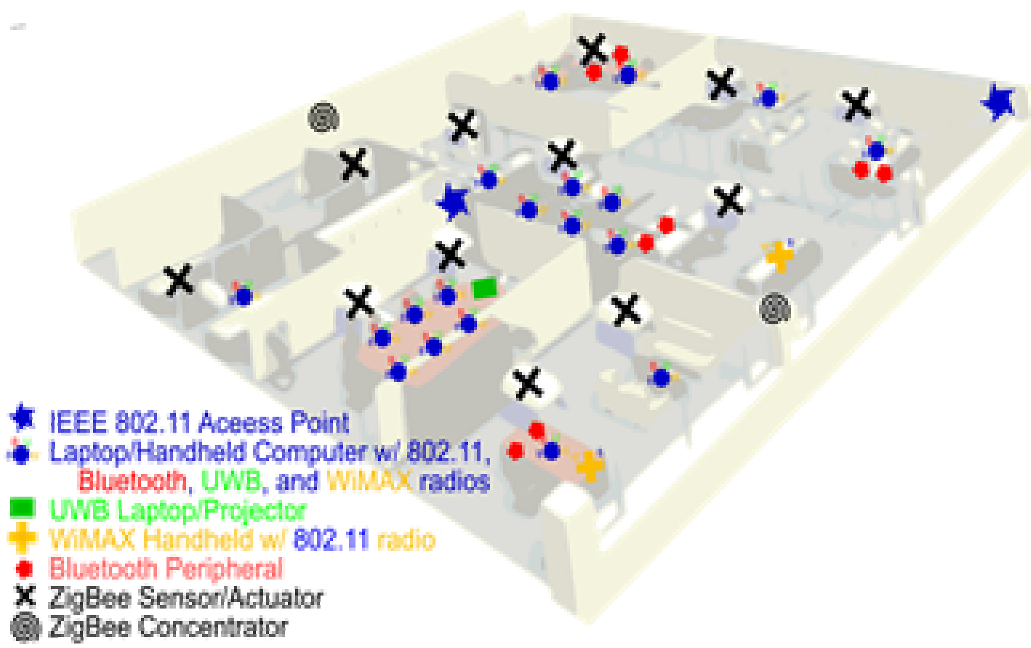


Fig. 1 SOHO scenario for multi-radio co-existence.

Here we use the SOHO (Small Office, Home Office) scenario as a sample multi-radio scenario for our discussion. This scenario homes the wireless technologies of WiFi, Bluetooth, ZigBee, WiMax and UWB. Figure 1 illustrates the baseline SOHO scenario with about 20 active people working in a semi-partitioned dry-wall space of about 20m x 20m. The habitat has one active main conference room (on the left, middle), a smaller meeting room (far upper corner), as well as office, cubicle and lab spaces (on the center and rightmost side). Laptops with WiFi and Bluetooth radios are clustered in the conference room and distributed in cubicle areas and we use their topology in our experimental evaluations given in chapter 4. The conference room is also equipped with an UWB projector for *laptop-to-wall* streaming. WiMax handhelds or laptops are also used for wide-area access by the visitors. Sensors with ZigBee radios are distributed throughout the habitat and communicate for the *smart building* infrastructure.

The WiFi network for this office (about 20 people) can be supported by two access points where one of them is closer to the central area of activity, *the conference room* and the other is on the rightmost corner of the floor plan. The typical workload for the WiFi network is obtained from an observation study of a similar office WiFi network used in [18]. In summary, 97% of workload is composed of TCP traffic (remaining 3% being UDP for VoIP communications), which further decomposed as 75% WWW browsing over HTTP, and 25% other background traffic (such as NETBIOS, FTP and SSH file transfers, printing, etc.) The Bluetooth radios in this scenario are mostly used for cell-phone-to-headset and laptop-to-headset audio streaming. It is appropriate to consider this workload as point-to-point CBR-type streams with different service levels corresponding to different audio CODECs requiring 64Kbps, 128Kbps, 256Kbps, 320Kbps and 512Kbps.

Also, WiMax traffic is considered to carry VoIP data using 96Kbps UDP streams of 300-byte frames, tolerating a maximum of 5% loss with 30ms delay requirement. The smart building infrastructure uses ZigBee sensors/actuators on each light fixture as well as climate sensors and the two ZigBee concentrators act as relays for the communication to the rest of the infrastructure in the building. The sensor traffic is assumed to be sub-minute readings of 50-byte frame updates and occasional reactive actuation communications not exceeding a couple of Kbps. Figure 2 gives a mapping of how SOHO would appear in ORBIT Testbed

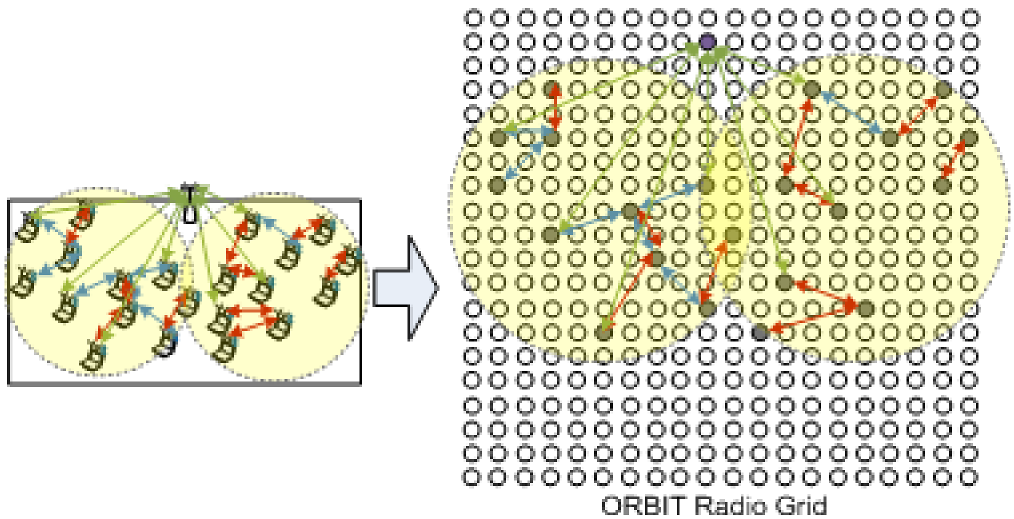


Fig 2 SOHO to ORBIT Testbed Mapping – A visual representation

As the first stage of our evaluation study, we are mapping the WiFi and Bluetooth part of the outlined SOHO scenario on to the ORBIT testbed with IEEE 802.11a/g and Bluetooth dual-radio nodes. While this serves as a starting point for evaluating spectrum coordination protocols and algorithms for our multi-radio scenarios, we are in the process of augmenting ORBIT testbed with WiMax, Zigbee, and UWB radios to enable a holistic evaluation of co-existence in future.

2.3 CSCC Spectrum Etiquette Protocol

When dense multi-radio scenarios possibly with hidden nodes are considered, simple reactive spectrum coordination methods (i.e., trying to act after interference degrades the performance) or in-platform scheduling algorithms (i.e., assuming the only interference source is the other radios of the same device) usually have limited performance and value. Lack of the global view of the radio network is to blame for the limited performance of such approaches. For improved performance, the concept of protocol-assisted coordination between radio nodes has been investigated in [19,20], leading to a specific scheme called the Common Spectrum Coordination Channel (CSCC) [21]. As shown in Figure 3, each wireless node in the environment uses a common control radio standard, operating at a known frequency for control and coordination purposes.

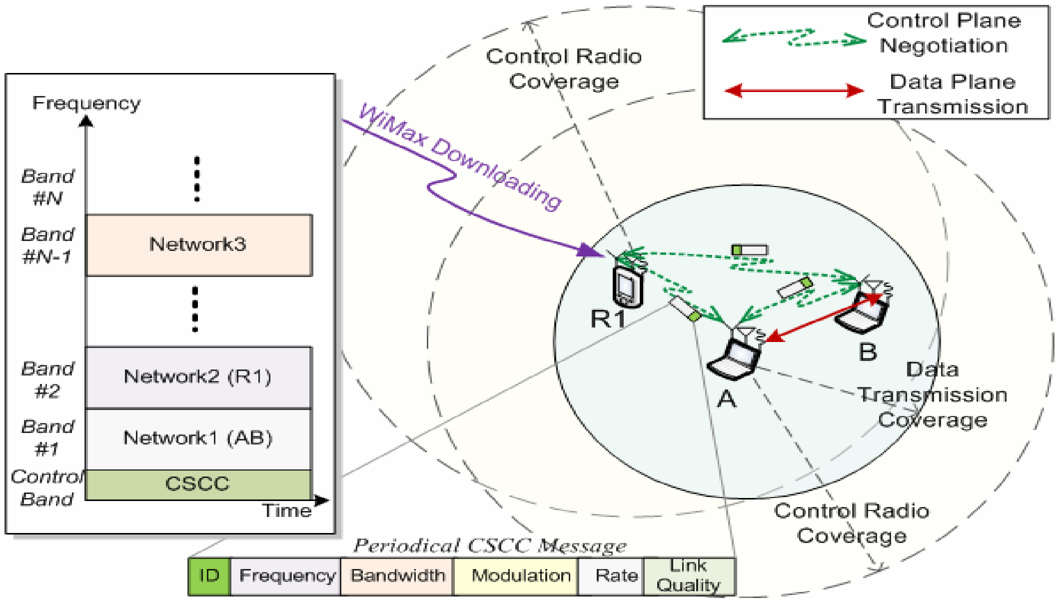


Fig. 3 The CSCC spectrum etiquette protocol.

The CSCC protocol is based on a common signaling mechanism, which can be implemented either using a common control channel at the edge of the shared spectrum, or in a control mode (time slot) where the same radio can periodically switch back and forth between control and regular communication states. In the example of Figure 3, the CSCC protocol uses Channel 1 of the 2.4GHz ISM Band for 1 Mbps IEEE 802.11b communication as the basis – in a multi-radio system, this means that each platform must be capable of periodically tuning to the specified CSCC channel to obtain control information. Spectrum and radio usage information are exchanged via CSCC messages which contain information such as node ID, radio type, center frequency, bandwidth, transmit power, data rate, modulation type, service type, etc. It is also possible for radio nodes to aggregate information received from other neighboring radios and forward them to create a global awareness of radio resource usage among nearby platforms. Thus, radio nodes can explicitly execute coordination algorithms and adapt their transmit parameters by using appropriate distributed algorithms that exercise control over the radio's operating frequency, time duty cycle or power level. Hidden node problem can be overcome if the control radio coverage is several times wider than the typical data-path radio coverage (i.e., lower-rate, higher power robust modulation schemes), as shown in Figure 3. In our prior work, we have studied co-existence between IEEE 802.11b and Bluetooth using an experimental prototype setup [21], demonstrating 30-40% performance gains. We have also applied CSCC to hypothetical co-existence scenarios with WiFi and WiMax radios sharing the same unlicensed band [9,10], again identifying significant capacity gains relative to simpler reactive schemes.

2.4 Spectrum Coordination Algorithm – An Overview

CSCC creates regional awareness by allowing information exchange over control channels. It acts as an information service to gather necessary information for coexistence interference analysis and guiding radio control. For example, we can collect time schedule (e.g., start time and end time of next transmission or reception), spectrum / energy profile (e.g., channel width, central frequency, modulation, power, Source Rate). Distributed spectrum coordination algorithms then listen to these collected information from radios within range, and back off their transmission parameters to avoid contributing excessive interference to the network. Three CSCC based source rate adaptation algorithms: BT Defer Transfer (BT-BO), BT Rate Backoff (BT-RT), and SIR-based Coordination (SIR-BT) are proposed in our work and have been evaluated on the Orbit testbed with ~1-20 radio. These algorithms define rules and procedures that each device has to follow in a distributed way based on a QOS/Coexistence policy for the node. To mediate the discussion and lead to evaluations, we tailor the coordination algorithms for IEEE 802.11b/g and Bluetooth dual-radio platforms, which is the most commonly found multi-radio platform. The details of the algorithms and implementation are discussed in chapter 3.

Chapter 3

Distributed Spectrum Coordination Algorithms

3.1 Bluetooth Adaptation to Favor WiFi and Network Throughput

Through repeated experimentation and evaluation, for more than 5 different topologies, it was found that, for the particular case of 802.11g – Bluetooth coexistence, under no spectrum coordination, there is a drop of 60-70% throughput of WiFi whereas Bluetooth radio only suffers by 30-40%. Hence as part of the design decision, the low rate (~100's of Kbps) Bluetooth radio is compromised at the cost of high rate (~1000's of Kbps) WiFi. This ensures a boost to the overall network throughput in a Bluetooth-WiFi scenario and also compensates the badly affected WiFi (60-70%) against the better performing Bluetooth radio which is due to the frequency hopping of Bluetooth.

3.2 Basic Adaptation Algorithms

In the basic version of adaptation algorithms, we have designed two non-intelligent, conservative adaptation schemes namely Defer transfer (Bo) and Rate Backoff (Rt). In both these schemes, the information needed from the CSCC protocol is bare minimum and hence the associated overhead for both these schemes is the least. In these basic schemes, one of the radios is made to adapt its source encoding rate depending on the interfered radio node's activity. In this approach, the only information required is the starting time and ending time of every session of the neighboring interfered node.

Once the start and end times are known, Bo and Rt schemes are aware about the potential interferer's session activity at application level and calculate the appropriate source encoding rate for its radio. Specifically in our case of dual-radio BT-WiFi scenario, Bluetooth (BT) radio listens for the session activity information from neighboring WiFi radios through CSCC and adapts its source encoding rate depending on the number of WiFi interferers and duration of activity.

3.2.1 Defer Transfer Scheme:

Let us consider the multi-radio scenario shown in Fig. 4, where each device is equipped with one IEEE 802.11b/g radio and one Bluetooth radio. The CSCC protocol can be run over a simplified-radio (e.g. operating at 900MHz band) and exchanges the control packet specified in Fig. 4 periodically. We emulate this common radio channel in our ORBIT experiments by using a low bandwidth logical channel over wired Ethernet connections. Each device exchanges its (data) radio parameters using the CSCC protocol to allow for coordination of transmissions.

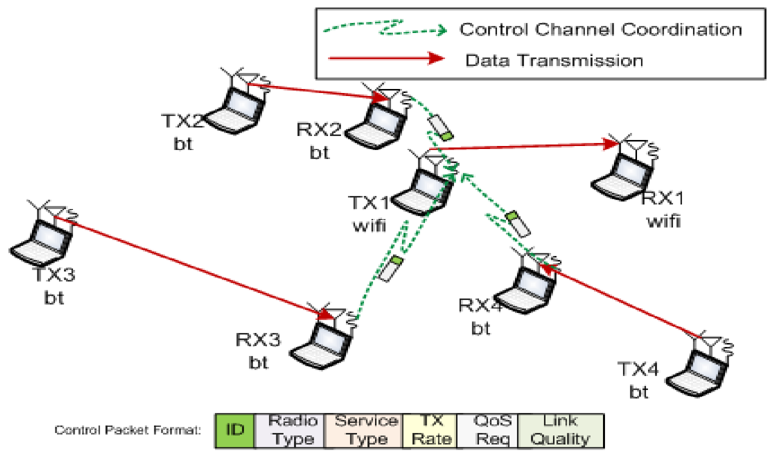


Fig 4 CSCC protocol in an IEEE 802.11g and Bluetooth coexistence scenario.

The simple algorithm to avoid interference is to allow radios to reserve the channel for duration of a session, which is on the order of seconds. Specifically in our case, Bluetooth radios (low rate, preempt-able) will have to avoid to WiFi radios' (high rate, preferred) communication to reduce interference. When a Bluetooth device receives a periodical CSCC control message indicating an ongoing WiFi reception, be it between its neighbors or involving its own platform, the Bluetooth transmitter will be turned off during the session period WiFi receiver is supposed to be receiving. The underlying conservative assumption with this algorithm is that any BT transmission will prevent proper WiFi reception. The variation on this on-off scheme is called BT Rate Backoff and explained in the following subsection.

3.2.2 Rate Backoff Scheme:

As an extension to the BT defer transfer algorithm, we can allow BT radios to backoff its source encoding rate or in turn its airtime to reduce interference, but still guarantee certain levels of minimum BT service rate requirements. The proposed rate-backoff algorithm allows Bluetooth transmitters to control its source rate in a cooperative and distributed way. The CSCC protocol can overcome the hidden node problem where each node explicitly announces operating parameters in its active state using a common signaling channel, thus transmitters are able to detect the existence of hidden receivers within their interference range. Each BT transmitter will calculate its source rate based on the observation of the control channel and knowledge of the activities in its neighborhood. Necessary rate backoff will be executed when hidden receivers are discovered based on a cooperative model, which first applies to only BT transmitters. We plan in the future work to apply this algorithm to both Wifi and Bluetooth transmitters.

3.3 Operating Region for Coordination Schemes

Fig. 5 shows a coexistence region defined as the feasible set of (total) Bluetooth and WiFi service rates for a given network topology. Any given CSCC algorithm will aim to support operation at the upper end of this region, and will balance between BT and WiFi throughput to satisfy service level performance criteria. Simple priority schemes, for example backing off BT source rate when WiFi is detected, will tend to position system performance at the bottom right, while favoring BT will push the operating point to the top left as shown in the figure. More complex strategies (outlined briefly below) can be devised to provide the desired balance in BT/WiFi performance ideally achieving some level of balanced performance for both the device.

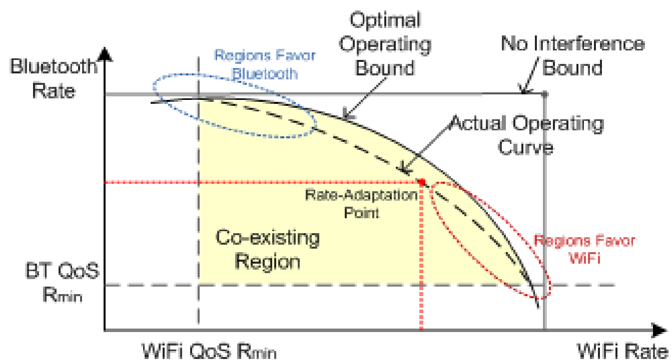


Fig. 5 Coexistence Region of Operation for BT-Wifi

We assume Bluetooth has audio type CBR traffic with different levels of service rate quality, which are defined using the streaming rate from 64Kbps up to 512Kbps. The rate-backoff algorithm requires BT transmitter to reduce its service rate when WiFi receivers are detected using CSCC protocol. Each time when there is a WiFi receiver detected, the BT transmitter reduces its service rate by one level until reaching the lowest level of streaming. To address the interference in the same platform, when a co-located WiFi radio is receiving, the BT transmitter will always transmit in the lowest service rate. When there is no WiFi receiver detected, the BT transmitter will work in the highest service rate to make the most use of the available channel.

3.4 Pros and Cons of BT-BO and BT-RT

Both the schemes are highly conservative and their intrinsic simplicity is due to the assumption that any Bluetooth transmission will cause interference to the WiFi session. In these schemes, without any knowledge about the distance from the interfered node, power levels and SINR available at the interfered receiver, the bluetooth radios compromise on their service rate. Due to this simple approach, advantages are

- Overhead of information exchange is only few bytes and corresponding performance improvement is by a factor of 60-100% for overall network and WiFi throughput.

While the disadvantage is that

- The bluetooth radio is unnecessarily over-compensated in the cases when it is not contributing significantly to the WiFi interference. Thus bluetooth adaptation is not commensurate with the interference that it offers.

Hence a more advanced and efficient scheme is proposed below with better correlation between the service rate adaptation and the corresponding interference contributed.

3.5 Advanced Adaptation Algorithms

These are schemes which try to operate in a more balanced region on the co-existence region curve shown in figure 5. This can be achieved by sharing more information about the neighboring network devices such as the source encoding rate, transmission (link) rate: both of which control the effective duty cycle of the radio, transmission power, QOS requirements of a radio such as delay and throughput requirements etc. With more information, a need based adaptation policy can be formed and the adaptation would achieve a balanced performance for all the radios in the network. In this genre, we have designed an SIR based source rate adaptation for bluetooth radios that ensures bluetooth service rate adaptation only when it is of utmost necessity.

3.5.1 Distance Based SIR: SIR-BT

Signal to Interference Ratio based coordination scheme is another CSCC based approach where service rate adaptation at a bluetooth transmitter is based on the observed SIR contributed at the neighboring receiver belonging to a different network (WiFi). The overall objective of rate adaptation is to maximize the signal to interference ratio at the interfered receiver (WiFi) while maintaining the minimum service rate requirements at every node in the network.

SIR observed at each receiver is theoretically calculated using the information shared by the neighboring transmitters through CSCC. An example of SIR-BT Adaptation is shown in Fig 6 where a WiFi Receiver collects the nearby Bluetooth transmitter’s activities. The coordination information exchanged from nearby transmitters is the not same as in the basic adaptation schemes discussed above. Now each node in the network communicates:

- Session on-time
- Session duration/off-time
- Source encoding rate or service rate

Using CSCC information such as service rate, radio type, and distance of the interferer (which can be determined in ORBIT, in real world SIR of heterogeneous radios can be approximately estimated using the control channel RSSI values), the Interference caused by the Bluetooth transmitter is theoretically calculated as shown in the algorithm below. With aggregated information from all interfering bluetooth transmitters the total Interference and hence the SINR is calculated at the WiFi receiver. The optimum service rate for co-existence, for each Bluetooth transmitter is then derived using the calculated SIR above and a predetermined link budget SIR threshold value. This information is updated by the WiFi receiver to the neighboring BT transmitters using Rate update packet as shown in Fig.6 below.

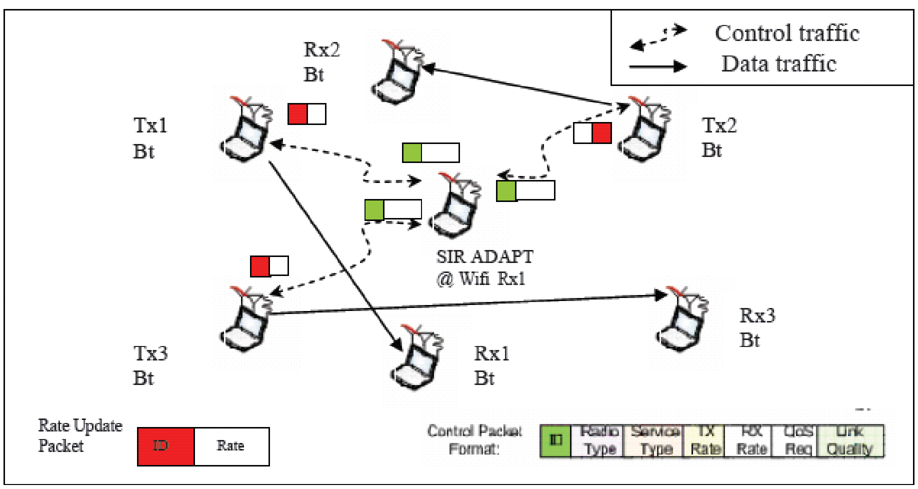


Fig. 6 SIR-BT Rate Adaptation for Wifi/BT Coexistence.

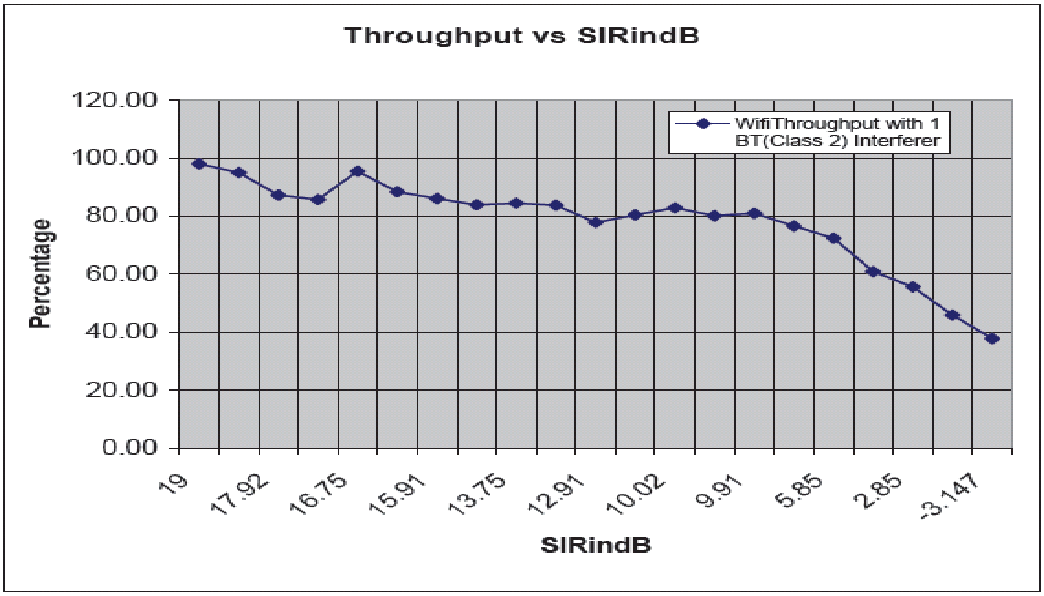


Fig. 7 Throughput vs Distance based SIR curve for 802.11g with BT (Class 2) Interferer.

An initial experimental evaluation to arrive at appropriate link budget SIR threshold for WiFi-BT dual-radio scenarios was carried out in orbit in auto transmission mode. The setup consisted of one pair of WiFi-802.11g and Bluetooth (class 2), in which experiments revealed a steady >75% WiFi-802.11g throughput for SIR >10dB at WiFi receiver, as shown in Fig.7. Optimum service rate vector for the interfering Bluetooth transmitters is calculated in such a way that the corresponding SIR meets the SIR link budget threshold value. SIR link budget was experimentally evaluated to be 10dB for auto transmission mode, which is, in line with link-budget expectations for 802.11g OFDM modulation in Auto transmission (10 dB is roughly the mean value between 23dB(54Mbps) and 0 dB(6Mbps) for OFDM).

The objective function and the set of constraints along with the optimum service rate determination protocol are given below.

While (SIRj($\vec{R}$) < SIR_linkbudget_threshold)

{

Maximize SIRj($\vec{R}$) where

$$SIR_j = (P_t - lp) - I_j(\vec{R})$$
$$I_j(\vec{R}) = 10\log(\sum_{i=1}^{N} I_{ij}(R_i))$$
$$I_{ij} = 10^{[(P_i - lp(d_{ij}) + 10\log(R_i / R_t))/10]} \forall i = 1, 2, 3....N$$
$$lp(d_{ij}) = 40 + 10 * \alpha * \log(d_{ij}) where \ldots \alpha = 2$$

Subject to:

$$R_{\max}(Qos\_Max) >= R_i >= R_{\min}(Qos\_Min)$$
$$where \ldots \vec{R} = [R_i]_{1xN_{BT}} \forall i = 1, 2, 3 \ldots N_{BT}$$

}

In the equations above, N_{BT} is the number of active Bluetooth transmitters detected by WiFi receiver j and Ri is the optimum service rate calculated by the Wifi receiver j for each of i Bluetooth interferers and updated through rate update packet sent from j. $\vec{R}$ is the vector representing service rates of all the N_{BT} active Bluetooth transmitters. This approach ensures an optimum WiFi performance by maintaining an SIR >= SIR_linkbudget_threshold whenever possible and also invoke a bluetooth rate adaptation commensurate to the interference levels observed at the nearby WiFi receiver. This algorithm has been tested in 5 different scenarios. The results show an average of > 20% improvement in overall network throughput in each of the scenarios, along with greater mutual co-existence which is represented by >10% growth in both the Bluetooth and Wifi-g network throughput. The source rate adaptation is planned to be extended in future, for WiFi radios as well, to favor bluetooth communication as and when required for fairness.

3.5.2 Pros and Cons of SIR-BT

The advantages of the SIR-BT scheme are:

- It's a more balance approach and Bluetooth radio is compromised only when its interference affects the SIR at the WiFi receiver and in the rest of the situations both Bluetooth and WiFi co-exist with marginal degradation.
- It gives a better handle to control the operating point on the co-existence region curve by adjusting the link budget SIR threshold value.

One of the major disadvantages of this distance based SIR approach is its applicability to the real world scenario. In real world setups, devices cannot determine accurately the distance and propagation constant which are two essential parameters for SIR calculation. The closest approximate of SIR for a heterogeneous radio that can be obtained is using the control channel RSSI values. Again here the assumption is that the control channel and data channel have similar fading/path loss model. Therefore one could think of the distance based SIR scheme as the ideal upper bound for any real world estimated SIR scheme and provides results for maximum throughput that could be achieved in any SIR based multi-radio coordination scheme. Distance based SIR-BT used here in particular is asymmetric and favors the WiFi more than the Bluetooth, hence only with a symmetric distance based SIR scheme where both bluetooth and WiFi adapt, a perfect balance can be found, which would be part of the future research.

Chapter 4

Experimental Setup and Results

4.1 Methodology

An experimental methodology has been adopted for this project in view of the relative lack of realism in available ns2 simulation models. We believe that a dense radio environment is particularly difficult to model accurately and therefore made a decision to use the ORBIT testbed for at-scale realistic evaluations.

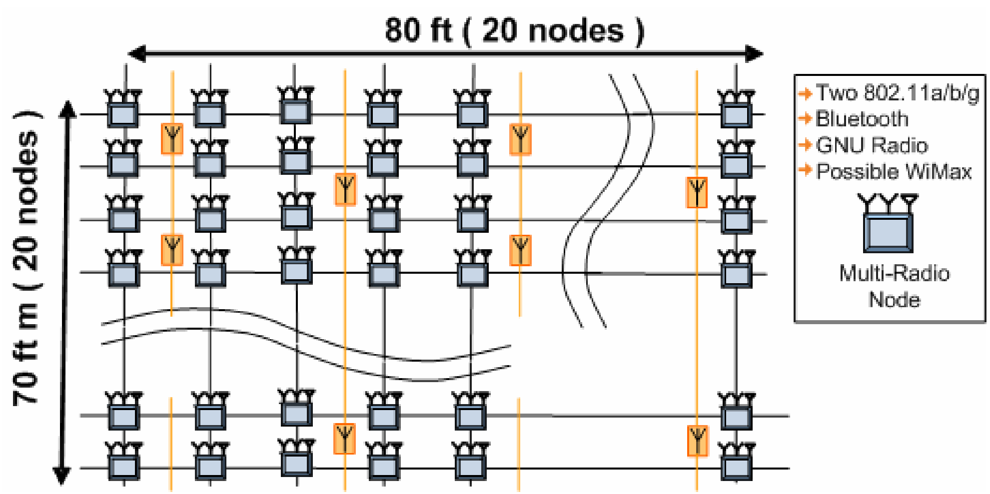


Fig. 8 ORBIT multi-radio grid testbed

Multi-radio nodes are available in the ORBIT radio grid, shown in Fig. 8, which are equipped with two 802.11a/b/g radios, Bluetooth, Zigbee, GNU radio, etc. Other radios such as WiMax may be added later depending on availability of suitable interfaces and Linux drivers. Control signaling can be implemented using the wired support network or a specific 802.11b channel (e.g. Channel 1) on one of the dual WiFi radios at each node. The coordination algorithm module is designed to be flexible so that a variety of alternative priority, rate backoff or scheduling strategies can be tested. Both TCP (file transfer) and UDP (VOIP streaming) applications are considered in the study since the traffic type (elastic vs. inelastic) is expected to have an effect on achievable performance.

4.2 Experiment Parameters

- Traffic type and Session duration:
    - Bluetooth radios in real world are extensively used to carry voice and/or audio data over UDP, hence in our experiments all Bluetooth radios exchange continuous audio data encoded at different service rates [64kbps, 128kbps, 320kbps, 512kbps and 1 Mbps] for 1 minute over UDP Transport protocol.
    - WiFi-802.11g radios are used for predominantly www/http browsing, file transfer, audio/video streaming with random on/off session, hence in our experiments all WiFi radios exchange data over UDP in multiple sessions each lasting for 10 seconds and a random/fixed off period in between. To study TCP file transfer performance, a 1MB file is being exchanged between the radio pairs over TCP and the total time to transfer is monitored. Similarly, to study the effects of audio/video stream performance, VLC application is used as the audio/video stream server/client at WiFi terminals respectively.
- Power levels
    - Bluetooth radios operate at 4dBm in order to replicate the real world Bluetooth dongles/headsets which are low power 0 or 4dBm predominantly.
    - WiFi-802.11g radios transmit at 18dbm
- Wireless settings at each node
    - WiFi-802.11g operate at two transmit modes Fixed 36Mbps and Auto. Each WiFi radio link use atheros card (AR5212) operating in channel 11 set in adhoc mode.

Table below lists all the radio parameters used in the setup

	Data Radio Service	
PHY Type	IEEE 802.11g (Atheros AR5212)	Bluetooth (Belkin / IOgear USB Dongle)
Frequency	2427-2447MHz	2402-2483.5MHz
Modulation	OFDM (256 FFT) QAM	GFSK + FHSS (DQPSK for EDR)
Transmit Power	18dBm	4dBm (~20m) (class 2) 20dBm (~100m) (class 1)
PHY Rate	Up to 54Mbps AutoRate and Fixed Rate 36Mbps	Upto 1Mbps (class 2) Upto 2.1Mbps (class1 w/ EDR)
Data session	Pareto ON/OFF variable rate CBR: 5 sec random session	Constant audio streaming (64,128,320,512, 1024kbps)

Table 2 List of ORBIT Experiment Parameters

4.3 Experiment Scenarios

The following figure shows the experiment scenario used in ORBIT testbed with a total of 400 wireless nodes spread over a 60x60 sqft area. Some of the nodes have multiple radios including Bluetooth and WiFi. A picture of one node is shown in Fig. 9(a), and we can see a Bluetooth USB dongle is used, with a separation from WiFi antenna of about one foot.

Fig. 9(b) shows the experiment setup where we use both class 1 and class 2 Bluetooth nodes and the data transmission is pair-wise, i.e., when a BT transmitter transmits, the WiFi receiver will receive. This evaluates the worst interference scenario. Fig 9(c-f) are setups with class-2 Bluetooth (low power) and 802.11g radios which evaluate inter-node interference due to proximity located interferers. The experiment parameters are shown in Table 2. For WiFi traffic, we consider random ON/OFF type CBR sessions with randomized session intervals. The Bluetooth traffic is a CBR type traffic representing audio streams with different service levels.

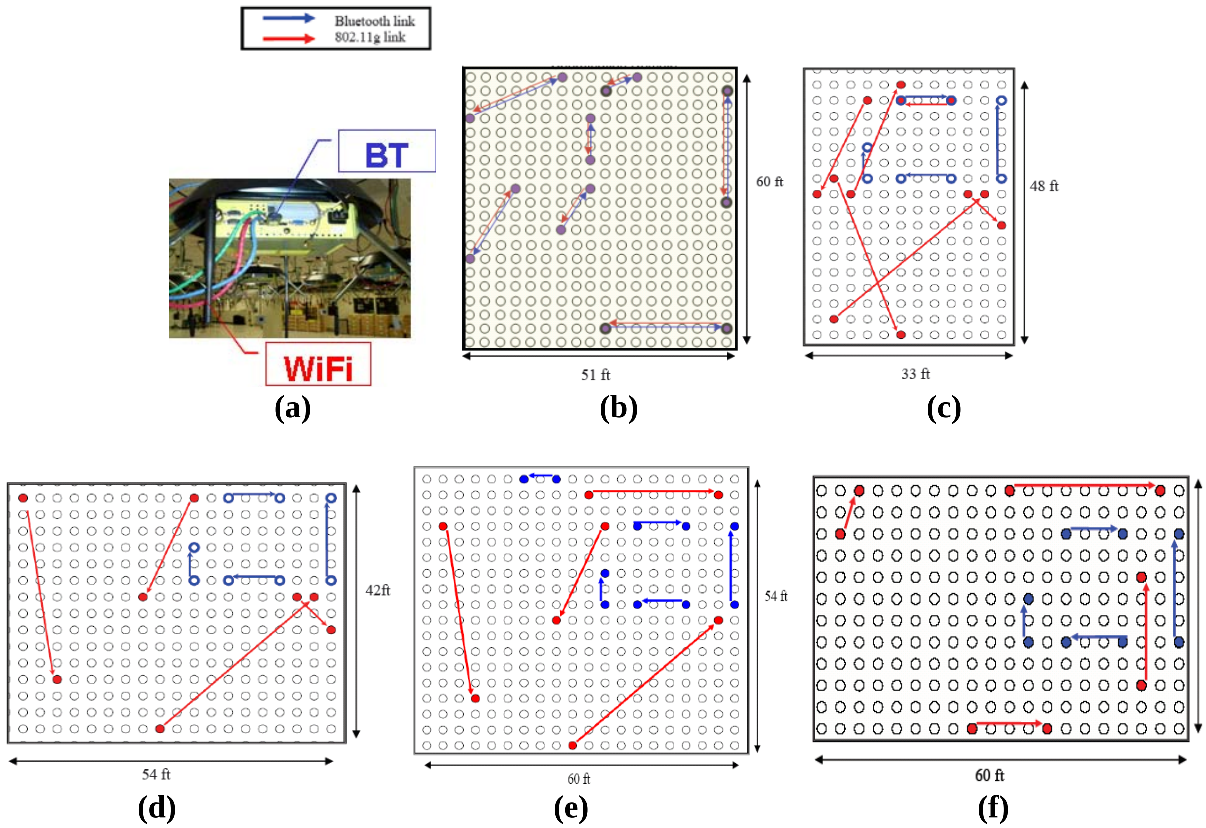


Fig. 9 Experiment Scenarios
9(a) Physical ORBIT multi-radio node
9(b - f) Evaluation Scenarios/topologies 1 through 5

The red arrows indicate the WiFi-802.11g link and the blue represent the Bluetooth pairs. Each Scenario is uniquely characterized by the size of the topology, number of radios present per 100 sqft area (density of topology) and the types of radios present. Since ORBIT consists of 400 radio arrangement, it is possible to select any such random distribution of radios with a particular density in mind.

4.4 Experiment Results

4.4.1 Results illustrating effects of uncoordinated Bluetooth-WiFi-g scenarios and the need for Distributed Spectrum Coordination

In order to study the need for coordination and efficient co-existence algorithms, multiple WiFi-g and Bluetooth radios were thrown in different small office/home situations and their individual throughputs were measured. The idea was to estimate the losses and effects of closely placed multi-radio platforms (WiFi 802.11g and Bluetooth) in the absence of any spectrum coordination. For this the scenarios/topologies shown in Fig 9(b-f) were used. The following figures 10(a) and 10(b) show the Co-existence effect/losses on WiFi and Bluetooth respectively. From, the experiments it was seen that in the absence of spectrum coordination, due to proximity interference (inter-radio interference), the WiFi overall session throughput drops by 50-60%, while Bluetooth's drops by 25-40%. The Fig 10(a,b) is averaged over 4 topologies shown in Fig 9(c-f). Bluetooth radio is able to get more packets across without interference than WiFi due to frequency hopping.

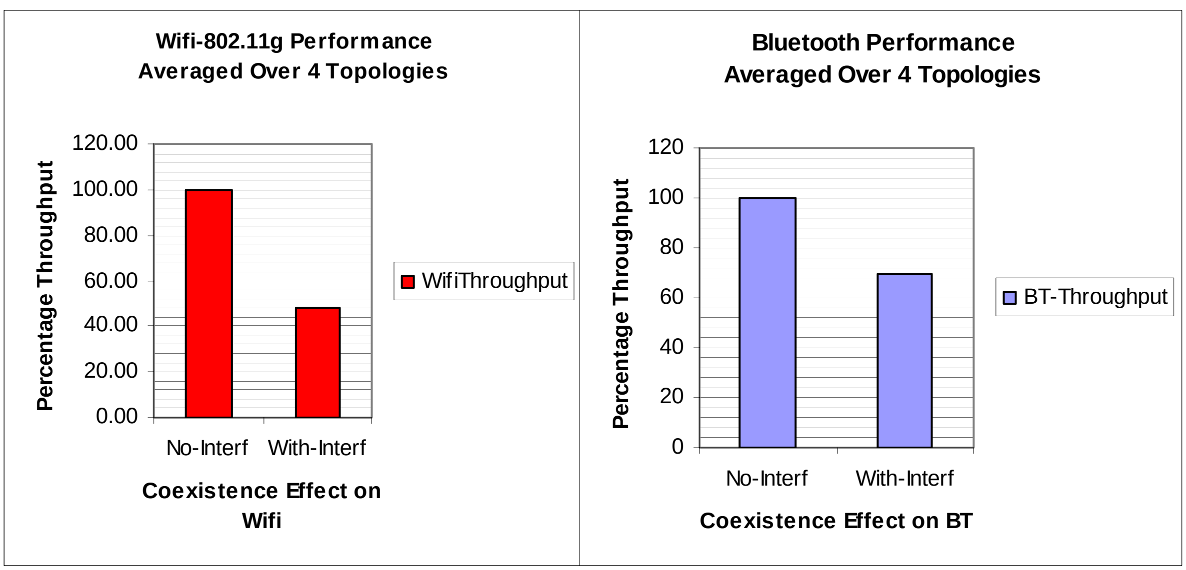


Fig 10(a) Coexistence Effect on WiFi session throughput (b) Effect on Bluetooth throughput

Similarly to study the effect on delay in TCP file transfer time, topology 4 in Fig 9(e) was chosen to exchange 1MB files across each WiFi link when the Bluetooth radios actively transmit audio streams close by. The time taken to transmit 1 MB file at each Wifi link was noted and the average time to transmit over all topologies is plotted below in Fig 11 under no interference and with Bluetooth interference case.

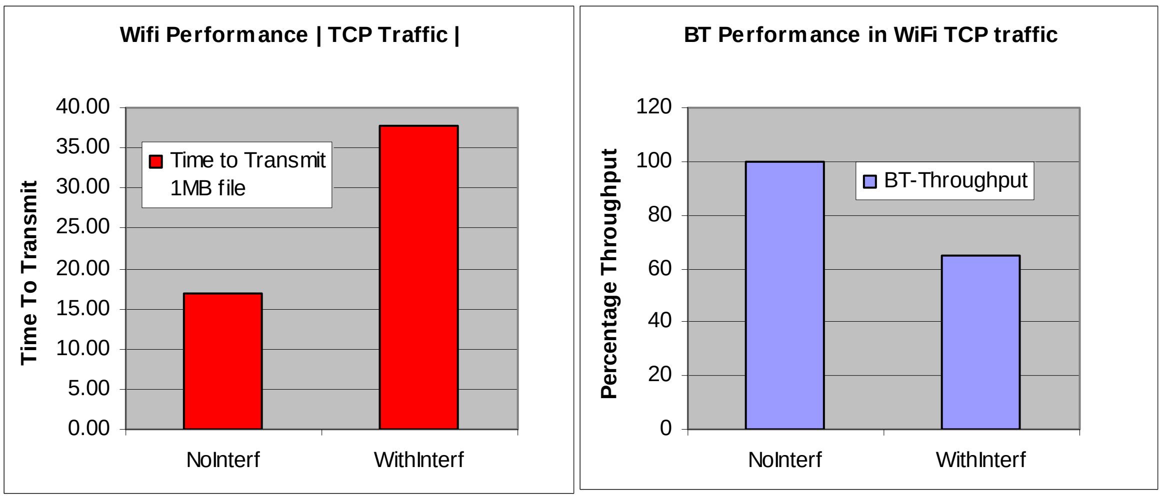
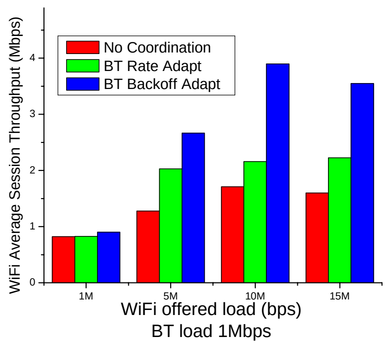


Fig 11 (a) Time to transmit (in seconds) a 1MB file between WiFi pairs (b) Bluetooth throughput with a background WiFi TCP 1MB file transfer operation.

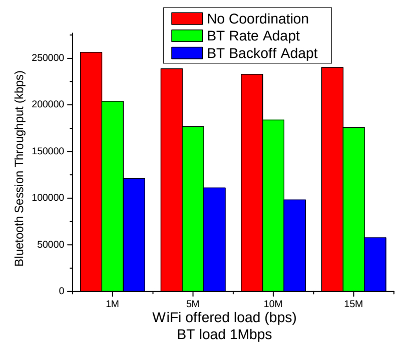
From the experimental results shown in Fig 11(a), we see that for TCP, time to transfer a 1MB file more than doubles from 15 second to 38 seconds on an average at all the WiFi nodes for all the topologies evaluated. This result is significant and it indicates the adverse effect of inter-node interference. Our results experimentally verify the fact that the average user download times would double with interference from Bluetooth under no coordination. Thus these results corroborate the fact that multi-radio platforms that are located close enough as is common in office/home scenarios cause significant degradation in performances and motivate us to do a detailed experimental study on distributed spectrum coordination schemes for such scenarios.

4.4.2 Results for BT-Bo and BT-Rt Schemes in Topology 1

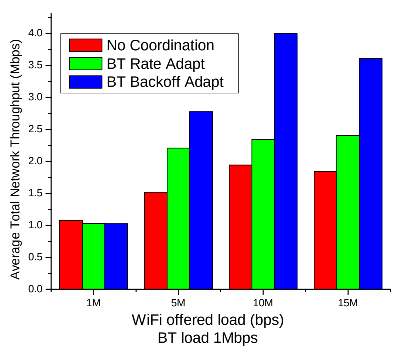
Experimentally obtained throughput measurement for Wifi sessions, Bluetooth data streams and total network throughput are plotted in Fig. 12(a-c), and the percentage throughput improvement is shown in Fig. 12(d). In this proof-of-concept setup, we have implemented BT-Bo and BT-RT backoff approach in which BT transmitters tries to avoid high rate WiFi-g system by changing its service rates as mentioned in chapter 3.



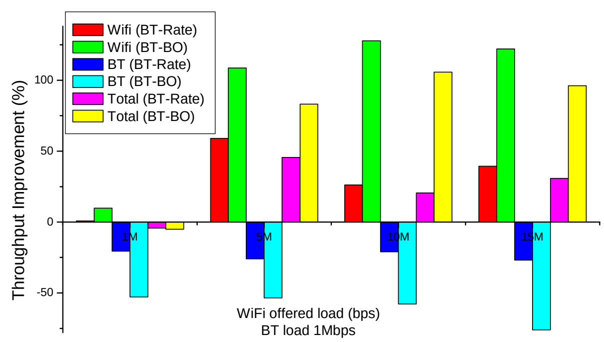
(a)



(b)



(c)



(d)

Figure 12 Experiment results for Throughput vs. WiFi loading rate. (a) WiFi session throughput (b) BT throughput (c) Average total network throughput (d) Throughput improvement for each case

The WiFi Session throughput is measured at each receiver and averaged over all the WiFi receivers and same is the case with Bluetooth throughput. The setup consisting of 8 dual-radio platforms as shown in Fig 9(b) is used for this case and the WiFi offered load is varied with each iteration keeping the Bluetooth offered load at maximum (1 Mbps).From Fig. 10(d), it can be inferred that by backing off Bluetooth (Defer Transfer scheme), Bluetooth completely shuts down but at the same time we can obtain between 30-100% improvements in WiFi and Total network throughput. The “BT-Rate” scheme while achieves a better operating point for both systems, with a moderate 20% degradation for Bluetooth throughput, while WiFi-g throughput improves up to 50%.

Thus BT-Rate scheme can be used to arrive at a more balanced approach than the BT-Bo scheme. But intrinsically this scheme performs same as the Bt-Bo scheme when number of active interferers (WiFi-g) is greater than or equal to the number of possible service rates (64,128,320,512,1024 kbps) that Bluetooth can choose to encode.

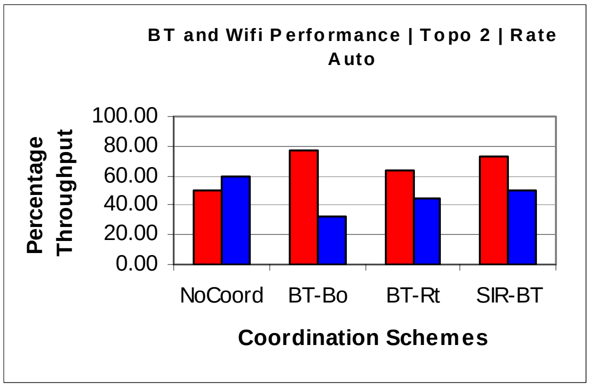
In both these schemes, Bluetooth is being over compromised and hence there is a need for a more advanced, balanced approach which would be based on the interference level based rate adaptation.

4.4.3 Results for SIR-BT(Distance based) Scheme and Comparison with BT-Bo and BT-Rt

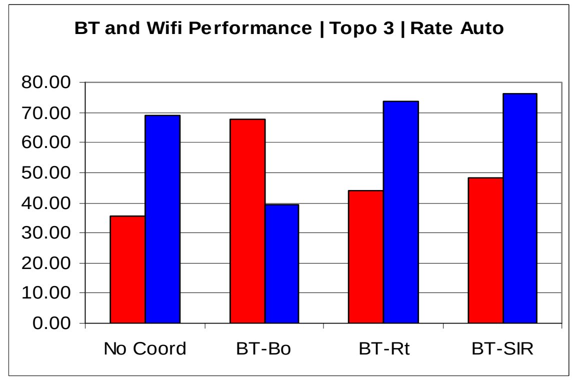
SIR-BT algorithm proposed in chapter 3 is tested in 4 different scenarios as shown in fig 9(c-f) with 16-18 radio dense topologies. The 4 topologies help to study the effects of inter-node interference, overhead involved and ability to coordinate multiple proximity located devices with minimum or no in-platform interference.

Experimental throughput achieved for SIR-BT coordination scheme for different SIR_link budget threshold values, BT-Bo and BT-Rt is plotted in Fig 13(c-f). Results in Fig 13(c-f) correspond to the scenarios discussed in Fig 9(c-f) respectively. The throughput is plotted with respect to the no interference scenario in percentage. For example, in the absence of any Bluetooth interferers, the WiFi session’s average throughput is measured and that is treated as the baseline for the other experimental throughputs measured with different interference scenarios. Similarly for Bluetooth, the baseline result is obtained in the absence of WiFi interferers.

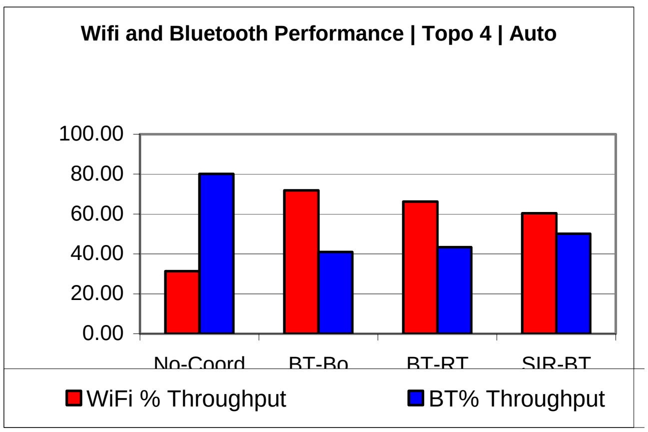
SIR-BT approach essentially is designed to improve WiFi throughput by ensuring that a particular level of Link budget SIR value is maintained at the WiFi receiver. Bluetooth is compromised only when the SIR at the WiFi receiver does not meet link budget constraints. Hence only depending on the amount of interference contributed by the Bluetooth node, Bluetooth service rate adaptation is carried out. This leads to significant improvement in both BT and WiFi network throughputs when compared to the basic BT-Rt(Rate Back off) and BT-Bo(BT Defer Transfer) schemes as shown in Fig 13(c-f).



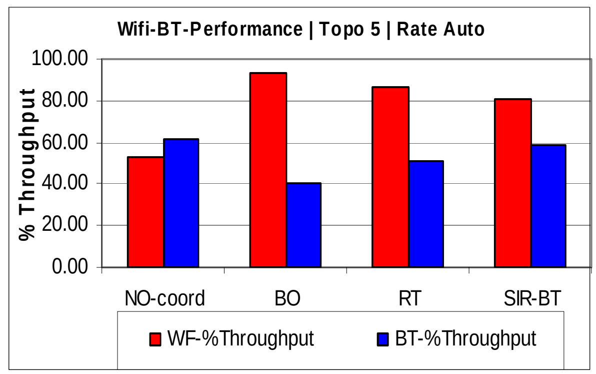
(c)



(d)



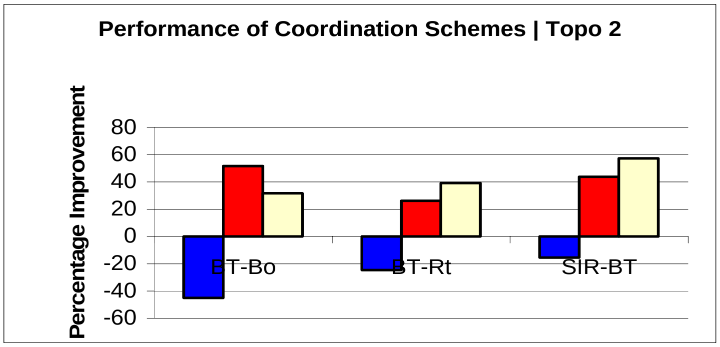
(e)



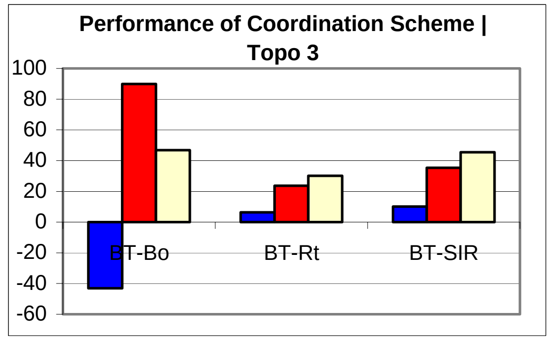
(f)

Figure 13 Results for WiFi-BT throughput vs. Coordination Scheme, Fig 13(c-f) correspond to Topologies 9(c-f)

Fig 14(c-f) shows the overall performance of each coordination scheme with respect to the no-coordination (complete interference) case. The negative scale implies the drop in performance due to a particular scheme when compared to the no-coordination. The results in the experiments show that SIR-BT scheme for appropriately chosen SIR_link_budget threshold value provides, on an average, 50% improvement in throughput for the overall network, while maintaining a balanced Bluetooth and WiFi performance. For example in Fig 14(c,d) we see that, the network is operating at a more balanced region on the curve in Fig 5. Bluetooth throughput is improved by 10-15% when compared to BT-Rt and WiFi is improved by 20-30% resulting in a overall improvement of 30-40% in the Total network throughput for SIR-BT scheme in Topology 2 & 3.



(c)



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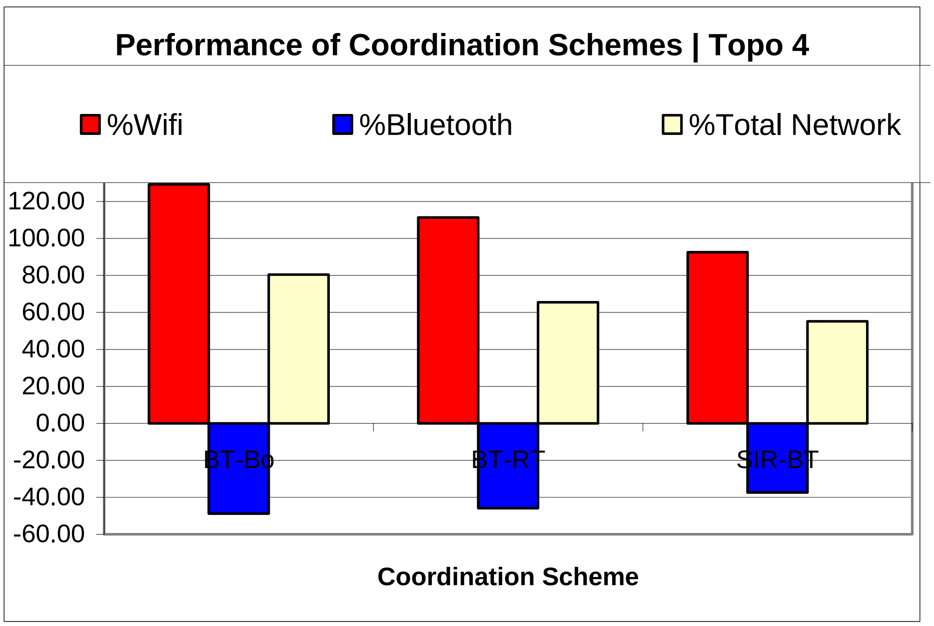
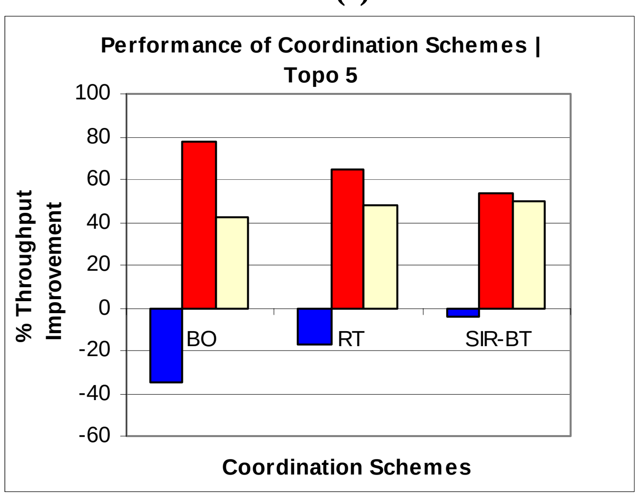


(e)



(f)

Figure 14 Percentage Improvement in (BT, Wifi, Total Network) Throughput vs Coordination Schemes

4.5 Choice of SIR link budget threshold value

In our SIR-BT scheme, the SIR_link_budget threshold for the WiFi receiver is chosen such that:

- For auto transmission mode, SIR_linkbudget_threshold = ~10dB.
- For fixed transmission mode of 36Mbps = ~16dB

Experimentally it was determined that only around these SIR_link budget threshold values, the overall network throughput for bluetooth and WiFi is high. For WiFi (IEEE 802.11g) and Bluetooth (class 2) dual radio experiments revealed that 10dB of an SIR budget at WiFi receivers resulted in a worst case maximum of 25% deviation from the throughput that was achievable in the absence of any interference as shown in fig 7. Theoretically too, it is well known that for the 802.11g OFDM, the SIR thresholds in dB for different modulation schemes is found to be 4-7 dB for 6-9Mbps, 10-13dB for 12-18Mbps, 16-19 dB for 24-36Mbps and 19-25dB for 48-54Mbps.

4.6 Sensitivity of SIR Link Budget Threshold Value

To study the sensitivity of the threshold values, Multi-Radio scenarios where tested for different SIR threshold values (around 10dB for auto and around 16 dB for fixed transmission modes) as shown in fig 16. Experimental results thus confirm that this threshold value is not meant to impose any hard limit but the SIR_linkbudget threshold values serve mainly as pointers to the section of operation region on curve in Fig 5 with a balanced Bluetooth and WiFi network performance. Experimental results confirm low sensitivity to exact values of the SIR budget, thus making practical implementations for adaptation feasible.

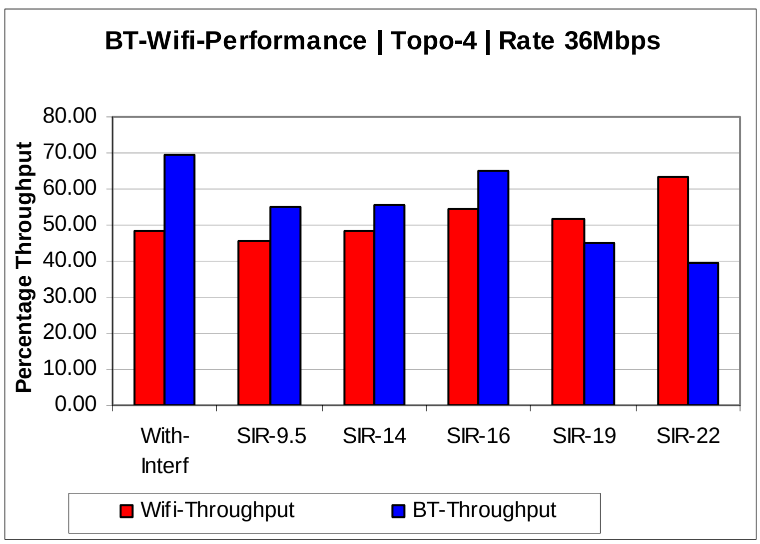


Fig. 16 Sensitivity of SIR_link_budget around 16dB for fixed rate 36Mbps

4.7 Overhead Calculation

The overhead involved in our approach is in terms of memory and bandwidth requirements for control data exchange through CSCC. The control channel itself could be viewed as a separate cheap control radio for example, 802.11b or a reserved channel in 802.11g (WiFi radio). We have used Ethernet between the radios as a control channel in our experiments. Since memory is no more a bottleneck with modern devices having gigabytes of cheap storage space, bandwidth requirement becomes critical.

Table 3.0 lists the overhead in terms of bandwidth required for control CSCC data exchange payload. Since the size of CSCC packet structure at each radio is 11+16*n bytes, which in dual-radio case is 43 Bytes and they are exchanged periodically every second leading to 43*8*N = B bps of Control bandwidth, where N is the total number of radios in the network. Thus the overhead is negligible when compared to the gains as seen from the table. This overhead computation is only w.r.t payload of CSCC. Additionally in real world setups, there would be overhead due to the physical layer chosen, like the Ethernet overhead or the 802.11b overhead.

	Control Data Size(CSCC Packet)		**Total Control Data per second**	**Throughput**		**Overhead ratio (%)**
				Without Coordination	**With Coordination**	
# of radio nodes K	**Fixed Part 11 bytes**	**Variable Part 16*N bytes (N=2 for dual radio setup)**	**B in bps**	**No Coordination (X in bps)**	**Bluetooth Backoff Coordination (Y in bps)**	**B/(Y-X)**
8	88B	256B	2752	1.59E+07	2.45E+07	0.03
16	176B	512B	5504	1.11E+07	2.26E+07	0.05
22	242B	704B	7568	1.6E+07	2.17E+07	0.13

Table 3.0 Overhead for the adaptation schemes due to CSCC protocol

Thus compared to the gains achievable in the CSCC based schemes, the overhead is marginal and can be neglected for all practical purposes.

Chapter 5

Conclusion, Future Scope and References

Conclusion

In this thesis work we have investigated the spectrum coexistence of multi-radio platforms in multiple dense radio environments, as a particular case for the dual-radio (WiFi and Bluetooth) platform scenarios. We use the CSCC spectrum etiquette protocol as a mechanism to allow spectrum coordination in a distributed way. In particular, we proposed three levels of spectrum coordination algorithms including Bluetooth defer-transfer, rate-adaptation and SIR-based (distance based scheme) adaptation. We have implemented a scalable radio-independent spectrum control and coordination service for efficient Multi-Radio Coexistence as hinted in [13]. We have also evaluated the proposed schemes in 5 different topologies. The Results show that

- BT-defer transfer algorithm can improve the total network throughput by 30-100% at the cost of Bluetooth performance.
- The “BT-Rate” scheme can achieve a slightly better operating point for both systems, with a moderate 20% degradation for Bluetooth throughput, while WiFi-g throughput improves up to 50%.
- The SIR based algorithm can improve BT throughput by a factor of 10-15% and simultaneously improve Wifi network by 20-30% when compared to the “BT-Rate”. SIR-BT(distance based) scheme ensures that the overall network operates in a more balanced region where both the networks (WiFi and Bluetooth) get their share of the bandwidth thus leading to upto 50% growth in overall network throughput.

In order to study the effect on other system parameters apart from throughput, TCP file transfer times and video/audio streaming application too were evaluated and the results presented. Also to comprehensively conclude the need for coordination and to prove the practicality of the performance gains achieved, the overhead involved in the CSCC exchange was calculated. The overhead in terms of bandwidth required for control channel was marginal when compared to the performance gains as shown in chapter 5.

Future Scope

In future work, further intelligence could be embedded in the CSCC adaptation algorithm and use the network awareness to carry out multi-radio data forwarding to facilitate cooperative coexistence. Also SIR-BT algorithm and Rate Back-off scheme can also be further enhanced to a closed loop format with self throughput feedback information. Other multi-radio platforms can be studied in the ORBIT testbed including radios such as WiMax, Zigbee and UWB with greater number of radios.

Open Issues

In all the CSCC exchanges, it is assumed to have cooperative devices sharing valid information. But in real-world scenarios, not all devices need to be cooperating and trustworthy. Hence a lot of security issues with information exchange need to be addressed in the CSCC spectrum coordination approach.

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