TRAFFIC SCHEDULING WITH EFFICIENT CHANNEL ASSIGNMENT IN WLAN MESH NETWORKS

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A THESIS
SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF APPLIED SCIENCE

McMaster University

MASTER OF APPLIED SCIENCE (2008)
(Electrical and Computer Engineering)

McMaster University
Hamilton, Ontario

TITLE:	Traffic Scheduling with Efficient Channel Assignment in WLAN Mesh Networks
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SUPERVISOR:	Dr. Terence D. Todd
NUMBER OF PAGES:	x,71

Abstract

Wireless mesh networks have received increasing interest in recent years due to the fast expanding Wi-Fi market. More and more, individual communities and companies are beginning to set up intranets with multiple Wi-Fi access points, so that clients can communicate using wireless connections. Because the traditional IEEE 802.11 standard cannot provide efficient performance for mesh networks, the IEEE set up a task group in 2001 to establish a wireless mesh network standard, IEEE 802.11s. For compatibility, IEEE 802.11s will be an extension of the IEEE 802.11 MAC/PHY, and as a result, the new standard has inherited both the pros and cons of IEEE 802.11.

Co-channel and inner-channel interference are the dominant factors affecting the system performance of wireless networks. Since there are a number of available non-overlapping channels one can always use these in order to eliminate inner-channel interference. However, the number of channels is not sufficient for an ESS Mesh if channel reuse is not considered, not only because of the network size, but also because of the non-licensed nature of the IEEE 802.11 PHY ISM band, where the network will suffer interference from other co-located networks. For this reason, channel reuse in an ESS Mesh is essential and reducing co-channel interference is a key issue in channel assignment.

In this thesis, we investigate the performance of deterministic traffic scheduling with channel assignment in an ESS Mesh based on a TDMA MAC framework while still using the IEEE 802.11 PHY. We first analyze an upper bound on channel assignment performance, considering both binary interference models and cumulative interference models. Then, a scheduling solution for deterministic traffic is proposed, based on heuristic channel assignment and path selection algorithms. Our simulation results show that the scheduling solution is feasible and the performance is close to the theoretical value.

Acknowledgments

First of all, I would like to thank Prof. Terence D. Todd, my master thesis advisor, for his support, encouragement and research ideas. My thanks also goes to Dr. Sasthi C. Ghosh and Mr. M.N.A. Smadi. I have benefited greatly from their help.

I also appreciate the help and support of Ms. Cheryl Gies, and the other administrative staff of the ECE department.

I also owe a huge debt of gratitude to my supportive wife, Ping Ai. She has kept me focused and confident during my toughest times, and I thank her for all her support, encouragement and love.

Finally, I would thank my adorable baby son Daniel and daughter Jenny, who have always been my source of happiness.

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Chapter 1

Introduction

Wireless Mesh Networks (WMNs) present an attractive decentralized, extensible infrastructure with the ability to interconnect different wireless local area networks (e.g., WLANs). This ability can be used to distribute excess bandwidth and minimize the number of Internet gateways required and consequently the cost associated with gateway management. Furthermore, being extensible over long distances, WMNs can reduce or eliminate the need for leased backhaul lines and reach areas where installing conventional cabling is impossible or cost prohibitive. Characteristically, WMNs are very reliable, since the transmitting node is only required to reach any peer on its one-hop list. This self-healing ability adds resiliency to WMNs and makes them feasible for a wide range of applications and deployable over a variety of terrain, including oil rigs, military battlefields, security surveillance, and disaster relief and rural areas.

The choice of radio is crucial in WMNs because it determines the number of channels, the interference, bandwidth available and frequency switching times. Since IEEE 802.11 is the de facto standard for WLANs, it is reasonable to assume that the first attempt of developing WMNs will resort to its use. The IEEE 802.11s group is carrying out an industry-wide effort to establish a standard for medium access control (MAC) and physical (PHY) layers for WMNs. The WMN based on IEEE 802.11s is also known as ESS (Extended Service Set) Mesh. However, IEEE 802.11 suffers from inherent contention overhead associated with CSMA/CA including DIFS, random backoff periods and hidden-terminal problems, in addition to the high overhead associated with the physical layer. Quantitatively, CSMA/CA capacity is around 60% of the bandwidth, which is considerably less than the theoretic 100% achieved by TDMA MAC. This improvement in overall system capacity may not justify the administrative overhead associated with TDMA systems in situations where non-real-time sessions can tolerate the 60% bandwidth utilization of CSMA/CA. However, as real-time traffic starts to constitute a higher portion of the arriving sessions, satisfying quality of service becomes an issue. Yet, real-time applications with deterministic packetization intervals can benefit from a circuit-switching setup where bandwidth is reserved for the duration of the session. One example of these types of applications is Voice over Internet Protocol (VoIP). Therefore, we consider using a hybrid MAC running over the conventional IEEE 802.11 PHY where the MAC frame is split into two subframes, one of which allows for setting up circuit-switching connections suitable for voice and other real-time sessions with deterministic packetization and arrival rates, and the other of which is for different traffic, including real-time flows, which do not have deterministic packetization and arrival rates. For example, we can define a superframe consisting of a ρ portion operating in TDMA circuit-switched mode and the remaining $1 - \rho$ portion operating in packet-switched mode.

In this thesis, we only consider the problem of session admission control (SAC) in the circuit-switched portion of the superframe operating in a TDMA MAC where we assume that the bidirectional session and its overhead require a single time slot in the frame. A session is admitted if it is guaranteed a slot over all the ESS Mesh links constituting the route from the source to the destination of that session. Since the conventional IEEE 802.11 PHY is suggested in this thesis, two features of the IEEE 802.11 PHY that may affect performance of our SAC have to be noted. First, as defined in the IEEE 802.11 standard, the number of channels is 12 in IEEE 802.11b/g and 52 in IEEE 802.11a. Some of these channels overlap, resulting in inter-channel interference. Although it is possible for two APs operating on different but overlapping channels to transmit packets, we only focus on non-overlapping channels in this thesis. Thus, the number of non-overlapping channels is reduced to 3 in IEEE 802.11b/g and 12 in IEEE 802.11a. Since IEEE 802.11b/g and IEEE 802.11a operate at different frequency bands with different modulation techniques, it is reasonable to assume that

IEEE 802.11b/g and IEEE 802.11a will not co-exist in our ESS Mesh design. Second, the IEEE 802.11 ISM band is license-free, that is, the usage of IEEE 802.11 channels is not controlled. Anyone can setup a BSS (Basic Service Set) WLAN or ESS Mesh with any channel defined in the standard thus causing spectrum pollution. Therefore, when designing an ESS Mesh, the number of available channels depends on not only the standard version we choose (IEEE 802.11 b/g or IEEE 802.11a), but also the current external interference. Because of the shortage of available non-overlapping channels, a channel assignment scheme is needed so as to reduce the SAC blocking probability.

Many channel assignment schemes have appeared for cellular systems. In a cellular system, channels are divided into groups, each of which is assigned to a base station. Because of the limited number, the channels have to be re-used in different cells when the minimum re-use distance is defined. As surveyed in [1], several dynamic and static channel assignment schemes are proposed. However, all the base stations involved in channel assignment are connected through wired, not wireless, links. Each channel is used for one end user to communicate with its corresponding base station. In an ESS Mesh, APs have the same role as that of cellular base stations, providing services for end users. But different from cellular base stations, all APs in an ESS Mesh are not connected through wired links but rather through wireless links. Each assigned channel is used for setting up a link between two neighboring APs, denoted as relaying channels. As for end users, they will operate at a specified channel, denoted as the home channel, which is provided by their associated AP. Discussion of home channel allocation, unfortunately, is outside the scope of this thesis. We assume that the home channel will not interfere with any relaying channel in the ESS Mesh. Because of the characteristics of wireless connections between APs and the small coverage area of the IEEE 802.11 PHY radio, we can not just simply define a minimal re-use distance when implementing a channel assignment scheme. Instead, we have to consider real-time SINR (Signal to Interference Ratio) in the channel assignment scheme.

In this thesis, we propose a SAC solution with channel assignment. In our solution, a TDMA technique is used, based on the IEEE 802.11 PHY. All the IEEE

802.11 radios are allowed to change channels during different TDMA time slots. Similar to [2], we present an optimization formulation for the channel assignment scheme, which is more efficient than that in [2] and consumes less computing time. We also study the optimization with a cumulative interference model. In order to further reduce computing time, heuristic channel assignment schemes are presented, which are Unforce Channel Assignment (UCA), Perturbation Minimizing Channel Assignment (PMCA) and Slot-Channel Selection with Interference Awareness (SCSIA). Additionally, we consider dynamic path selection combined with our channel assignment schemes as a way of improving the system performance as compared with static path selection. Various simulations are implemented to compare our schemes and validate the correctness of the optimization model.

The remaining chapters are organized as follows. Chapter 2 provides a review of background material. Chapter 3 formulates the problem that will be addressed in this thesis, given reasonable assumptions. Chapter 4 presents the details of the proposed traffic scheduling solution with efficient channel assignment. Chapter 5 shows simulation comparison results and Chapter 6 summarizes this thesis.

Chapter 2

Background

2.1 IEEE 802.11

In this fast-paced world, efficient communication is in high demand. The Wireless Local Area Network (WLAN) is a technology designed to meet this demand. This network can be setup without cables, can be maintained when nodes in the network change their physical locations and can be built in an ad hoc manner. Since 1997, IEEE has released several versions of IEEE 802.11 specification. In general, the IEEE 802.11 specification is a wireless standard that specifies an "over-the-air" interface between a wireless client and a base station or access point, as well as among wireless clients. (http://standards.ieee.org/wireless/overview.html)

In the IEEE 802.11 standard, the WLAN can be configured in either infrastructure mode or ad hoc mode. Nowadays, infrastructure WLAN, called BSS (Basic Service Set), is widely used throughout the world. In a BSS, stations can communicate with each other or can access outside the BSS through a base station, also known as an access point (AP). Figure 2.1 shows multiple BSSs: BSS1 formed by Station 1 and 2, BSS2 formed by station 3, 5 and 6 and BSS3 formed by station 3, 4 and 5. These three BSSs can become a DS (Distribution System) if their APs are interconnected. The figure also shows that BSS2 and BSS3 overlap with each other. This overlapping provides a chance for stations to roam between BSS2 and BSS3.

In the remaining parts of this section, we review portions of the IEEE 802.11

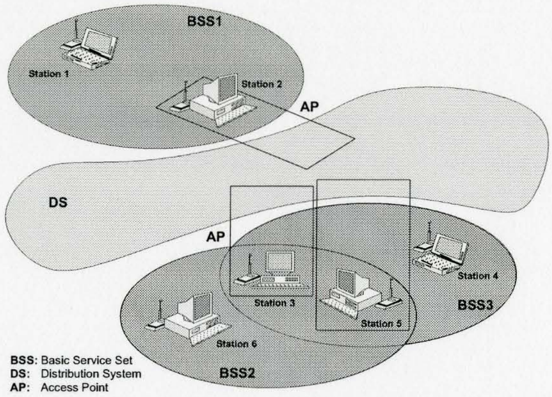

Figure 2.1: Infrastructure Mode in IEEE 802.11

specification and introduce the MAC layer protocols as defined in this specification.

2.1.1 Specifications

IEEE has released several versions of IEEE 802.11 specification, which are IEEE 802.11 legacy, IEEE 802.11a, IEEE 802.11b and IEEE 802.11g. In the following, we will introduce and discuss these specifications.

The first version of IEEE 802.11 was released in 1997, now commonly referred to as IEEE 802.11 legacy. It operates in the 2.4GHz Industrial Scientific Medical (ISM) frequency band and specifies only two transmission rates: 1Mbps and 2Mbps. The outdoor transmission range for this is roughly 75 meters. In its PHY layer, a signal is transmitted by either frequency hopping (FH) or direct-sequence spread spectrum (DSSS). The IEEE 802.11 legacy standard is basically a "beta specification." From the industry vendor's point of view, it is the most flexible specification in the IEEE 802.11 standard family. However, this flexibility is also its biggest weakness since compatibility amongst vendor products is very poor. Therefore, in 1999, IEEE published IEEE 802.11a and IEEE 802.11b in order to address compatibility issues.

The IEEE 802.11a standard operates in the 5.0GHz ISM frequency band and can provide 52 channels with up to a 54Mbps transmission rate. Obviously, IEEE 802.11a was a significant improvement with respect to transmission rate. Realistically, the transmission rate can be reduced to 48, 36, 24, 18, 12, 9 and 6 Mbps as the background interference increases. The IEEE 802.11a standard also has a better outdoor transmission range, which is approximately 100 meters. As for the PHY layer, IEEE 802.11a uses orthogonal frequency-division multiplexing (OFDM) instead of DSSS. It can provide 52 channels, 12 of which are non-overlapping.

The IEEE 802.11b standard is an amendment to IEEE 802.11 legacy, operating in the 2.4GHz ISM frequency band. It can transmit as far as 110 meters outdoors at 11, 5.5, 2 and 1 Mbps based on background interference. It only supports 12 channels, 3 of which are non-overlapping.

Although both the IEEE 802.11a and IEEE 802.11b specifications were released in 1999, the first IEEE 802.11a product appeared on the market much later than IEEE 802.11b products. This is why the IEEE 802.11b products currently have a much higher market share than for IEEE 802.11a. In fact, IEEE 802.11a takes advantage of IEEE 802.11b. One significant advantage of IEEE 802.11a is the working frequency. As we know, 2.4GHz is widely and heavily used in industry, including in microwave ovens, 2.4Ghz cordless phones, bluetooth products, etc. Therefore, using 5.0GHz means less interference. Another advantage is that OFDM can achieve better propagation than DSSS in multipath environments (e.g., indoor office). This propagation advantage can compensate for the disadvantage that a higher frequency (5.0GHz) signal travels less well through solid objects than a lower frequency (2.4GHz) signal. Thus, IEEE 802.11a can achieve the same indoor transmission range as IEEE 802.11b. In conclusion, IEEE 802.11a is the preferred specification due to its capacity and reliability.

In order to improve the capacity and reliability of IEEE 802.11b, IEEE released IEEE 802.11g, which combined the advantages of IEEE 802.11a and IEEE 802.11b. As an extension of IEEE 802.11b, IEEE 802.11g also operates on the 2.4GHz ISM band, providing 12 channels (4 of the 12 channels are non-overlapping). By using OFDM, IEEE 802.11g can support up to a 54Mbps transmission rate, which also can be reduced to 48, 36, 24, 18, 12, 9 and 6 Mbps as required. Because it operates in the 2.4Ghz frequency band, IEEE 802.11g has the same transmission range as IEEE 802.11b. On the interference side, IEEE 802.11g suffers interference not only from existing 2.4GHz industry products, such as microwave ovens, cordless phones and

Version	Release Time	Frequency	Maximum Rate	Range
IEEE 802.11 legacy	1997	2.4GHz	2Mbps	75 meters
IEEE 802.11a	1999	5.0GHz	54Mbps	100 meters
IEEE 802.11b	1999	2.4GHz	11Mbps	110 meters
IEEE 802.11g	2003	2.4GHz	54Mbps	110 meters

Figure 2.2: Summary for IEEE 802.11 specifictions

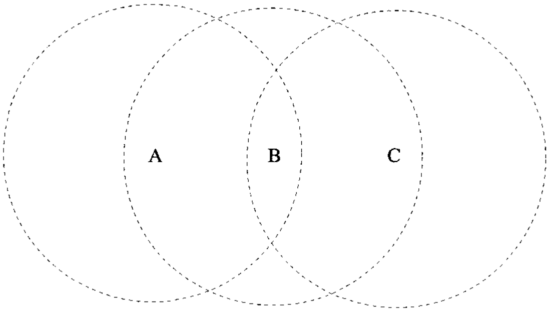

Figure 2.3: Hidden Terminal Problem in WLAN

bluetooth products, but also from existing IEEE 802.11b devices. The interference from IEEE 802.11b is a significant factor in reducing the capacity of IEEE 802.11g.

Figure 2.2 provides a summary of the IEEE 802.11 legacy, IEEE 802.11a, IEEE 802.11b and IEEE 802.11g standards. There are also several IEEE 802.11 specifications under construction; for example, IEEE 802.11e is designed to provide quality of service for IEEE 802.11 networks and IEEE 802.11n is a broadband version, supporting much higher transmission rates. In each IEEE 802.11 specification, the MAC protocol used is the same. In the next section we will discuss the details of this IEEE 802.11 MAC protocol.

2.1.2 CSMA/CA

In the MAC layer, the major difference between IEEE 802.11 (WLAN) and the IEEE 802.3 (LAN) is that IEEE 802.11 uses Carrier Sense Multiple Access With Collision Avoidance (CSMA/CA) rather than Carrier Sense Multiple Access With Collision Detection (CSMA/CD). In CSMA/CD, a transmitting station will try to detect colliding transmissions during packet transmission. This collision detection is suitable for LANs because all stations are physically connected by a wired cable. When one station is actively transmitting, the other stations will detect this quickly. However, this type of collision detection is less effective in a WLAN. One reason is that as defined in the IEEE 802.11 PHY standard, the IEEE 802.11 radio works in half-duplex mode, which means it can be in either listening mode or transmitting mode but can not listen and transmit at the same time. To effectively use collision detection, full-duplex mode is required. Another reason is that when one station is sending a packet, not all stations can detect the transmission. This is the well-known hidden terminal problem as shown in Figure 2.3. In this example, there are three nodes: A, B and C. Nodes A and B can communicate with each other. Nodes B and C can communicate with each other, and nodes A and C cannot communicate with each other. When node A is sending packets to node B, node C can not detect the transmission from node A and will assume its channel is idle. If node C has a packet for node B, it will transmit this packet immediately. Thus, node B will receive the transmitting signal from both node A and node C. Collision will occur and node B will not receive any packet successfully, either from node A or from node C.

In CSMA/CA, a station must first listen on the channel. If the channel is idle, it can transmit the packet immediately. Otherwise, it has to wait until the channel becomes idle and then transmit the packet after waiting a random interval. The extra waiting period can reduce the collision probability and thus increase the system capacity.

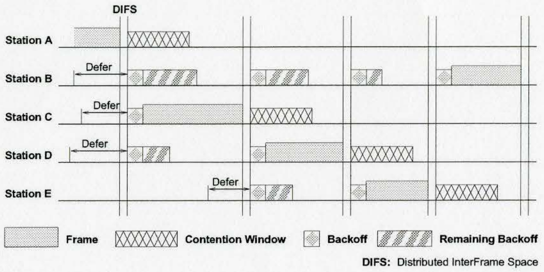

Figure 2.4: Distributed Coordination Function

2.1.3 DCF MAC Protocol

DCF stands for Distributed Coordination Function and is the basic MAC protocol used in the IEEE 802.11 family, based on the CSMA/CA mechanism. Other MAC protocols, such as PCF, HCF, etc., are based on it. DCF can give each station in WLAN a fair chance to transmit its packet without any assistance from a central controller, such as an access point.

The concept of the DCF is illustrated in Figure 2.4, where Stations A, B, C, D and E are all IEEE 802.11 nodes and can communicate with each other. When station A is in transmitting mode, Stations B, C and D begin to send packets. By listening to the channel, all three stations can detect a busy channel and defer their transmission. The channel will become idle when Station A finishes its transmission. Then all the stations in the network will wait for a DIFS (Distributed InterFrame Space) time interval. After that interval, stations that are wanting to send out packets will do a random backoff in order to reduce the collision probability. As shown in Figure 2.4, Station C has the shortest backoff time and will win the contention and send out its packet after its backoff period has expired. Once station C begins transmitting, the stations with active backoff time have to hold their backoff and wait until the channel becomes idle again. Note that during the transmission period of station C, station E has packets for sending but has to defer its transmission because it detected a busy channel. When station C's transmission is over after a DIFS waiting period, Stations B and D will continue their remaining backoff, while station E will begin its random backoff. Because the backoff period is randomly chosen, it is possible that station E

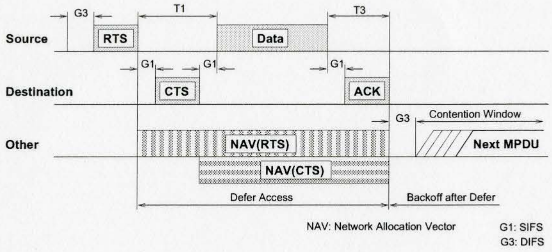

Figure 2.5: RTS/CTS Mechanism

could have a shorter backoff time than station B's remaining backoff time, as shown in Figure 2.4. Therefore, station D will win the next contention, then station E and finally station B.

In the example above, there is no hidden terminal problem because all the stations can communicate with each other. In reality, hidden terminal problems do exist, especially when an AP is involved and when all the stations can communicate with the AP but some of them can not communicate with each other. In DCF, a RTS-CTS mechanism is used to reduce the collision probability arising from the hidden terminal problem. Figure 2.5 is an example showing how the RTS-CTS mechanism works. Note that both the RTS and the CTS packets are very small and do not introduce significant overhead into the DCF protocol. When a station wins the contention, it will send an RTS (Request-to-send) packet to the receiver. The RTS packet will indicate the length of the entire transmission period as estimated by the sender. All the neighboring stations of the sender, excluding the receiver, will block their transmitting activity for the estimated period. Once the receiver receives RTS, it will return a CTS (Clear-to-send) packet to the sender immediately. This CTS packet will also indicate the length of the entire transmission period as estimated by the receiver. Similarly, all the neighboring stations of the receiver, excluding the sender, will block their transmitting activity for the estimated period. We need to keep in mind that the potential hidden terminals must be neighboring stations. Since all the neighboring stations of the sender and receiver will defer their transmission until the estimated blocking period is over, the hidden terminals must also be blocked. Thus, the sender can transmit data payloads to the receiver more safely.

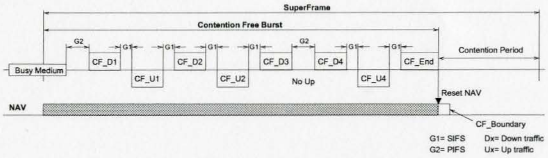

Figure 2.6: Point Coordination Function

2.1.4 PCF MAC Protocol

PCF stands for Point Coordination Function in the IEEE 802.11 specification. and is a central-controlled protocol, where the central controller is an AP. This implies that PCF is not suitable for ad hoc mode but for infrastructure mode in IEEE 802.11. In infrastructure mode, every station that is accessing the WLAN has to register with an AP, which is also known as association. Once the association is complete, the AP will add the station onto its poll list for the PCF protocol. The AP will poll the stations listed on the poll list one-by-one, in a round robin fashion. When the station is polled, it is allowed to transmit (and/or receive) data to (and/or from) the AP.

Figure 2.6 is an example of a PCF transmission. As we can see, there is a waiting time period, PIFS (PCF InterFrame Space), at the beginning of the PCF transmission period. After that, the AP will begin to poll stations on the polling list. If the AP has data packets for the polled station, it will send out the polling packet piggybacking the data packet. After receiving the packet, the polled station will reply with an ACK packet after a SIFS (Short InterFrame Space) waiting time interval. If the polled station has data packets for the AP, a data packet is allowed to be piggybacked with the ACK packet. After sending out the polling packet, the AP will wait for, at most, a PIFS time interval. If there is nothing received from the polled station during the PIFS period, the AP will remove the polled station from its polling list and will poll the next station immediately. If the AP does receive a response from the polled station, it will continue to poll the next station after a SIFS time interval. At the end of the PCF period, the AP will issue a CF-End packet to terminate the PCF period.

Obviously, PCF can achieve better system capacity than DCF, because there is less transmission overhead. In DCF, the overhead comes from DFIS, random backoff, SIFS, RTS/CTS packets and ACK packets. In PCF, the overhead comes from PIFS,

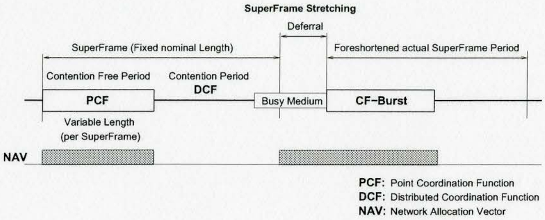

Figure 2.7: HCF Superframe

SIFS and Polling/ACK packets. PCF can also solve the hidden terminal problem inside the WLAN, since all the stations are centrally controlled by an AP. However, PCF can not avoid contention from a neighboring WLAN that is using the same channel. Once a collision occurs, the transmission cannot be recovered at the MAC layer level. This is a significant reason why PCF is not recommended by the Wi-Fi alliance.

2.1.5 HCF MAC Protocol

HCF stands for Hybrid Coordination Function and combines DCF and PCF together into one superframe. Figure 2.7 describes the details of the HCF superframe. Basically, each superframe has the same length and is divided into two parts. One part is for PCF, called the contention free period (CFP); the other is for DCF and is called the contention period (CP). The superframe always begins with a CFP followed by a CP. The length of CFP is variable and controlled by the AP. As mentioned in 2.1.4, the AP will broadcast a CF-End packet at the end of CFP such that all the stations in WLAN will be activated to transmit their data packets using the DCF protocol. If a new superframe begins but the channel is still busy because of the remaining transmissions from the last superframe, the CFP of the new superframe will be deferred until the channel becomes idle. This kind of deferral is called superframe stretching.

HCF gives more flexibility than DCF or PCF alone. Because the CFP in HCF superframes is variable, we can easily set CFP to zero if we only want only DCF or to the length of the superframe if we only want PCF.

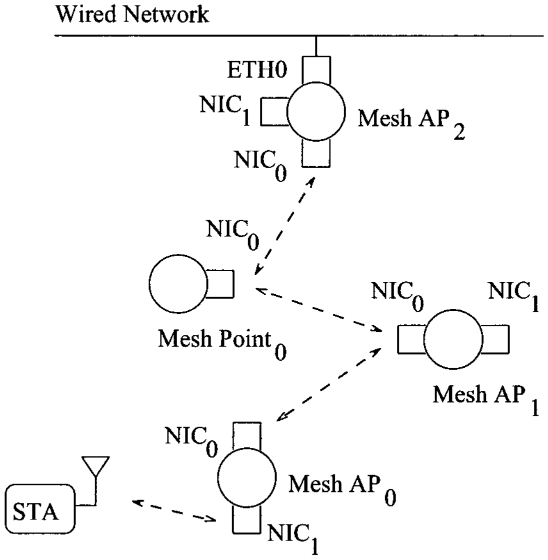

Figure 2.8: A Mesh Network

2.2 Wireless Mesh Network

Wireless mesh networks have received increasing interest in recent years due to the fast expanding Wi-Fi market. More and more, individual communities and companies are beginning to set up intranets with multiple Wi-Fi access points, so that clients can communicate using wireless connections.

In Fig. 2.8 we illustrate a four-node WMN. These nodes represent access points (APs) and are equipped with multiple air interfaces. Typically, at least one AP in the mesh network will have a wired interface connected to the wired network and is referred to as the root AP. As we can see in the figure, there is one root AP, namely AP_2. Basically, there are two types of APs in a WMN, Mesh APs and Mesh Points. A Mesh AP can provide network services for mobile stations (MSs), such as AP_0, AP_1, and AP_2 shown in Fig. 2.8. Mesh Points act only as repeaters and do not provide network connectivity for MSs, such as MP_0 in Fig. 2.8.

Aside from the business model, WMNs have numerous technical challenges to solve including capacity, routing and link redundancy, frequency planning, meeting delay and quality of service (QoS) requirements, load balancing, resource fairness, and security and privacy. Moreover, if a WMN is taken in the context of a specific WLAN technology, such as IEEE 802.11[3] operating in the ISM band, then issues such as spectrum pollution and limited channel availability can make the solution of the aforementioned problems very challenging.

2.3 Related Work

This thesis focuses on traffic scheduling solutions using channel assignment schemes in ESS Meshes. Since the number of channels is limited, the major challenge is in channel assignment. In this section, we will review the relevant literature concerning channel assignment.

2.3.1 Related works based on IEEE 802.11

Many protocols based on the IEEE 802.11 standard have been proposed to control inter-channel interference, most using multi-channel mechanisms [4] [5] [6] [7] [8] [9].

Raniwala et al. [4] presented two approximated, centralized control mechanisms to manage channel switching and to provide backbone connectivity in mesh networks. The first assigns channels based on network topology and is called "Neighboring Partitioning Scheme". The other, which is aware of current traffic load, is called "Load-Aware Channel Assignment".

In Raniwala et al., the traffic was assumed to be stable over a long period, which is different from our research. In this thesis, we focus on deterministic traffic, such as VoIP calls with smaller duration. Raniwala et al.'s approach requires that each AP be equipped with at least two radio interfaces for backbone traffic relaying. After being assigned a particular channel, a radio interface is not allowed to change the channel until the next call of channel assignment, which results in bandwidth competition between nodes assigned with the same channel. The authors also consider the impact of routing on the traffic load on each link.

Feng et al. proposed a tree-topology-based MAC layer mechanism that can be used in a distributed manner [5]. This protocol only requires one air interface per

AP for relaying traffic. Each AP will have one and only one parent AP (excluding the root AP) and one or more child APs based on the tree topology. Because there is only one radio for each AP, channel switching is allowed in order to periodically relay traffic to parent and child APs. The authors also assume that channel assignment is perfect such that any simultaneous transmission on different links will not interfere. One novel advantage of Feng's protocol is that it allows power saving on the AP side. This is a valuable feature for APs powered by a rechargeable energy resource such as solar power.

So and Vaidya described a distributed multi-channel MAC (MMAC) in [6]. In MMAC, each node maintains a Preferable Channel List (PCL), which indicates which channel is preferable to use for the node. During every ATIM window, nodes will negotiate with their neighbors for channel selecting in one predefined channel, based on their PCLs. Once the operating channel is decided, all the nodes will switch to it for packet transmission after the ATIM window. Although the authors suggest using a random backoff mechanism to avoid collision during the channel negotiation period (ATIM window), collisions cannot be totally eliminated. Considering the cumulative interference in WMN, the number of successful channel negotiations will be limited and thus the system capacity will be degraded.

In [7], Wu et al. proposed a Dynamic Channel Assignment (DCA) in an on-demand manner. In this protocol, an extra control channel is required for nodes to exchange control messages that help the transmitter and receiver to decide which channel they will operate on for on-demand packets. Each node is assumed to maintain two lists. One is the Channel Usage List (CUL), which records the channel usage status of neighboring nodes. The other is the Free Channel List (FCL), which indicates the current available channels for the node, based on CUL. The authors also assume that each node is equipped with two transceivers for the control channel and data channel respectively. As in [6], it is difficult to avoid collision in the control channel; therefore, system performance is affected. Moreover, collisions can not be eliminated if two pairs of nodes are assigned to the same data channel simultaneously and the cumulative interference is taken into consideration.

Bahl et al. proposed a seed-slotted channel-hopping (SSCH) scheme in [9]. SSCH can be regarded as a virtual MAC protocol, working on top of the IEEE 802.11 MAC, without any modification of the standard. In SSCH, each node is equipped with one radio interface, which can change its orthogonal operating channel in different time slots. Since at least one overlapped time slot between two neighboring nodes is guaranteed through a channel-hopping scheme, distributed synchronization is achieved by broadcasting a signaling packet from nodes in each slot. Every node also maintains its own channel-hopping schedule, which will be learned by its neighbors periodically so that the node and its neighbors can regulate their channel-hopping schedules when transmission is needed. Obviously, SSCH is not a contention-free mechanism, especially in a multi-hop wireless network. Additionally, one time slot is assumed to be $10ms$, which is too long to handle deterministic traffic, such as VoIP, when the particular node has traffic with different neighbors.

In [10], Leung et al. investigated the channel assignment problem for Multi-Cell IEEE 802.11 networks. First of all, the authors classify APs in the multi-cell network as different interferers. The class-1 interferer is defined as the AP, whose interference is large enough to destroy the transmission of desired APs. Similarly, a class-2 interferer is one pair of APs, whose total interference can affect desired APs. The authors only consider class-1 and class-2 interferers, which is not accurate. They then propose two mathematical models for channel assignment. One is to minimize the maximum channels effective utilization of particular APs. The other is to minimize the overall interference of APs. After proving them both to be NP-complete problems, they proposed a heuristic iterative algorithm. However, in their validation, each AP is supposed to use a sectorized antenna, which reduces the complexity of the problem significantly. Leung et al. only focus on channel assignment for individual APs, without any links between APs.

In [11], the authors considered channel assignment for WLANs, wherein overlapping channels can be used. They formulated their problem for three different objectives as a weighted edge-coloring problem and proceeded to prove that it is NP-hard for all three cases. They then presented two heuristic algorithms for channel assignment. The first technique assumes that APs cannot co-operate, as in the case of different WLANS. The second one assumes that APs can co-operate to minimize interference. Finally, they presented some results from an experimental test bed. Since the channel assignment scheme is for WLANs, not a mesh network, the wireless communication between APs has not been considered.

2.3.2 Related Work Based on TDMA

In [12], Ramanathan et al. developed a unified framework and an algorithm for channel assignment in wireless networks, including TDMA, FDMA and CDMA. The unified framework includes two phases. One is a "labelling phase," which assigns a unique label to each vertex in the mesh graph. The other is "coloring phase," which schedules the least color for the edges or vertexes without violating the required constraints. Three heuristic algorithms were proposed in this paper. "RAND" labels vertices in random order. "MNF" picks up the vertices with more neighbors. In "PMNF", the labeled vertex and its corresponding edges are ignored while the rest of vertices are picked up as per "MNF". Ramanathan et al. do not limit the number of colors. Their algorithms simply give the solution with the minimally required number of colors. However, the constraints are based on a binary matrix, which is not quite ideal when considering interference.

Ju et al. presented a TDMA scheduling algorithm in multihop packet radio networks using latin squares[13]. In a multi-channel TDMA network, the time slot assignment solution can be found from a corresponding orthogonal family of $p \times p$ latin square. From the theorem of latin squares, each neighbor can cause at most one collision to a specific node. Thus, multi-channel TDMA scheduling based on latin square is not contention-free. It is also assumed that each node has the same number of radios with the same number of available channels. In practice, however, this is difficult to implement.

In [2], Das et al. studied the channel assignment problem in mesh networks, considering multiple channels for the network and multiple radios for APs. They focus on a mathematical model for maximizing the number of links that can be used simultaneously in a given snapshot. By proving it as an NP-complete problem, the authors use the LINDO mixed integer linear programming solver to obtain the optimal result. However, the computing time to solve the problem is very large, as well as the network size and the number of channels needed. In addition, they didn't consider the traffic scheduling along the route, the channel switching of the radio and the cumulative interference, but rather only a given snapshot of WMN. In such a snapshot, even the network is not fully connected but partitioned into subnets by the channel assignment solution.

Bjorklund et al. proved that spatial reuse TDMA (STDMA) scheduling is an NP-hard problem [14]. Gronkvist investigated the spatial reuse TDMA schedule on both link and node points of view [15]. Their conclusion was that the network connectivity and the traffic load of the network determine whether node or link assignment is suitable for spatial reuse TDMA scheduling. However, the authors did not limit the number of radios per node, which is one of the factors affecting the scheduling performance.

In [16], Tasaki et al. investigated the channel assignment problem in wireless mesh networks. They proposed an edge coloring channel assignment algorithm, considering carrier-to-interference ratio (CIR). The CIR between two edges is the maximal value in the CIRs of four interference patterns from two pairs of vertices. For simplicity, they defined a minimum distance D which is the minimum distance between any two nodes working on the same channel. The interference from the node, which is far away from D, is neglected. However, this makes for a very inaccurate model, considering the cumulative interference that occurs in reality. Moreover, their edge coloring algorithm finds the minimal required number of channels in the system, which is different from finding the channel assignment solution with a limited number of channels that is used in our research.

Chapter 3

Problem Formulation

3.1 Assumptions

3.1.1 TDMA MAC

In the IEEE 802.11 standard, CSMA/CA is used as its basic coordination function, called the distributed coordination function (also known as DCF). The benefit of DCF is that every station in the same BSS will share the wireless medium equally without any centralized coordination. However, this equality also brings extra overhead, which comes from collision avoidance and retransmission. The overhead from collision avoidance results primarily from random backoff. The overhead from retransmission is counted when there is a collision during the last transmission. Collision is a significant issue in a distributed transmission method, as well as when several transmitters contend for the wireless media simultaneously. Therefore, in this thesis, we suggest using TDMA instead of CSMA/CA in the MAC layer. The obvious reason is that TDMA is a centralized protocol that can efficiently avoid transmission collisions.

Of course, we have to address to two issues in TDMA. First, synchronizing all transmitters is very important. If transmitters are not synchronized well, transmissions will interfere with each other and eventually collision and retransmission will degrade the overall system. There are a number of time synchronization protocols available in TDMA research. Regardless of the complexity, every protocol will need

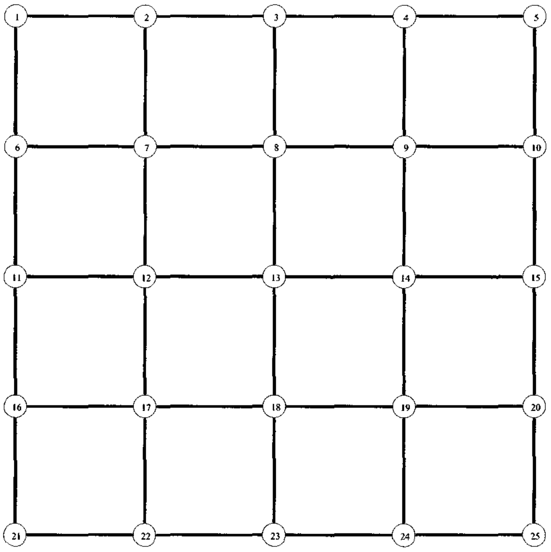

Figure 3.1: Grid Topology

to implement reserved time slots, which to some degree degrades resource utilization. In order to achieve better resource utilization, we can also consider synchronization through a GPS system. Currently, a GPS system is designed to give standard error of about 150 nsec relative to UTC on a single time fit [17], which is sufficient for time synchronization in an ESS Mesh. Moreover, implementing a GPS system in an ESS Mesh is inexpensive and may just require connecting a serial or USB GPS device. Thus, we assume that a GPS device (or chipset) is installed in each MP so that synchronization can be achieved easily. How to deliver centralized signaling messages is the second key point in TDMA. Appropriate centralized signaling messages will indicate to the transmitter when to transmit its packets such that no critical interference will affect the transmission. One way to guarantee the successful delivery of centralized signaling messages is to reserve one channel and assign a unique time slot to each transmitter in the system. This means that each transmitter will operate on the reserved channel in its assigned time slot to avoid the interference from either non-signaling message transmissions or other signaling message transmissions. Theoretically, reserving one channel is possible, and, generally speaking, when the number of transmitters in the system is large, the utilization of the reserved channel will be efficient. There may be other ways to implement the signaling message transmissions. We always assume that signaling messages will be transmitted perfectly and never interfere with non-signaling traffic, such as VoIP voice packets.

Considering the compatibility with IEEE 802.11, we can also derive a TDMA-like MAC to replace the TDMA MAC. In the TDMA-like MAC, all transmission is based on an HCCA protocol, which is defined in the IEEE 802.11e standard. Each time slot in the TDMA MAC can be regarded as a service interval in the HCCA superframe. As stated in the IEEE 802.11e standard, the service interval is scheduled by the AP. In order to achieve the TDMA-like MAC, a centralized controller is still needed to coordinate the scheduling within APs. In this thesis, we will focus on the TDMA MAC for simplicity.

3.1.2 Central Controller (CC)

Since the TDMA MAC is a centralized protocol, a central controller (CC) is required for coordination within MPs. CC could be one of the MPs or an existing node outside of the ESS Mesh. When a new VoIP session enters the system, the source MP will send a request to the CC. Then the CC will try to allocate a group of time slots to all the MPs involved in the new VoIP traffic transmission. The allocation of these time slots has to guarantee not only the correct transmission of current active traffic in the system, but also the transmission of the new VoIP traffic. In order to achieve this, the CC needs to collect certain information such as the status of all the time slots of each radio, the interference between any two MPs, etc. The time slot status will indicate how many radios are working on a particular time slot and who they are. Thus, a decision whether or not to allocate the particular time slot could be made based on our interference model, which will be discussed in Section 3.2. The interference collected by the CC will be used by our interference model to improve the time slot allocation. Since we only consider non-overlapping channels, the interference here always means co-channel interference. The value of the interference indicates the signal strength from A to B if A and B operate on the same channel and A is the signal producer. How to obtain the interference is a challenge. Basically, there are two possible solutions. First, since the MPs are not movable but rather in a fixed location, we can physically measure the interference between any two. Second, if we lack tools for measurement, we can also use a path loss model to estimate it. Of course, this type of calculation may not be accurate in reality, but it will give us a hint as to the quality of the channel. For simplicity, we will use the path loss model as the reference of interference throughout the remainder of this thesis. Note that regardless of the path loss model or physical measurement, the interference value is always off-line and assumed to be unchanged in time, and is called internal interference. On the contrary, there exist other factors resulting from the variety of interference types. For example, during a change of environment, if an external AP happens to operate on a particular channel that is used by some MPs in ESS Mesh, the interference on those MPs will definitely be increased. In addition, if the ESS Mesh happens to be deployed near a railway and a train passes by, the internal interference will be briefly affected. In this thesis, we refer to this variable interference as external interference. For simplicity, we ignore external interference.

3.1.3 VoIP Traffic

As compared with traditional internet traffic such as web browsing, email, instant message, etc., real time traffic has much more critical requirements concerning transmission delay. There are currently two typical real-time applications: video streaming and VoIP. For video stream traffic, selective packet dropping will not disturb the continuity of the video stream but will degrade the video quality. For VoIP traffic, any packet dropping may result in a misunderstanding between two communicators. Thus, VoIP traffic needs to be given more attention, especially when traffic load is high and will delay the transmission. Therefore, we will focus on VoIP traffic, investigating its performance in an ESS Mesh. We assume that VoIP calls use the G711 codec with $20ms$ audio payload. Thus, the transmission latency of each VoIP packet over one hop can be easily obtained from $T_{trans} = \frac{B_p}{R}$, where T_{trans} is the transmission latency, B_p is the VoIP packet size including overhead of each layer in the OSI model and R is the transmission rate (e.g., $11Mbps$, $5.5Mbps$, $2Mbps$ or $1Mbps$ in

IEEE 802.11b). We also assume that the superframe has a length of $20ms$ which will be completely used for the ρ portion operating in TDMA circuit-switched mode. As mentioned in Chapter 1, packets in the bidirectional session and their overhead require a single time slot in each superframe. Note that the overhead includes the ACK for each VoIP packet and the necessary interframe spaces. Hence, we have $T_{slot} = 2 \times T_{trans} + 2 \times T_{ack} + \Delta t + \xi$, where T_{slot}, T_{ack} and Δt respectively for time slot size, transmission latency of the ACK and total interframe space. We also reserve a small time interval ξ in order to compensate for the delay of channel switching and synchronization. Therefore, the number of time slots in one superframe, N_{slot}, is given by $N_{slot} = \frac{20ms}{T_{slot}}$. As we know, end-to-end transmission delay is a critical requirement for VoIP applications (the total round-trip delay is no more than $300ms$). Since each superframe is $20ms$, the maximum packet transmission delay for one hop is roughly $20ms$ (packet has been transmitted in the last time slot). Typically, the size of an ESS Mesh is expected to be small (up to 32 MPs) and therefore, the number of hops for traffic traversing through the ESS Mesh is limited. For example, suppose there is traffic between MP_1 and MP_{25} in Fig. 3.1. Based on the shortest path routing protocol, the number of hops of is 8. So the maximum end-to-end transmission delay is $160ms$, which satisfies the delay constraint for VoIP. Therefore, the delay constraint in such an ESS Mesh is very loose and will be ignored in the remainder of this thesis. This also indicates that if the route of the particular traffic flow is known, the time slot selection for each hop along the route does not have to be in order. For example, we can choose 5^{th} time slot for the first hop, 3^{th} time slot for the second hop, 1^{st} time slot for the third hop, etc.

3.1.4 Channel Switching

In the IEEE 802.11 standard, each AP is defined to have only one radio interface. Once the radio is assigned a workable channel, it will remain on that channel. This is a reasonable assumption because the AP only communicates with associated mobile hosts and the association between mobile host and AP is expected to be static. If the AP switches its operating channel, the mobile host has to somehow either re-scan the channel or be notified through other means, which increases the system complexity. In the IEEE 802.11s draft standard, each MP is allowed to be equipped with multiple radios. Out of these radios, one will serve mobile hosts if it is a mesh AP, and the others will be used to communicate with other MPs. We always refer to the network where mobile hosts are involved as the home network and the network where MPs are involved as the mesh network. Accordingly, radios in the home network and the mesh network are called home radios and mesh radios, respectively. Of course, the home radio will obey the rule mentioned above to reduce complexity. As for the mesh radio, remaining on a channel is not flexible and will reduce the system capacity, because the mesh radio can only access the time slots relative to the permanent channel. In order to improve the utilization of channel resources and to further achieve better system performance, we assume that each radio is allowed to switch its current operating channel. As mentioned in Section 3.1.1, the TDMA MAC is assumed. We also assume that the assigned channel on a radio is only valid for one time slot in the TDMA superframe and will repeat the channel in the next superframe until the channel assignment is released by the central controller. The radio may switch to another channel, remain on the same channel or go into sleep mode in the next time slot. In theory, channel switching will produce extra overhead. So we need a period of guard time to make sure the channel has already been switched successfully. In [18], the authors concluded that channel switching only consumes a very tiny time period, $80\mu s$. If we assume that the number of time slots in one TDMA superframe is 10, then the total channel switching time in one TDMA superframe is about $720\mu s$, roughly 3% overhead. In this thesis, we just ignore this overhead for simplicity. This implies that the ξ appearing in the calculation of T_{slot}, mentioned in Section 3.1.3, can be regarded as 0 with perfect synchronization and fast channel switching techniques.

3.1.5 Routing

In this thesis, we consider deterministic traffic flow (VoIP call) from the end user attached to one of the MPs to another user in the same ESS Mesh or the Internet. If one end user is from the Internet, we will treat the root MP in the mesh network as the end user's MP. Here, we define MP_s and MP_d as the MP serving the source end user and the MP serving the destination end user, respectively. Suppose the location of the MPs is known by a central controller that is assigned in advance and can be either one of the MPs in the ESS Mesh or one node outside of the ESS Mesh. In this case it is possible for the central controller to calculate the route between MP_s and MP_d with an assumed routing protocol. (shortest path routing protocol is assumed.) However, the route for one pair of MP_s and MP_d is not unique. Fig. 3.1 shows an ESS Mesh consisting of a 5 × 5 grid topology, where the solid line indicates a wireless link between any two neighboring MPs. Considering the route from MP_1 to MP_{25}, there are multiple solutions based on the shortest path routing protocol. For example, route $\{1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 10 \rightarrow 15 \rightarrow 20 \rightarrow 25\}$, route $\{1 \rightarrow 6 \rightarrow 11 \rightarrow 16 \rightarrow 21 \rightarrow 22 \rightarrow 23 \rightarrow 24 \rightarrow 25\}$, etc.. We denote $\{R_{s_id_i}\}$ as the set of routes for one particular traffic flow, T_i. We also regard $\{T_i\}$ as a set of traffic flows for the system. If we pick one route from $\{R_{s_id_i}\}$ for each T_i, obviously, different combinations of routes of $\{T_i\}$ result in different traffic scheduling and channel assignment solutions. In theory, we can go through all of the possible $\prod_{\{T_i\}} |\{R_{s_id_i}\}|$ combinations and obtain the optimal solution. However, would require a very large computing time, as well as $|\{R_{s_id_i}\}|$ and $|\{T_i\}|$ can have large values. An admission decision (accepting or dropping) must be made quickly so as not to waste the end user's waiting time. Thus, we only assume one route when scheduling the traffic session. This route could be pre-defined before the system runs or dynamically chosen based on a particular route metric. If it fails to schedule the traffic session on the route, the traffic session will be dropped immediately.

3.2 Problem Formulation

Our network model is based on a reachability graph $G(N, E)$. Here, N denotes a set of MPs and E is a set of bidirectional edges between vertices. For any two vertices $u, v \in N$, the edge between u and v is in E if u and v can communicate with each other directly, as denoted by $u \leftrightarrow v$. Suppose that each MP has K radios and the number of non-overlapping channels is F. We say the link (between u and v) is active if we can assign one of F available channels to the radios, which is picked up from K radios of each vertex (u or v). We assume that the communication range of each node is equal and hence all links are bi-directional.

In practice, the communication range of each vertex is based on the propagation path loss model, given by

$$P_i(d_{i,j}) = \bar{P}(\frac{\bar{d}}{d_{i,j}})^{\gamma} \tag{3.1}$$

where γ is the path loss exponent characterizing the rate of signal degradation with distance, $P_i(d_{i,j})$ is the signal power at receiver i which is $d_{i,j}$ distance away from transmitter j and $\bar{P}$ denotes the signal power at a reference distance $\bar{d}$. Note that $P_i(d_{i,j}) = P_j(d_{j,i})$ because of the bi-directional assumption.

Based on the propagation path loss model, the interference between any two links operating at the same channel could have four possible values; for example, in Fig. 3.1, suppose link 7 ↔ 8 and link 19 ↔ 24 are operating on the same channel, then we could have four possible interferences:

1. interference between node 7 and node 19, $P_7(d_{7,19})$ or $P_{19}(d_{19,7})$
2. interference between node 7 and node 24, $P_7(d_{7,24})$ or $P_{24}(d_{24,7})$
3. interference between node 8 and node 19, $P_8(d_{8,19})$ or $P_{19}(d_{19,8})$
4. interference between node 8 and node 24, $P_8(d_{8,24})$ or $P_{24}(d_{24,8})$

Obviously, the maximum interference above is given by $P_8(d_{8,19})$ (or $P_{19}(d_{19,8})$) because $d_{8,19}$ is the shortest distance. In our results we always consider the worst case interference, which means we will regard $P_8(d_{8,19})$ as the interference between link 7 ↔ 8 and link 19 ↔ 24. Based on this assumption, we maintain a symmetric $E \times E$ matrix IM to record the interference information between any two edges in the network, where E denotes the number of edges in $G(N, E)$. When we calculate the interference, we temporally assume that the two edges are operating on the same channel. Note that we regard the diagonal element of IM as a very large value so that the same link won't be picked up twice on the same channel.

In our results we consider both non-cumulative interference and cumulative interference whose formulations are given in Section 3.2.1 and Section 3.2.2 separately. The solution of those two formulations will give the upper bound on the number of links that can be activated simultaneously. By using these upper bounds we can validate our simulation results.

3.2.1 Non-Cumulative Interference Model[1]

In the non-cumulative interference model, the interference range of a transmitter is fixed. Any receiver out of this range is assumed to receive zero interference. Therefore, we can simply use 0 or 1 to indicate the interference between any two MPs. As mentioned above, there are four possible interference values between two different links, and we always choose the worse case as the interference value, which is also 0 or 1. Thus, the $E \times E$ interference matrix IM becomes a binary matrix. $IM_{ij} = 0$ means link i and link j are potentially non-interfering, and, hence, they are allowed to be activated simultaneously on the same channel. Conversely, $IM_{ij} = 1$ means link i and link j are potentially interfering with each other and cannot be activated simultaneously on the same channel.

We assume that the $E \times E$ interference matrix IM is always known. Based on this matrix and given the time slot, if we plan to assign a particular channel for a pair of links i and j, we can easily obtain the amount of interference that link i and link j will receive from other links working on the same time slot and the same channel. Then we can assign the channel if the amount is 0 or reject the channel if the amount is greater than or equal to 1.

Let us now consider the ILP formulation of the non-cumulative interference model. Given the reachability graph, our objective is to find a channel assignment that would maximize the number of links that can be activated simultaneously, subject to the constraints F, K and the interference matrix IM. Below we provide an Integer Linear Programming (ILP) formulation of this optimization problem. Let us first define two sets of binary variables as follows:

$$C_{ef} = \begin{cases} 1, & if\ link\ e\ has\ been\ assigned\ channel\ f \\ 0, & otherwise. \end{cases}$$

$$X_e = \begin{cases} 1, & if \sum_f C_{ef} = 1\ (part\ of\ the\ solution) \\ 0, & if \sum_f C_{ef} = 0\ (not\ a\ part\ of\ the\ solution). \end{cases}$$

Subject to the following three constraints:

$$X_e - \sum_f C_{ef} = 0\ \forall\ e \in E \tag{3.2}$$

$$\sum_{e \in E, n \in en(e)} X_e \leq K\ \forall\ \{n \in N : degree(n) > K\} \tag{3.3}$$

$$C_{ef} + C_{e'f} \leq 1\ \forall\ \{e, e' \in E : UT(IM_{ee'}) = 1\},\ \forall\ f \in F \tag{3.4}$$

Constraint 3.2 ensures that each link will be assigned at most one channel. Constraint 3.3 ensures that at most K links can be activated simultaneously among the set of links, one of whose end nodes is n. Note that we need to check that constraint 3.3 can be satisfied only for the nodes whose degree in the reachability graph is more than K. This is because if a node u has degree less than or equal to K in the reachability graph, we can not choose more than K links (from the set of links one of whose end nodes is u) to be activated simultaneously, since there do not exist more than K such links. Constraint 3.4 ensures that the same channel can not be assigned to two links e and e' whose corresponding entry in the interference matrix IM is 1. As the matrix IM is symmetric, we consider here only the upper triangular portion of IM, just to remove some duplicate variables.

The number of binary variables in this model is $EF + E$ (EF is for C_{ef} and E is for X_e) and the number of constraints is equal to $E + Z + T$ (E, Z and EF are for constraint 3.2, constraint 3.3 and constraint 3.4 respectively), where E is the number of links in the reachability graph, Z denotes the number of nodes having degree greater than K in the reachability graph, T denotes the number of 1's in the upper triangular portion of the matrix IM.

3.2.2 Cumulative Interference Model[1]

In the cumulative interference model, the interference range of a transmitter is not fixed. Any receiver in ESS Mesh is assumed to receive interference from the transmitter, regardless of how far away the receiver is. Therefore, we have to use real values rather than 0 or 1 to indicate the interference between any two MPs. Based on the worst case assumption for interference between links, the $E \times E$ interference matrix IM becomes a non-binary matrix. We have to measure the real-time interference received by each link operating on the same channel. The calculation of real-time interference is given by

$$INT_i = \sum_k IM_{ik} \tag{3.5}$$

where i is the target link and k stands for any active link operating on the same channel. Recall that IM_{ik} is the interference between link i and link k if i and k operate on the same channel.

Theoretically, considering cumulative interference is much closer to reality than considering non-cumulative interference. An example of this is given in Fig. 3.1. For simplicity, we assume that any two MPs can operate on the same channel if they are more than two hops away. Suppose we have 2 links, $1 \leftrightarrow 2$ and $16 \leftrightarrow 17$, operating at channel f and decide to assign the same channel to link $10 \leftrightarrow 15$. There should be no problem with this when using a non-cumulative interference model. However, depending on the path loss model and the interference threshold, it is possible that the sum of interference from any two links may destroy the transmission on the third link.

Let us now consider the ILP formulation for the cumulative interference model. We assume that the $E \times E$ interference matrix IM is known whose *ij-th* element IM_{ij} indicates the measured interference if link i and link j operate on the same channel.

For this cumulative interference model, the objective function and constraints 3.2 and 3.3 will be the same as in the non-cumulative case, but the constraint 3.4 will be replaced by 3.6. Constraint 3.6 ensures that channel f is only assigned to link e when the cumulative co-channel interference due to other links' usage of the same channel f is below the pre-defined threshold B. The left side of this constraint is the sum of interference received by link e from all other links operating on the same channel f in the network. If $C_{ef} = 1$, the right side of this constraint equals to the interference threshold B. If $C_{ef} = 0$, the right side of this constraint equals to the sum of interference received by link e (Suppose all other links operate on channel f). Thus, this constraint can be directly used in an ILP solver, like LINDO.

$$\sum_{e'(\neq e)\in E} IM_{ee'}C_{e'f} \leq BC_{ef} + (1 - C_{ef}) \sum_{e'(\neq e)\in E} IM_{ee'} \forall e \in E, \forall f \in F \tag{3.6}$$

The number of binary variables in this model is $EF + E$ (EF is for C_{ef} and E is for X_e) and the number of constraints is equal to $E + Z + EF$ (E, Z and EF are for constraint 3.2, constraint 3.3 and constraint 3.6 respectively), where E is the number of links in the reachability graph, Z denotes the number of nodes having degree greater than K in the reachability graph and F denotes the number of available channels.

[1] Thanks to Dr. Sasthi C. Ghosh helped in formulating the interference models.

Chapter 4

Traffic Scheduling Solution

In this chapter, we will focus on traffic scheduling for ESS Mesh networks. We will restrict our focus to VoIP traffic. Our traffic scheduling solution will guarantee the integrity of both the new VoIP call and other active VoIP calls. With the assistance of a central controller, a decision whether or not to accept this new VoIP call will be made. Generally speaking, the most efficient method is to re-schedule all the active VoIP calls including the new one. The more VoIP calls that are in the system, the more time is needed for global optimization. It is intolerable if the time consumption of the optimization is large. In our approach, we split the complete scheduling process into three sub-processes: path selection, link selection and time slot and channel selection. We always try to determine the path first and then select links to assign the time slot and channel.

The path selection is actually a routing issue. Theoretically, the longer the path is, the easier it is for the traffic scheduling to break down. This is because more mesh MPs are involved, increasing the failure probability. From the interference point of view, if the traffic session is scheduled successfully, the longer the path is, the more interference the system must tolerate. Therefore, shortest path routing is used, as mentioned in Section 3.1.5 of Chapter 3. Moreover, in order to further simplify the problem, we only try one route when scheduling the traffic session. This route could be pre-defined or dynamically chosen from a set of shortest path routes. The details of path selection will be discussed in 4.1.

Link selection occurs directly after the path is selected. If one selected link is successfully assigned with a combination of time slots and channels, all the neighboring links will be blocked from using this combination. Here, the neighboring link means that if one link operates on the same slot-channel combination with the selected link, its maximal interference received from the selected link is above the pre-defined interference threshold. Since links are joined one-by-one to form a path, any link in the path has at least one neighboring link that is also in the path. Thus, assigning channels to links is a self-reflexive problem. If our channel assignment scheme fails on any link, we have to drop the traffic session immediately. Considering the efficiency of our traffic scheduling solution, it is better to select the link with more channel assignment difficulty in advance. In this thesis, we regard the current traffic load of the link as the weight of the link. The higher the traffic load, the higher the weight, and the more difficult a link can be assigned a channel successfully.

Once a link is discovered, our channel assignment scheme will be implemented. Generally, a channel assignment scheme has to make two decisions, selecting a time slot and selecting a channel. Based on the selection of the time slot and channel, we can have three mechanisms for channel assignment. One is to select the time slot prior to the channel; the other is to select the channel prior to the time slot. Another way to approach this problem is to select the time slot and the channel at the same time. Since the first two mechanisms are very similar, we can focus on one of them for performance investigation. In this thesis, we will either select the time slot prior to the channel or select time slot and channel at the same time.

In the remainder of this chapter, we will introduce the path selection and the channel assignment schemes.

4.1 Path Selection

As mentioned in Chapter 3, our network model is based on a reachability graph $G(N, E)$. For any two vertices $u, v \in N$, if $u \leftrightarrow v$ exists, we say u and v are neighboring nodes. Then, we can have a $|N| \times |N|$ matrix NEI to describe the neighboring relationship between any two vertices in N, where $|N|$ represents the number of vertices in $G(N, E)$. If $i \leftrightarrow j$, $NEI_{ij} = 1$, otherwise, $NEI_{ij} = 0$. Of course, NEI is a symmetric matrix, where $NEI_{ij} = NEI_{ji}$. Based on NEI, we can easily calculate the route between any two vertices through the shortest path routing protocol. Note that we always choose the shortest path route as our desired route. Any route that is not a shortest path will be filtered out. The reason for this is that in a reachability mesh network, for example in Fig. 3.1, even the shortest path of two MPs, say MP_{12} and MP_{13}, is only one hop, we can still easily find other routes whose number of hops is 3 ($\{12 \rightarrow 17 \rightarrow 18 \rightarrow 13\}$), 5 ($\{12 \rightarrow 17 \rightarrow 18 \rightarrow 19 \rightarrow 14 \rightarrow 13\}$), 7 ($\{12 \rightarrow 11 \rightarrow 10 \rightarrow 17 \rightarrow 18 \rightarrow 19 \rightarrow 14 \rightarrow 13\}$), etc. As mentioned in Chapter 3, we could have multiple shortest path routes for two MPs that are more than one hop away in the reachability graph. For simplicity, we only try one shortest path route in our traffic scheduling solution. Next we are going to introduce two path selection schemes, both of which are insensitive to interference as mentioned in Chapter 3.

1. Static Path Selection (Static PS)

   We pre-defined a shortest path for any two MPs. This path is randomly chosen from all the shortest path candidates and will never be changed, regardless of how bad the interference is, or how heavy the traffic load is on this path. If one link is overloaded, any new traffic session whose pre-defined path traverses this link will be dropped immediately. Static PS is an off-line solution and thus can save significant time on route computation. It requires obtaining the entire network topology in order to determine all of the shortest path routes. Since any mesh point is assumed not to change its location, it is very easy to figure out whether or not two particular mesh points can communicate with each other, and, thus, the entire network topology can be easily obtained. Since it can select a path quickly, Static PS is quite suitable for VoIP traffic that has a critical time delay requirement. On the other hand, since Static PS is insensitive to traffic load, it is possible for multiple pairs of MPs to select their paths traversing one particular link. Thus, if VoIP calls occur on these pairs of MPs simultaneously, some calls may be dropped because of the heavy traffic load on the particular link. This obviously degrades the system performance. Therefore, an on-line path selection scheme is needed to improve the system performance.

2. Dynamic Path Selection (Dynamic PS)

   In contrast to Static PS, Dynamic PS is an on-line solution which selects the best path from all the shortest path candidates. In order to find the best path, we need to perform the following steps. First, we assign a metric to each link, denoted as L_{metric}. Since we consider path selection and channel assignment separately in order to reduce the complexity, the link metric will only consider traffic load. In TDMA systems, the traffic load of a link can be regarded as the number of time slots being used, denoted as L_{slot}. Thus, L_{metric} is equal to L_{slot}. Second, we define the metric of a path candidate as the maximal L_{metric} of the link on the path, denoted as R_{metric}. Last, the path candidate with the minimal R_{metric} will be selected as best. The $MinMax$ algorithm mentioned above tries to provide a better condition for incoming channel assignment. The less traffic load that the link has, the more options the channel assignment can try, resulting in a higher success probability for channel assignment. Although it can not be guaranteed as the best solution for channel assignment, this channel assignment reflects the relationship between the path selection scheme and the channel assignment scheme. Obviously, Dynamic PS is more feasible than Static PS from a traffic load balance point of view and can improve the system performance.

Neither Static PS nor Dynamic PS considers interference issues; therefore, they cannot guarantee the success of the channel assignment. When our channel assignment scheme fails, we have to drop the corresponding traffic session. This dropping is called call blocking and the possibility of dropping is called the call blocking probability. The call blocking probability can be used to investigate the performance of a traffic scheduling solution, which will be discussed in Chapter 5. Another issue we will focus on in Chapter 5 is the computation time of our path selection schemes. There is a tradeoff between call blocking probability and computation time, which will also be revealed in Chapter 5.

4.2 Channel Assignment

In this section, we propose three channel assignment schemes. Each of them can co-operate with either Static PS or Dynamic PS path selection to provide a complete traffic scheduling solution. Before we go into the details, we must first introduce several key definitions. First, we define Assignment Searching as the attempt to assign one channel on one time slot of a link, regardless of success or failure. Given a selected path, we say a traffic session is scheduled successfully only when Assignment Searchings succeed on all the links on the selected path. These Assignment Searchings are called Assignment Searching combinations. In our channel assignment schemes, we set an upper bound for the number of Assignment Searchings on each link, denoted as $RETRY_{link}$. When $RETRY_{link}$ is reached and we still cannot find a scheduling solution, the channel assignment on this particular link will be regarded as a failure and the traffic session will be dropped. Obviously, the larger $RETRY_{link}$ is, the better the call blocking probability.

Second, we must define two terms associated with Assignment Searching. One is Channel Binding, which is defined as assigning a channel onto a time slot; The other is Slot

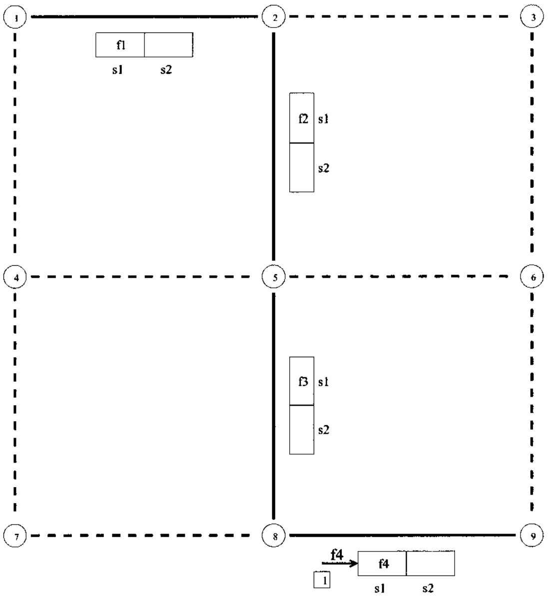

Figure 4.1: UCA

Binding, which is defined as assigning a time slot onto a traffic session. Both bindings will be determined if an Assignment Searching succeeds. Once a traffic session is scheduled into the system successfully, its corresponding Slot Bindings are always fixed throughout the session period. Any other traffic sessions are not permitted to alter these bindings. On the contrary, Channel Bindings are allowed to change, which will be discussed in our channel assignment schemes.

In the remainder of this chapter, we will introduce two time slot searching mechanisms, Direct Timeslot Searching (DIRTS) and Random Timeslot Searching (RANTS), and three channel assignment schemes: Unforced Channel Assignment (UCA), Perturbation Minimizing Channel Assignment (PMCA) and Slot-Channel Selection with Interference Awareness (SCSIA).

4.2.1 Time Slot Searching

Since both UCA and PMCA choose time slots prior to channel selection, the first problem to solve is how to select the time slot. In this section we derive two time slot searching mechanisms: DIRTS and RANTS.

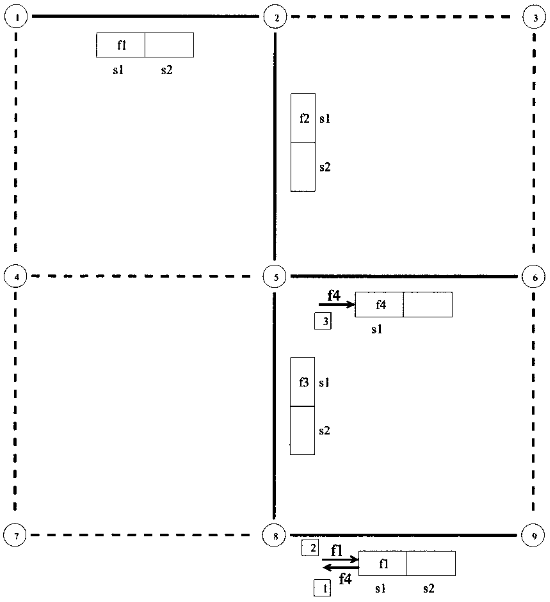

Figure 4.2: PMCA

1. DIRect Timeslot Searching (DIRTS)

   DIRTS is very simple to implement. It selects the first unused time slot in the superframe as the searching result. Then, the selected time slot will be marked as "used" and attempted by Assignment Searching. If Assignment Searching succeeds, a new link will be defined based on our link selection algorithm and then DIRTS and Assignment Searching will be implemented on the new link again. Otherwise, DIRTS will continue to select the next unused time slot as the candidate. If it cannot find an unused time slot, the channel assignment on the particular link will fail and the traffic session will be dropped. The drawback of DIRTS is that the time slot is always ordered so that the time slot with a lower Slot Label has more simultaneous active links than one with higher Slot Labels. Therefore, it is more difficult to have successful Assignment Searching in the time slot with a lower Slot Label. The difficulty of Assignment Searching will eventually result in a poor call blocking probability.

2. RANdom Timeslot Searching (RANTS)

   In contrast to DIRTS, RANTS will first count the number of unused time slots and then randomly pick one. Similarly, after being selected, the time slot will be marked as "used" by Assignment Searching. If Assignment Searching fails, the number of unused time slots will decrease by 1 and a new time slot will be selected from the remaining unused ones. Compared with DIRTS, the time slots with lower Slot Label in RANTS have less simultaneous active links. In fact, if the traffic is uniformly distributed in the mesh, each time slot in RANTS will have an equivalent number of simultaneous active links. Therefore, RANTS will achieve a better call blocking probability than DIRTS, which will be further discussed in Chapter 5.

4.2.2 Channel Assignment Schemes

Once one unused time slot is found, a channel assignment scheme will be used to set up the Channel Binding. A successful Channel Binding requires two conditions to be met. First, the interference from other identical Channel Bindings (working on the same channel and the same time slot) should be below the interference threshold so that the new Channel Binding can receive the signal properly. The other condition is that the transmitting signal of the new Channel Binding should not destroy the transmissions on other identical Channel Bindings. These two conditions are necessary and should be obeyed by any channel assignment scheme. In order to reduce the complexity, we assume that picking a channel from a set of channels is based on an unchanging, pre-defined channel list. How one would make the channel list more efficient is outside the scope of this thesis, but could be a topic for future research.

Next, we propose three channel assignment schemes: Unforced Channel Assignment (UCA), Perturbation Minimizing Channel Assignment (PMCA) and Slot-Channel Selection with Interference Awareness (SCSIA). Here, both UCA and PMCA will choose the time slot prior to the channel, while SCSIA will choose the time slot and channel at the same time.

Unforced Channel Assignment (UCA)

UCA is a greedy channel assignment scheme. It picks up a channel from the channel list and tries to bind the channel to the time slot selected by either DIRTS or RANTS. If the interference conditions are satisfied, UCA is successful. Otherwise, it will try the next channel on the channel list. If none of the channels can be assigned successfully, it means that Channel Binding fails on the selected time slot and our time-slot searching scheme will try to find another unused time slot. Since it only assigns the channel to the selected time slot, UCA will create new Channel Bindings but never change existing Channel Bindings. Once the new Channel Bindings are created, they will be kept until the corresponding traffic session is terminated.

Fig. 4.1 gives us an example, where we assume an ESS Mesh with a 3×3 grid topology and 4 available non-overlapping channels ($\{f_1, f_2, f_3, f_4\}$). For simplicity, we consider a non-cumulative interference model, which means the interference only comes from neighboring MPs. We also assume that each superframe has 2 time slots, marked as 1 and 2, respectively. Moreover, traffic sessions only occur between neighboring MPs such that their routes are one hop. In this example, we have 4 traffic sessions scheduled with UCA as follows:

1. Traffic T_1 on link $1 \leftrightarrow 2$; Slot Binding: $\{T_1, s_1\}$; Channel Binding: $\{s_1, f_1\}$
2. Traffic T_2 on link $2 \leftrightarrow 5$; Slot Binding: $\{T_2, s_1\}$; Channel Binding: $\{s_1, f_2\}$
3. Traffic T_3 on link $5 \leftrightarrow 8$; Slot Binding: $\{T_3, s_1\}$; Channel Binding: $\{s_1, f_3\}$
4. Traffic T_4 on link $8 \leftrightarrow 9$; Slot Binding: $\{T_4, s_1\}$; Channel Binding: $\{s_1, f_4\}$

As can be seen, these 4 traffic sessions pick up channels from the 4-channel list and set up their corresponding Channel Bindings, all of which are relative to time slot 1. If a 5th traffic session comes into the network, it will realize that it is impossible to bind a channel onto time slot 1 because all of the channels on the list have interference problems. Thus, it has to go to time slot 2 for channel assignment. This means that the maximum number of simultaneously active links in this case is 4. In order to improve the maximal value, we propose another channel assignment scheme, called Perturbation Minimizing Channel Assignment (PMCA).

Perturbation Minimizing Channel Assignment (PMCA)

In PMCA, we first select an unused time slot using either DIRTS or RANTS. Then, we choose a channel from the channel list for Channel Binding. If the channel can be bound to the selected time slot without any adjustment, the channel assignment is successful and PMCA works like UCA (at this point). Otherwise, a special adjustment is required. The adjustment is to change the existing Channel Bindings working on the same time slot and the same channel such that a new Channel Binding can be found for the link candidate. Here, changing the existing Channel Binding means to bind another channel onto the original selected time slot.

One important point is that any change of Channel Binding may destroy other Channel Bindings and thus trigger more changes. This effect will not stop until all the Channel Bindings in the mesh satisfy their necessary interference conditions. This type of effect is called perturbation. Theoretically, it is possible to find multiple perturbations for the channel assignment solution. The question is which perturbation is best. In this thesis, we define a term, cost, as the number of changes of Channel Bindings in a given perturbation. The more changes the perturbation has, the higher the cost. We will choose the perturbation with minimal cost as our final channel assignment solution, which is called Perturbation Minimizing. In theory, Perturbation Minimizing is an NP-complete problem with general breadth level and depth level, as discussed in [19]. Here, we denote B_{level} and D_{level} as the breadth and depth of perturbation, respectively. Obviously, the computing complexity of Perturbation Minimizing is $O((|\{F\}| \times B_{level})^{D}_{level} \times |\{F\}|)$. In order to reduce the computational complexity, one has to heuristically limit the breadth level and depth level of the perturbation.

Limiting the breadth level and depth level of the perturbation can obviously solve the Perturbation Minimizing problem much faster. But this is still not enough. In order to discover the best perturbation, one has to know all the perturbations with limited breadth and depth. This leads to long compute times and thus is not suitable for VoIP traffic. Therefore, we set a cost threshold, $COST^*$ heuristically. For a particular perturbation, if $COST^*$ is exceeded, we will stop the perturbation process and try another. Once the perturbation is found and its cost is less than or equal to the $COST^*$, we will regard the perturbation as our channel assignment solution and will not try any other perturbations. If the perturbation can not be found within the range of limited breadth level and depth level, we will give up the channel assignment on that particular time slot.

Obviously, PMCA is helpful in situations where UCA cannot find a solution but the theoretically maximal number of simultaneously active links in the given time slot has not yet been reached. An example is given in Fig. 4.2, whose traffic pattern is based on Fig. 4.1. In this figure, we consider one more traffic session T_5 on link $5 \leftrightarrow 6$. Since none of the 4 channels can satisfy the interference constraints, we have to drop the new traffic session by using UCA. However, with PMCA, if we change the Channel Binding on link $8 \leftrightarrow 9$ from $\{s_1, f_4\}$ to $\{s_1, f_1\}$ and then assign f_4 onto s_1 of link $5 \leftrightarrow 6$, all the active links can satisfy

	S_1C_1	S_1C_2	S_1C_3	S_2C_1	S_2C_2	S_2C_3
$Link_1$	3	2	4	1	5	**6**
$Link_2$	**4**	0	0	3	0	0
$Link_3$	0	1	0	0	0	4
$Link_4$	0	0	0	0	**8**	2
$Link_5$	2	0	0	0	0	3
$Link_6$	0	**6**	0	**5**	0	0
$Link_7$	0	0	3	0	0	3
$Link_8$	0	0	**5**	0	0	4
$Link_9$	0	3	0	0	0	0
$Link_{10}$	0	0	0	4	1	0

Figure 4.3: SCSIA

their interference constraints. Thus, the maximum number of simultaneously active links becomes 5 which is one more than that in UCA. Note that in this example, the perturbation cost is 1 because there is only one channel binding change.

1. Traffic T_1 on link 1 ↔ 2; Slot Binding: $\{T_1, s_1\}$; Channel Binding: $\{s_1, f_1\}$
2. Traffic T_2 on link 2 ↔ 5; Slot Binding: $\{T_2, s_1\}$; Channel Binding: $\{s_1, f_2\}$
3. Traffic T_3 on link 5 ↔ 8; Slot Binding: $\{T_3, s_1\}$; Channel Binding: $\{s_1, f_3\}$
4. Traffic T_4 on link 8 ↔ 9; Slot Binding: $\{T_4, s_1\}$; Channel Binding: $\{s_1, f_1\}$
5. Traffic T_5 on link 5 ↔ 6; Slot Binding: $\{T_5, s_1\}$; Channel Binding: $\{s_1, f_4\}$

Slot-Channel Selection with Interference Awareness (SCSIA)

Considering the system performance, both UCA and PMCA have the same shortcoming, which is that their Slot Binding is independent of their Channel Binding. Slot binding does not consider the interference issue while channel binding does. Once the Slot Binding is selected, it will not change throughout the active period of the traffic session. It is quite possible that a failed traffic session scheduling would be successful if we had changed some active slot bindings. However, the change of Slot Bindings and the change of Channel Bindings are relative to each other. This situation resembles a dead-lock loop and makes the problem overly complicated. In this section, we will consider a new channel assignment scheme that is fundamentally different from UCA and PMCA. This scheme is aware of the interference and will assign both the Slot Binding and the Channel Binding at the same time. It is called Slot-Channel Selection with Interference Awareness (SCSIA).

Basically, SCSIA maintains an $E \times F$ Cumulative Interference Matrix (CIM) for each time slot in the TDMA superframe, where E and F represent the number of links and the number of channels, respectively. The element in the matrix, CIM_{ij}, indicates the current received cumulative interference if link i works on channel j in the particular time slot. Based on CIMs, we are trying to find the slot-channel combination that will minimize interference. Obviously, each column of CIMs stands for one slot-channel combination that can be used for Assignment Searching. During Assignment Searching, we first select a column in one CIM as the candidate column so as to select the slot-channel combination. Then, we update the corresponding cumulative interference listed in the candidate column by assuming that the selected slot and channel are bound to the target link. Next, we find the element with maximal cumulative interference and regard it as the characteristic value of this slot-channel combination. After reviewing all the slot-channel combinations, we choose the one with the minimal characteristic value as our final solution. This Min-Max selection can fairly distribute interference to the whole system.

An example is given in Fig. 4.3. Suppose we have 3 available channels (C_1, C_2 and C_3) and 10 links (from $Link_1$ to $Link_{10}$) in the system. We are going to assign a channel to $Link_1$ that only has 2 unused time slots, S_1 and S_2. Fig. 4.3 gives us the current cumulative interference. For simplicity, we set the element value as an integer. Note that when the element in Fig. 4.3 is equal to 0, it means that the link does not operate at the particular channel on the particular time slot. With the *MinMax* policy mentioned above, we can easily pick $S_1 - C_1$, whose characteristic value is only 4, as our solution. If the characteristic value of $S_1 - C_1$ is less than the pre-defined interference threshold, we can claim that the SCSIA channel assignment succeeds.

Obviously, SCSIA will spend more computing time than UCA and PMCA because all possible slot-channel candidates are checked, especially when the number of available slot-channel candidates is large.

```
$PATH_{T_i}$ = PathSelection ($T_i$)
for $Link_j \in PATH_{T_i}$
    while $RETRY_{link}$ has not been reached
        if UCA($Link_j$) (or PMCA($Link_j$) or SCSIA($Link_j$)) succeeds
            break
        else
            if $RETRY_{link}$ has been reached
                return FALSE
            end
        end
    end
end
return TRUE
```

Figure 4.4: New Traffic Session Scheduling Solution

4.2.3 Pseudo Code of Traffic Session Scheduling

To summarize, we show our traffic session scheduling process in Fig. 4.4, where the new traffic session is T_i.

Chapter 5

Simulation

In Chapter 4, we introduced two path selection and three channel assignment schemes. Our traffic scheduling solution can be any combination of the path selection and channel assignment schemes. In order to investigate the performance of these algorithms, detailed simulations were performed. In this chapter, we discuss the details of the simulations, including assumptions, results and analysis.

5.1 Assumptions

1. ESS Mesh

   It is assumed that the ESS Mesh has a grid topology. Each MP can only directly communicate with other MPs one hop away. This implies that each MP has up to 4 neighboring MPs in the grid topology. This assumption standardizes the metric of route to hop count so that shortest path routing protocols can be easily implemented. We also assume that each MP is allowed to have up to 4 IEEE 802.11 radios. Those multiple radios can guarantee simultaneous communication between one MP and its 4 possible neighboring MPs.

2. Traffic

   As mentioned in Chapter 3, only deterministic traffic (for example, VoIP calls) is considered. In the simulations, we assume that VoIP calls arrive to the network according to a Poisson process. The unit of traffic arrival rate is calls per second.

Data Rate (Mbps)	1	2	5.5	11
SINR Threshold (dB)	11	14	18	21

Figure 5.1: SINR Threshold for Different Data Rate of IEEE 802.11b

For example, a 0.1 arrival rate means 0.1 calls per second, or 360 calls per hour. If the mesh is a 6 × 6 grid where each MP has 10 mobile clients on average, then each mobile client will have 1 call per hour. If the mesh a 4 × 4 grid where each MP has 10 mobile clients on average, then each mobile client will have 2.25 calls per hour. When a VoIP call occurs, the proposed traffic scheduling solution is used to schedule it into the system. If the scheduling fails, the call has to be dropped. We regard the call dropping behavior as call blocking. The ratio between the number of call blockings and the number of call arrivals is defined as call blocking probability. In the simulations, each simulation run will simulate 30000 call arrivals, each of which lasts 60 seconds.

3. PMCA

   In the PMCA channel assignment scheme, we limit the breadth and depth levels in order to arrive at a solution heuristically. The breadth level is less than the cost threshold, $COST^*$ and the depth level is equal to 1. This implies that the perturbation will be terminated on the second depth level. Once the perturbation stops, UCA will be used for the second depth level to find the channel assignment solution.

4. Transmission Rate

   As was mentioned in Chapter 2, IEEE 802.11 supports different transmission rates, depending on different interference conditions. Fig. 5.1 gives the relationship between transmitting rate and SINR threshold [20] in IEEE 802.11b. Obviously, when we change the transmission rate, the SINR threshold will also be changed. The higher the transmission rate, the higher the SINR threshold. On the other hand, since the length of the superframe is presumed to be always 20ms, the number of time slots per superframe will change as the transmission rate changes. Basically, the higher the transmission rate, the larger the number of time slots.

In the remainder of this chapter, we investigate the performance of our traffic scheduling solution. The investigation will first focus on validating both non-cumulative and cumulative interference models mentioned in Chapter 3. Then, we will concentrate on comparing channel assignment and path selection schemes, based on different interference models and other system parameters, such as the number of channels, radios, MPs, etc.

5.2 Validation of Optimization Formulation

In order to validate the interference model mentioned in Chapter 3, we designed a special simulation in which the traffic session only occurs between neighboring MPs. Thus, the shortest path for every traffic session is one hop. Furthermore, the total number of time slots in the superframe is set to 1 for simplification. With this special design, we can eliminate the impact of path selection schemes and obtain the best possible performance of our channel assignment schemes. Therefore, the performance value from simulation is comparable with that from the interference model.

In order to obtain the theoretical performance from the interference model, we use a ILP solver, LINDO, to solve the formula proposed in Chapter 3. (The LINDO code[1] is listed in the Appendix.) Fig. 5.2 provides the comparison between simulation results and mathematics results, based on different system parameters, such as the number of radios, the number of channels and the network size. Note that Maths1 and Sim1 are for the non-cumulative interference model, and Maths2 and Sim2 are for the cumulative interference model, respectively. Specifically, the system parameters for the cumulative interference model are 11Mbps transmission rate and 2.0 path loss exponent. This result obviously shows that our channel assignment scheme can achieve the same system performance as the mathematical model. This not only validates our interference model but also verifies the performance of our channel assignment schemes. However, this result is conditioned on a special design where all traffic sessions are between neighboring MPs. Considering a more realistic traffic session with multihop paths, it is not adequate to show the performance of our channel assignment schemes. Therefore, in Section 5.3, we will implement more complex simulations to analyze their performance.

[1] Thanks to Dr. Sasthi C. Ghosh for help with the optimization.

MPs	Radios	Channels	Maths1	Sim1	Maths2	Sim2
16	2	3	12	12	3	3
16	2	4	16	16	4	4
16	2	5	16	16	5	5
16	3	3	12	12	3	3
16	3	4	16	16	4	4
16	3	5	20	20	5	5
16	4	3	12	12	3	3
16	4	4	16	16	4	4
16	4	5	20	20	5	5
25	2	3	17	17	6	6
25	2	4	21	21	8	8
25	2	5	24	24	10	10
25	3	3	17	17	6	6
25	3	4	22	22	8	8
25	3	5	26	26	10	10
25	4	3	18	18	6	6
25	4	4	22	22	8	8
25	4	5	26	26	10	10

Figure 5.2: Validation of Optimization Formulation

5.3 Simulation Results

5.3.1 Investigation of Channel Assignment Schemes

Fig. 5.3 and Fig. 5.4 show the change of call blocking probability and average computation time under the impact of traffic arrival rate, where the star solid line, the x solid line and the square solid line are UCA, PMCA and SCSIA, respectively.

As can be seen in Fig. 5.3, the blocking probability increases when the traffic arrival rate increases for all three schemes, due to the increasing traffic in the system. Moreover, the call blocking probability does not increase linearly. The higher the traffic arrival rate, the higher the increasing rate of call blocking probability. The reason for this is that under the cumulative interference model, multiple weak interferers can accumulate and cause strong interference, which will be enough to exceed the interference threshold. It is necessary to mention that when the traffic arrival rate changes from 0.1 to 0.2, the call

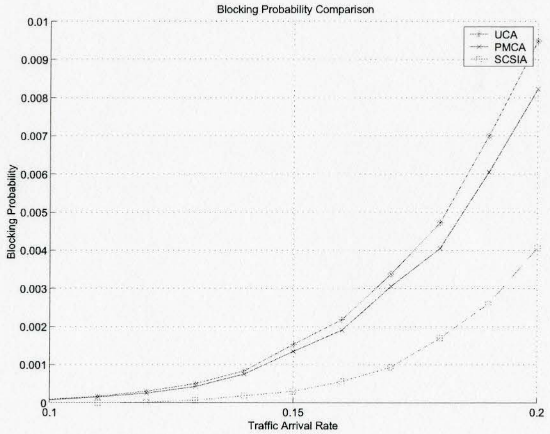

Figure 5.3: Channel Assignment Scheme Comparison with cumulative interference criterion: traffic session blocking probability, 4 grid mesh, 5 channels, 4 radios, 11Mbps transmission rate, 2.8 pathloss exponent, random timeslot searching with 3 searching tries, static path selection

blocking probabilities of UCA, PMCA and SCSIA vary from 0 to 0.95%, 0.82% and 0.4%, respectively. Obviously, SCSIA has a better call blocking probability than the other two and PMCA always outperforms UCA. If we focus on the performance improvement, we can see that higher traffic arrival rates have better performance improvements. For example, compared to the traffic arrival rate between 0.2 and 0.15, the improvement of PMCA versus UCA is from 0.95% to 0.82% (0.13 difference) and from 0.15% to 0.14% (0.01 difference), and the improvement of SCSIA versus UCA is from 0.95% to 0.4% (0.55 difference) and from 0.15% to 0.03% (0.12 difference). This is because a higher traffic arrival rate provides more opportunity for PMCA and SCSIA to solve the problem that UCA cannot solve.

The average computing time to schedule a traffic session increases when we increase the traffic arrival rate, as shown in Fig. 5.4. The average computing time of UCA is less than that of PMCA and SCSIA, and SCSIA always consumes more time than PMCA to find the channel assignment solution. Numerically, UCA, PMCA and SCSIA will spend around $20\mu sec$, $25\mu sec$ and $120\mu sec$, respectively. Considering the length of time slot discussed in Chapter 3, the assignment searching delay is reasonable and acceptable. We also note that there is a tradeoff between the call blocking probability and the average computing time. A better call blocking probability requires a longer time delay. If call blocking probability is the biggest concern, SCSIA is the best choice. If the average computation time is more

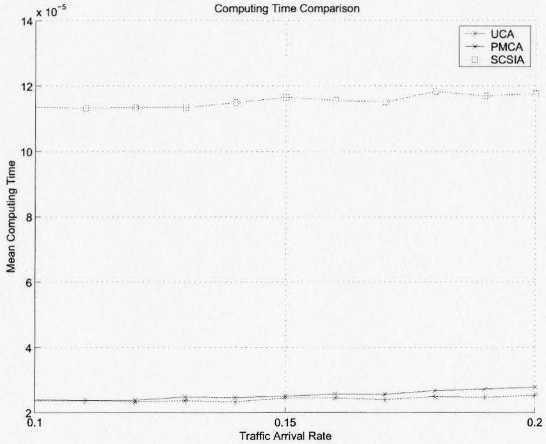

Figure 5.4: Channel Assignment Scheme Comparison with cumulative interference criterion: average computing time, 4 grid mesh, 5 channels, 4 radios, 11Mbps transmission rate, 2.8 pathloss exponent, random timeslot searching with 3 searching tries, static path selection

important, PMCA is then a good option, since it can guarantee not only short time delay but also an acceptable call blocking probability.

5.3.2 Investigation on Different Number of Channels

We now focus on performance comparisons between the number of channels. The simulation is also based on a 4×4 grid ESS Mesh using a cumulative interference criterion. Each MP is equipped with 4 radios and the transmission rate is 11Mbps with a 2.8 path loss exponent. Throughout the comparison, we only consider static path selection.

Fig. 5.5 illustrates the impact of the number of channels on different channel assignment schemes. Here, we compare PMCA and SCSIA with 3 and 5 channels. Note that star solid line, x solid line, square solid line and circle solid line correspond to SCSIA with 3 channels, SCSIA with 5 channels, PMCA with 3 channels and PMCA with 5 channels, respectively. The figure shows that SCSIA always outperforms PMCA, regardless of the traffic arrival rate and the number of channels. We can also see that SCSIA can achieve more improvement versus PMCA in the 3-channel case than in the 5-channel case. For example, if we look at the call blocking probability at 0.4%, SCSIA increases the support traffic arrival rate from 0.065 to 0.09 (0.025 difference) with 3 channels and from 0.18 to 0.2 (0.02 difference) with

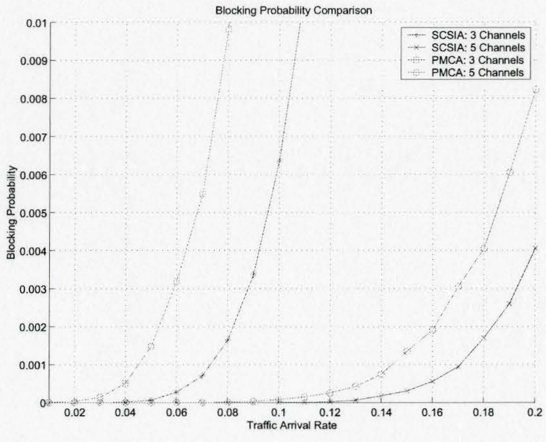

Figure 5.5: Number of Channels Comparison with cumulative interference criterion: traffic session blocking probability, 4 grid mesh, 4 radios, 11Mbps transmission rate, 2.8 pathloss exponent, random timeslot searching with 3 searching tries, static path selection

5 channels. When the number of channels is too small, it is difficult for PMCA to swap channel bindings. Therefore, SCSIA is highly recommended to replace PMCA when there is a lack of channels. On the contrary, if the number of channels is adequate, it is better to use PMCA instead of SCSIA in order to shorten the average computation time.

5.3.3 Investigation on Timeslot Searching Schemes

As mentioned in Section 4.2, SCSIA only needs one assignment search pass because it always considers all the slot-channel combinations automatically. Thus, the investigation of timeslot searching will only focus on UCA and PMCA. Our simulation runs in a 4×4 grid, which is configured to have 5 available channels, 4 radios for each MP, 11Mbps transmission rate and 2.8 path loss exponent.

Fig. 5.6 illustrates the performance of PMCA with respect to call blocking probability, where the square solid line and circle solid line depicts DIRTS and RANTS, respectively. As can be seen, RANTS always outperforms DIRTS. This is because DIRTS always begins assignment searching along a fixed time slot sequence, whereas RANTS randomly selects a time slot for assignment searching. Therefore, DIRTS's failure probability is larger than that of RANTS. In the simulation, we set $Retry_{limit}$ to 5 which is just half the number of time slots in one superframe, which means it is not possible for DIRTS to test all the

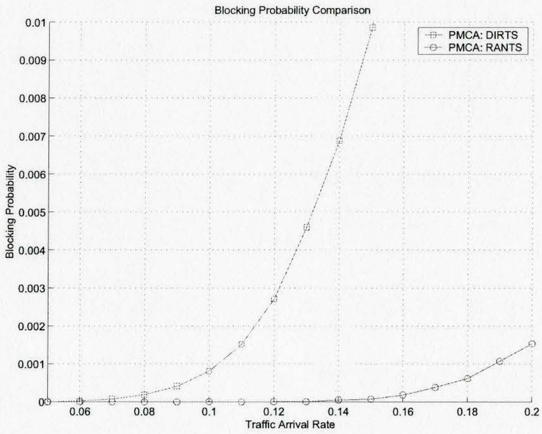

Figure 5.6: Timeslot Searching Schemes Comparison with cumulative interference criterion: traffic session blocking probability, 4 grid mesh, 5 channels, 4 radios, 2.8 path loss exponent, static path selection

available time slots, especially those time slots near the end of the superframe. On the contrary, RANTS has the chance to try those time slots near the end of the superframe. Thus, DIRTS results in a larger call blocking probability than RANTS. Another thing we need to consider is that the performance improvement of RANTS increases as the traffic arrival rate increases. This can clearly be observed from the figure.

Fig. 5.7 shows the average computation time comparison between DIRTS (square solid line) and RANTS (circle solid line). The result shows that RANTS can also achieve much better average computation time than DIRTS. For example, when the traffic arrival rate varies from 0.05 to 0.2, the compute time of DIRTS changes from 66μs to 200μs, while that of RANTS is from 35μs to 50μs. The explanation is the same as that for the call blocking probability, as seen in previous figures. Fig. 5.7 also reveals that the increase in rate of either DIRTS or RANTS is very linear as the traffic arrival rate increases. However, the increasing rate of DIRTS is larger than that of RANTS.

Both Fig. 5.6 and Fig. 5.7 are based on the same condition that $Retry_{limit}$ is fixed at 5. In Fig. 5.8, we illustrate the performance under a different $Retry_{limit}$. In the simulation, we consider 5, 7 and 9 as the $Retry_{limit}$. As we can see in the figure, star solid line, square solid line and diamond solid line represent 5, 7 and 9 $Retry_{limit}$ of DIRTS, respectively, while x solid line, circle solid line and plus solid line are for 5, 7 and 9 $Retry_{limit}$ for RANTS, respectively. We note that an increasing $Retry_{limit}$ results in a decrease in blocking

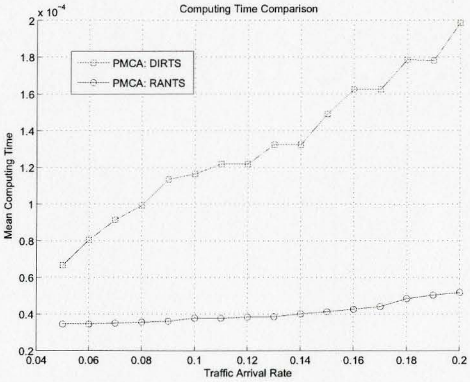

Figure 5.7: Timeslot Searching Schemes Comparison with cumulative interference criterion: traffic session blocking probability, 4 grid mesh, 5 channels, 4 radios, 2.8 path loss exponent, static path selection

probability. For example, when the traffic arrival rate is 0.2, the blocking probability for 5, 7 and 9 $Retry_{limit}$ of RANTS is 0.3%, 0.18% and 0.15%, respectively. Furthermore, the smaller the $Retry_{limit}$, the more performance improvement RANTS can achieve over DIRTS. Especially when $Retry_{limit}$ is large, both time slot searching schemes have very similar performance. For example, if we fix the blocking probability at 0.1%, the improved traffic arrival rate of RANTS over DIRTS with 5, 7 and 9 $Retry_{limit}$ is from 0.01 to 0.17, from 0.1 to 0.186 and from 0.16 to 0.19, respectively. This is because the large $Retry_{limit}$ can provide enough chances for DIRTS to consider all the available time slots.

From the 3 figures above, we conclude that RANTS is the preferred time slot searching option, considering both call blocking probability and average computation time.

5.3.4 Investigation of Transmission Rate

The IEEE 802.11 standard allows radios to operate at different transmission rates. Of course, different transmission rates require different SINR thresholds as shown in Fig. 5.1. The higher the SINR threshold, the higher the transmission rate. Moreover, if we fix the length of the superframe, the higher the transmission rate, the smaller the time slot and therefore the larger the number of time slots. In this simulation, we investigate the impact of transmission rate to system performance based on a 4 × 4 mesh network with 5 available channels, 4 radios for each MP and a 2.8 path loss exponent.

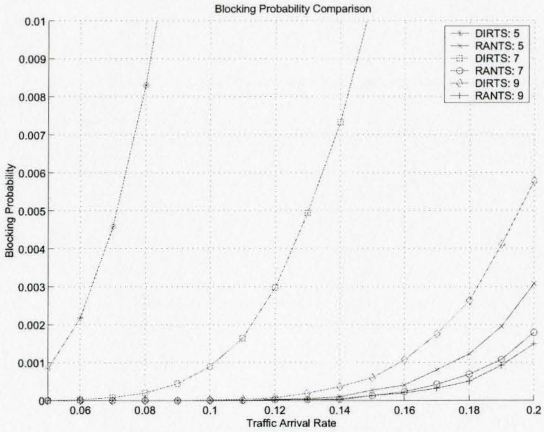

Figure 5.8: Timeslot Searching Schemes Comparison with cumulative interference criterion: traffic session blocking probability, 4 grid mesh, 5 channels, 4 radios, 2.8 path loss exponent, static path selection

First consider Fig. 5.9. In this figure, SCSIA is the default channel assignment scheme. We compare the performance of 2Mbps, 5.5Mbps and 11Mbps, which are described by the star solid line, x solid line and square solid line, respectively. It is clear that increasing the transmission rate can increase the system performance. For example, given a 0.4% blocking probability, the traffic arrival rate supported by 2Mbps, 5.5Mbps and 11Mbps is 0.07, 0.13 and 0.20, respectively. This implies that although a higher transmission rate results in a higher SINR requirement, the increase in the number of time slots still dominates the system performance and can definitely compensate for the performance degradation from the increasing SINR threshold.

Fig. 5.10 gives a comparison between PMCA and SCSIA with different transmission rates: 5.5Mbps and 11Mbps. The star solid line, x solid line, square solid line and circle solid line represents PMCA with 5.5Mbps, SCSIA with 5.5Mbps, PMCA with 11Mbps and SCSIA with 11Mbps, respectively. We can see that compared with PMCA, SCSIA produces a more significant improvement under 11Mbps than under 5.5Mbps. For example, suppose the required blocking probability is 0.4%, SCSIA can improve the traffic arrival rate from 0.12 to 0.13 under 5.5Mbps and from 0.18 to 0.20 under 11Mbps. This means that the higher the transmission rate, the better the system performance SCSIA can achieve.

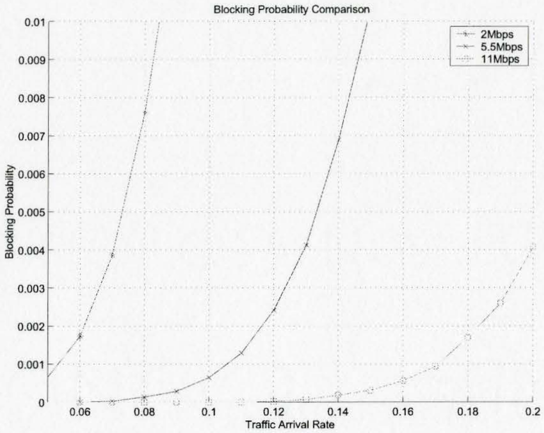

Figure 5.9: Transmission Rate Comparison with cumulative interference criterion: traffic session blocking probability, 4 grid mesh, 5 channels, 4 radios, 2.8 pathloss exponent, SCSIA with static path selection

5.3.5 Investigation of the Distance between Neighboring MPs

As mentioned in Chapter 3, the interference between two MPs is based on the path loss model (Equation 3.1), where the distance between two MPs is the key factor dominating the strength of the interference, especially when the transmission power of each MP is fixed. The larger the distance, the higher the path loss value. In this section, we investigate the impact of distance on different channel assignment schemes.

In Fig. 5.11, the system performance comparison between 100 meters and 250 meters is given. The star solid line and x solid line represent SCSIA with 100m distance and SCSIA with 250m distance. Obviously, the 250-meter grid system can achieve better call blocking probability than the 100-meter system. For example, under 0.21 traffic load, the 250m grid system has a 0.6% call blocking probability, while the 100m grid system has a 0.8% call blocking probability. This is a 25% performance improvement.

Fig. 5.12 shows a comparison between a 100-meter grid and a 250-meter grid when using PMCA and SCSIA channel assignment algorithms. As we can see, star solid line, x solid line, square solid line and circle solid line represents PMCA with 100m distance, SCSIA with 100m distance, PMCA with 250m distance and SCSIA with 250m distance, respectively. There are two important issues with this figure. First, when increasing the distance, PMCA can achieve a much larger performance improvement than SCSIA. For

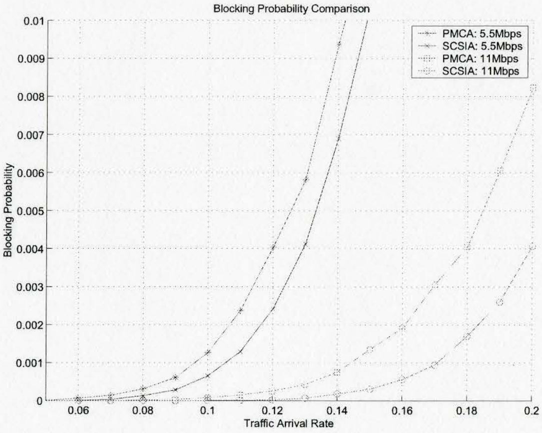

Figure 5.10: Transmission Rate Comparison with cumulative interference criterion: traffic session blocking probability, 4 grid mesh, 5 channels, 4 radios, 2.8 pathloss exponent, random timeslot searching with 3 searching tries, static path selection

example, with a 0.4% blocking probability, the traffic arrival rate for PMCA increases from 0.15 to 0.18 (0.03 improvement), while SCSIA supports from 0.193 to 0.20 (0.007 improvement). Second, when increasing the distance compared with PMCA, SCSIA can achieve a better performance improvement under a 100m distance than under a 250m distance. For example, with a 0.4% blocking probability, SCSIA supports 0.043 higher traffic arrival rate than PMCA under the 100m distance, while the difference is 0.02 using the 250m distance. This is because a larger distance results in a larger physical size for the mesh network, such that one active link assigned with a channel will block fewer links operating at that same frequency. Therefore, PMCA could have more perturbation opportunities to achieve a successful channel assignment solution. Although SCSIA can also obtain performance improvements over larger distances, its improvement is not comparable with that of PMCA.

5.3.6 Investigation of Path Selection

Now, we compare the performance between static path selection and dynamic path selection. The comparison is based on a 5×5 grid with 5 available channels, 4 radios for each MP and a 2Mbps transmission rate.

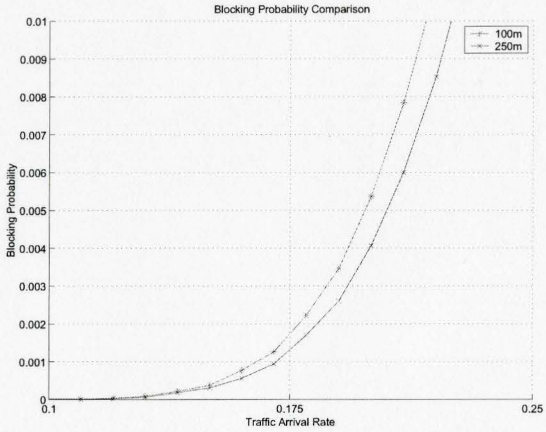

Figure 5.11: Distance Comparison with cumulative interference criterion: traffic session blocking probability, 4 grid mesh, 5 channels, 4 radios, 11Mbps, 2.8 pathloss exponent, SCSIA with static path selection

Fig. 5.13 and Fig. 5.14 show a comparison of blocking probability and average computation time, both of which are based on the cumulative interference model and simulated by UCA and PMCA. Obviously, dynamic path selection outperforms static path selection, regardless of which channel assignment scheme is used. For example, given a 0.4% call blocking probability, the traffic arrival rates of UCA are 0.135 and 0.14 for static and dynamic path selections, respectively, while PMCA has 0.16 for static path selection and 0.172 for dynamic path selection. Moreover, dynamic path selection can achieve a better performance improvement in PMCA compared to UCA. Consider the 0.4% call blocking probability. The improvement of dynamic path selection for UCA and PMCA are 0.005 and 0.012, respectively. In Fig. 5.14, dynamic path selection has to pay more in computation time in order to achieve better performance. When traffic load is light, these two path selections have very close average computation times. As the traffic load goes to higher levels, dynamic path selection needs more time to find the solution.

Fig. 5.15 also gives us a comparison under the non-cumulative interference model. We can see that the improvement of dynamic path selection is much larger than that in the cumulative interference case. This is because the non-cumulative interference model can provide more opportunities for one particular route to satisfy the interference constraints.

From the above comparisons between static and dynamic path selection schemes, we can see that if traffic load is low, the dynamic path selection scheme is highly recommended

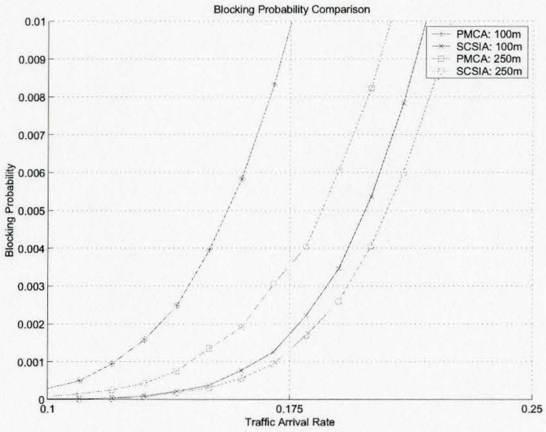

Figure 5.12: Distance Comparison with cumulative interference criterion: traffic session blocking probability, 4 grid mesh, 5 channels, 4 radios, 11Mbps, 2.8 pathloss exponent, random timeslot searching with 3 searching tries, static path selection

with either a cumulative or non-cumulative interference model and that if traffic load is high, we need to pay attention to the tradeoff between system performance and average computation time.

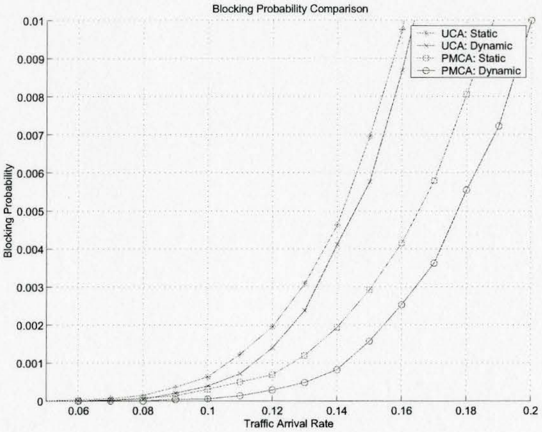

Figure 5.13: Path Selection Comparison with cumulative interference criterion: traffic session blocking probability, 5 grid mesh, 5 channels, 4 radios, 2Mbps, 2.8 pathloss exponent, random timeslot searching with 3 searching tries

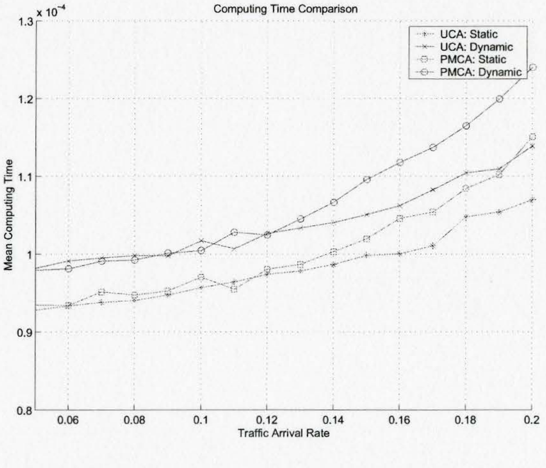

Figure 5.14: Path Selection Comparison with cumulative interference criterion: average computing time, 5 grid mesh, 5 channels, 4 radios, 2Mbps, 2.8 pathloss exponent, random timeslot searching with 3 searching tries

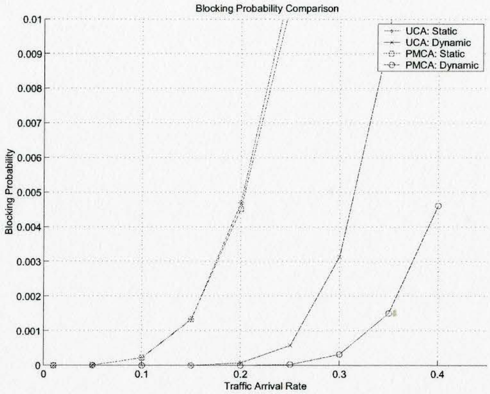

Figure 5.15: Path Selection Comparison with non-cumulative interference criterion: traffic session blocking probability, 5 grid mesh, 5 channels, 4 radios, 2Mbps, 2.8 pathloss exponent, random timeslot searching with 3 searching tries

Chapter 6

Conclusion

In this thesis, we investigated scheduling solutions for deterministic traffic, specifically for VoIP calls, in ESS Mesh networks. Our scheduling solution is a combination of a path selection and a channel assignment scheme. Based on shortest path routing, we derived both static and dynamic path selection schemes. Based on TDMA MAC over CSMA/CA MAC, we derived Unforced Channel Assignment (UCA), Perturbation Minimizing Channel Assignment (PMCA) and Slot-Channel Selection with Interference Awareness (SCSIA) schemes. We also formulated a mathematical model to obtain the maximum number of simultaneously active links per time slot, considering both cumulative interference and non-cumulative interference.

Our simulation first validated the mathematical model whose theoretical value is obtained from an ILP solver. Then, we investigated the performance of our scheduling solution based on different simulation cases, such as the comparison between channel assignment schemes, the comparison between different numbers of channels, the comparison between timeslot searching schemes, the comparison between different transmission rates, the comparison between different AP-to-AP distances and the comparison between path selection schemes.

Some conclusions can be made from these comparisons. First, there is a tradeoff between system performance (call blocking probability) and system cost (computation time). PMCA and SCSIA can achieve better call blocking probability than UCA but require a longer computing time. Second, the number of non-overlapping channels is a significant factor for system performance; the larger the number of channels, the better the system performance. If the number of channels is adequate, PMCA is preferred over SCSIA, considering the balance between system performance and system cost. Third, under the same conditions, Random Timeslot Searching (RANTS) always outperforms Direct Timeslot Searching (DIRTS). Fourth, working at high transmission rates can achieve better system performance than working at low transmission rates. Fifth, an ESS Mesh with a larger size can achieve better system performance than one with a small network size. Sixth, Dynamic Path Selection can achieve better system performance than Static Path Selection but incurs more system cost. Based on these conclusions, we can build a traffic scheduling solution for any system resource condition.

Last but not least, we have outlined the future work that these lines of research need to undertake.

As mentioned in Chapter 1, we defined a MAC layer superframe consisting of a ρ portion operating in TDMA circuit-switched mode and the remaining $1 - \rho$ portion operating in packet-switched mode. We then proposed a traffic scheduling solution for deterministic traffic on the ρ portion. It will be a challenge to propose a traffic scheduling solution for non-deterministic traffic on the $1 - \rho$ portion.

Future work should focus on the interference issue. As was mentioned in Chapter 3, the interference considered was assumed only from inside of the same ESS Mesh. In reality, this is not the most accurate set of assumptions. Because the IEEE 802.11 ISM band is license free, it is quite common to receive interference from outside of the ESS Mesh from sources such as another ESS Mesh, an infrastructure WLAN or an ad hoc WLAN, as long as they operate on the same channel. Thus, it would be quite interesting to investigate the impact of these interferers.

Our scheduling solution is a centralized solution wherein everything is controlled by a Central Controller (CC). When a new VoIP call occurs, a scheduling request will be sent from the original source MP to CC. Once the scheduling solution is found, CC will signal all the relative MPs in the ESS Mesh. This request-schedule-signal process will undoubtedly occupy some system resources. From a utilization of system resources point of view, it is worth focusing on distributed traffic scheduling solutions in the future.

Appendix A

LINDO code

The LINDO code listed here is for a 4 × 4 grid ESS mesh with 5 available channels and 4 radios for each MP.

A.1 ILP file

```
Maximize
    X0+X1+X2+X3+X4+X5+X6+X7+X8+X9+X10+
    X11+X12+X13+X14+X15+X16+X17+X18+X19+
    X20+X21+X22+X23
    Subject to
    X0-C00-C01-C02=0
    X1-C10-C11-C12=0
    X2-C20-C21-C22=0
    X3-C30-C31-C32=0
    X4-C40-C41-C42=0
    X5-C50-C51-C52=0
    X6-C60-C61-C62=0
    X7-C70-C71-C72=0
    X8-C80-C81-C82=0
    X9-C90-C91-C92=0
    X10-C100-C101-C102=0
```

```
X11-C110-C111-C112=0
X12-C120-C121-C122=0
X13-C130-C131-C132=0
X14-C140-C141-C142=0
X15-C150-C151-C152=0
X16-C160-C161-C162=0
X17-C170-C171-C172=0
X18-C180-C181-C182=0
X19-C190-C191-C192=0
X20-C200-C201-C202=0
X21-C210-C211-C212=0
X22-C220-C221-C222=0
X23-C230-C231-C232=0
X3+X7+X9+X10¡=3
X5+X9+X11+X12¡=3
X10+X14+X16+X17¡=3
X12+X16+X18+X19¡=3
C00 + C10 ¡=1
C01 + C11 ¡=1
C02 + C12 ¡=1
...
...
C120 + C130 ¡=1
C121 + C131 ¡=1
C122 + C132 ¡=1
...
...
C220 + C230 ¡=1
C221 + C231 ¡=1
C222 + C232 ¡=1
Binaries
X0 X1 X2 X3 X4 X5 X6 X7 X8 X9 X10
X11 X12 X13 X14 X15 X16 X17 X18 X19
```

```
X20 X21 X22 X23
C00 C01 C02
C10 C11 C12
C20 C21 C22
C30 C31 C32
C40 C41 C42
C50 C51 C52
C60 C61 C62
C70 C71 C72
C80 C81 C82
C90 C91 C92
C100 C101 C102
C110 C111 C112
C120 C121 C122
C130 C131 C132
C140 C141 C142
C150 C151 C152
C160 C161 C162
C170 C171 C172
C180 C181 C182
C190 C191 C192
C200 C201 C202
C210 C211 C212
C220 C221 C222
C230 C231 C232
End
```

A.2 Solution

```
Integer optimal solution: Objective = 1.2000000000e+01
    Solution time = 0.00 sec. Iterations = 97 Nodes = 0
    NAME F3-k3-16.lp MIP Start
    X0 1
```

```
X1 0
X2 1
X3 0
X4 1
X5 0
X6 0
X7 1
X8 1
X9 0
X10 0
X11 1
X12 0
X13 1
X14 0
X15 1
X16 0
X17 0
X18 0
X19 0
X20 1
X21 1
X22 1
X23 1
C00 0
C01 0
C02 1
C10 0
C11 0
C12 0
C20 0
C21 1
C22 0
C30 0
```

```
C31 0
C32 0
C40 1
C41 0
C42 0
C50 0
C51 0
C52 0
C60 0
C61 0
C62 0
C70 1
C71 0
C72 0
C80 0
C81 1
C82 0
C90 0
C91 0
C92 0
C100 0
C101 0
C102 0
C110 0
C111 0
C112 1
C120 0
C121 0
C122 0
C130 0
C131 1
C132 0
C140 0
```

```
C141 0
C142 0
C150 0
C151 0
C152 1
C160 0
C161 0
C162 0
C170 0
C171 0
C172 0
C180 0
C181 0
C182 0
C190 0
C191 0
C192 0
C200 1
C201 0
C202 0
C210 1
C211 0
C212 0
C220 0
C221 1
C222 0
C230 0
C231 0
C232 1
ENDATA
```

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