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INTERFERENCE-AWARE RESOURCE MANAGEMENT IN MULTIHOP WIRELESS NETWORKS

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Azin Neishaboori

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The dissertation of Azin Neishaboori was reviewed and approved[1] by the following:

George Kesidis
Professor of Electrical Engineering and Computer Science and Engineering
Dissertation Advisor
Co-Chair of Committee

John F. Doherty
Professor of Electrical Engineering
Co-Chair of Committee

Constantino M. Lagoa
Associate Professor of Electrical Engineering

David J. Miller
Professor of Electrical Engineering

Jun Shu
Assistant Professor of Smeall College of Business

Kenneth Jenkins
Head of the Department of Electrical Engineering

[1]Signatures on file in the Graduate School.

Abstract

This thesis is written with an attempt to address some of the challenges of resource allocation in multihop wireless mesh and ad hoc networks. The main focus of this thesis is on CDMA although some of the design issues considered are applicable to TDMA networks. A framework on implementation of different network design components is suggested including power control, routing and scheduling. Also, the deployment issues of each of these network components are investigated and suggestions are made on their design to address the problems involved. These suggestions include a new distributed power control algorithm that provides end-to-end QoS guarantee, an SINR-sensitive link metric for routing, and a hybrid centralized-decentralized scheduling scheme. We also consider a relaying incentivization mechanism in the context of mesh networks for Internet access when selfish but rational users are present.

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[2]in alphabetical order

Myself when young did eagerly frequent

Doctor and Saint, and heard great Argument

About it and about: but evermore

Came out by the same Door as in I went.

–Omar Khayam Neishaboori

Translated by E. Fitzgerald

Chapter 1

Introduction

1.1 Our Network Model

This thesis addresses some of the problems involved with the design of multihop wireless Code Division Multiple Access (CDMA) networks [1–3]. Extension of some of the proposed methods is also considered in the context of Time Division Multiple Access (TDMA) networks, mainly addressing 802.11 standard [4].

1.1.1 Ad Hoc Networks

Wireless communication commonly involves a central infrastructure such as a Base Station (BS) in cellular settings. When such a central unit is not present, other forms of wireless networks may be used, e.g., ad hoc networks, mesh networks and Bluetooth (including "Scatternets"). While ad hoc and mesh networks typically communicate through multihop paths, in its basic form, Bluetooth communication is achieved through single hop transmissions.

Multihop ad hoc networks have been considered important candidates for addressing the requirements of the emerging decentralized network application such as disaster recovery and tactical military. These networks are formed by a group of nodes that are not supported by any central infrastructure and therefore communicate with each other using only decentralized and distributed methods. Connections between out-of-range nodes in such settings is typically made feasible through multihop communication. The shared nature of wireless medium, the absence of any infrastructure to perform shared resource management, and the potentially conflicting requirements of nodes in an ad hoc setting therefore necessitates design of decentralized resource allocation mechanisms. As these mechanisms require close cooperation among the nodes, ad hoc networks are very vulnerable to malicious and even selfish user behaviors. Certain limitations such as limited power and computational capabilities of nodes in ad hoc networks further complicate the design of these systems.

Resource allocation schemes in a multihop wireless ad hoc network include components such as link activation scheduling, transmission power control, routing and admission control. In this thesis, we address some of the issues involved with the design of these components, with particular attention on ad hoc networks that use CDMA as their Media Access Control (MAC) scheme.

In the context of ad hoc CDMA networks, our network model assumes the following: All nodes share the same frequency channel for communicating data and a separate frequency channel, Common Control CHannel (CCCH), may be considered for signaling and control messages. Each node has an omnidirectional antenna and communicates with other nodes by modulating a unique signature code for each distinct flow it transmits/relays. Time is assumed to be slotted and therefore all nodes need to have a common and relatively accurate estimation of time. We assume that the duration of time-slots is chosen such that in each time-slot a large number of data packets can be communicated. Therefore, a synchronization mechanism with a precision order of the duration of one time-slot is sufficient for such a setting [5, 6].

To estimate the Signal-To-Interference-plus-Noise Ratio (SINR) in CDMA settings, each node requires information about the path-gains of all nodes in its vicinity. We assume that the CCCH will be used to communicate messages related to path-gain announcements. Several possible methods could be used to obtain the path-gain information of which one is for each node to have a GPS and advertise its location periodically. Instead, each node can broadcast a probe message with a standard transmit power level so that the recipient nodes can measure received power and calculate their associated path-gains [7, 8]. Herein, we do not consider the effects of instantaneous variations of path-gain due to e.g. different fading effects and focus on average path-gain. Note that CDMA systems inherently suppress the adverse effects of frequency-selective fading by either suppressing the copies of the signal received with a delay relative to the first (or strongest) copy of the signal through the auto-correlation properties of code sequences, or take advantage of this effect through appropriate receiver design, i.e. use of RAKE receivers [9].

1.1.2 Mesh Networks

Broadband Wireless Mesh Networks (WMNs) for residential broadband access are formed by a group of end-users, called Mesh Clients (MC), and an infrastructure that supports and facilitates their communication with the Internet, see e.g. [10, 11]. The infrastructure is formed by a mesh of wireless nodes that are: (*i*) mostly static, (*ii*) relay but do not generate data traffic, and (*iii*) have more capabilities than MCs. These nodes are called Mesh Points (MPs) or Mesh Routers (MRs). Those MPs that are the direct access points of MCs are sometimes called Mesh Access Points (MAPs). In broadband WMNs, the infrastructure also includes some Mesh Gateways, a.k.a. Mesh Portals or Base Stations, that are connected to the backhaul Internet tier via e.g. fiber or a wireless Point-to-Multipoint (P2MP) protocol such as 802.16 (the interactions of BSs with the backhaul tier is out of the scope of this study). These networks aim to provide a variety of services over inexpensive Internet access for underprivileged communities to public safety (e.g. emergency services) [11]. The benefits and advantages of these networks is a subject of ongoing study. In particular, the prototypes of these networks have been implemented and are under study in e.g., MSR's mesh network project [10], MIT's Roofnet project [12], IIT's DGP project, Rice's TFA project [13] and Purdue's wireless mesh testbed project [14].

Regarding CDMA WMNs, the assumptions made for ad hoc networks in Section 1.1.1 also hold for their mesh counterparts. As these networks are more supported by infrastructure (e.g. BSs and MRs) compared to ad hoc networks, they can be designed more resilient to selfish or malicious behaviors via more sophisticated policing mechanisms.

1.2 Contributions

The contributions of this thesis are as follows. We suggest a framework for implementing multihop mesh networks based on CDMA. Our framework includes several time-scales each of which manages one component of the network, e.g. routing, scheduling or power control. Our proposed integration scheme addresses the requirements of delay-sensitive and delay-insensitive traffic classes such as interactive multimedia and Voice Over IP (VOIP) for the former and File Transfer Protocol (FTP) and web-surfing applications for the latter class. The delay guarantees for the delay-sensitive traffic in our framework are achieved through a scheduling phase during which a group of conflict-free communications is set up. In this context, we have also proposed a centralized and a hybrid centralized-decentralized scheduling algorithm that provides conflict-free communications in multihop CDMA networks. Based on our framework, the delay-insensitive traffic class is serviced through a random-access medium as in 802.11.

To address the Quality of Service (QoS) requirements of users in terms of desirable end-to-end throughput, we propose a new power control algorithm for multihop CDMA settings. Our power control algorithm guarantees a QoS level to the users according to their requests and the total utility of the network. Though this algorithm is distributed, it requires cooperation among neighboring nodes for information exchange. Local optimizations of power resource utilization at all nodes leads to the network-wide global optimum at the convergence point.

To make the routing component of the network design more sensitive to the dynamics of the network, especially in terms of congestion and interference level, we also propose a new two-dimensional routing metric. While the first component may be any frequently used metric in multihop wireless contexts, the second component is a redeemed version of the average perceived SINR at each node. The redemption mechanism essentially attempts to capture the link load while the SINR itself accounts for interference level. While routes are still selected by the first component of the metric, thresholding on the second component allows filtering the links with high load/congestion or low quality due to e.g. high interference or severe fading.

In the context of wireless mesh networks, we also investigate scenarios where some fixed MCs provide some relaying services to their neighboring Mobile Mesh Clients (MMCs) that are out of direct access range to any MR. This relaying services are performed by MCs in exchange for the discounts they receive from the network for routing their own traffic. We study this problem in a CDMA context and devise a game that at its fixed point decides on the transmit power of the MR and MCs. The supported data rates are therefore determined by these transmit power levels through provided SINRs. Our study on this problem however involves only one MR and its extension to more complex scenarios is left as future work.

1.3 Outline of the thesis

The rest of this thesis consists of six chapters. Chapter 2 contains the motivation of CDMA for multihop networks and some background information on the implementation issues of CDMA in both multihop and the more conventional context of cellular networks. Chapter 3 addresses our proposed integration framework. Power control is addressed in Chapter 4. We discuss routing in multihop wireless networks in Chapter 5. Chapter 6 addresses relaying mechanisms for out-of-range MMCs. Finally in Chapter 7, we conclude this thesis and outline our future work.

Chapter 2

Related Work

2.1 Preliminaries of CDMA

Code Division Multiple Access (CDMA) is a communication technique that allows concurrent transmissions between multiple users in a shared wireless medium. This technique is commonly divided to two major categories: Direct-Sequence CDMA (DS-CDMA) and Frequency-Hopped CDMA (FH-CDMA) [15].

DS-CDMA involves modulation of each intended symbol by a signature code before its transmission and FH-CDMA involves pseudo-random selection of a frequency sub-band over which each node transmits its signal.

Each signature code in CDMA consists of a sequence of pulses (chips) with a duration much shorter than that of the original symbol itself. In the frequency domain, such modulation translates to spreading the bandwidth of the original signal [15, 16]. The signature codes in this technique are pseudo-random, or Pseudo-Noise (PN), which enables receiving nodes to interpret the interference generated by other concurrently transmitted signals as noise. The intended receiver nodes demodulate their received signals by using the same codes with which the signals were modulated at the sender. The correctness of the demodulation process strongly depends on the orthogonality of signature codes. Also, synchronization between the signature codes generated at the sender and receiver sides is of crucial importance as the correlation of any certain code with its lagged version decreases as the lag is increased. As under more distributed network settings such as uplink cellular, ad hoc and mesh networks achieving such degree of synchronization is practically impossible, design of codes with acceptably high auto-correlation and low (instead of zero) cross-correlation properties by itself was for long the subject of many studies in CDMA. Also, code design in presence of multipath, interference, mobility and unpredictable delay has also been studied for long [15].

One of the major and most conventional applications of CDMA is in cellular networks. In this regard, many different technical aspects of this technique, from transmitter/receiver design, code design, allocation and sharing in presence of fading and mobility, have been studied extensively in the wireless communication literature. The main focus of this thesis is on management of shared resources in a (multihop) wireless medium. We therefore restrict our attention to the sharing scheme, assuming that suitable sender/receiver designs are available. As power control in multihop CMDA networks is one of the main contributions of this thesis, we perform a literature review on classical power control methods for cellular settings in Section 2.2.3. In the rest of this thesis however, we address CDMA design issues mostly in the more recent ad hoc and mesh context.

2.2 CDMA in Multihop Networks

2.2.1 CDMA versus 802.11-Advantages and Disadvantages

Currently in multihop wireless mesh and ad hoc networks, most of the systems implement Carrier-Sense Multiple Access (CSMA) or its variants as their multi-access scheme. In a large network, CSMA systems may suffer from high packet queuing delays due at least in part to considerable amounts of collision and associated capture phenomena, despite measures [4, 10, 17, 18] in IEEE 802.11 to minimize these and other such effects to which large networks are prone, i.e., CSMA/CA networks do not scale well.

To enhance MAC performance in 802.11, many physical layer solutions are currently under development. These solutions involve techniques such as Multichannel MAC (MMAC) [10, 19–21], multiple radios [22] (or a hybrid of both [23, 24]) and directional and steerable antennas [10]. Such techniques may also be used for enhancing the performance of CDMA-based networks. However, in the rest of this thesis, we assume there is only a single frequency channel available and that each mesh node (MR or MC) is only equipped with a single transceiver. We also assume that no directional or steerable antennas are available.

The authors of [25] have a rather extensive discussion on the advantages and flexibilities of CDMA networks over 802.11 networks in an ad hoc context. One major advantage of CDMA over 802.11's MAC for multihop wireless networks has to do with 'graceful degradation' or 'soft capacity'. These terms refer to the fact that in CDMA networks nodes can interfere with each other to some degree without corrupting each others' data as long as interference levels are tolerable [26]. In other words, the number of users that can simultaneously use the network (commonly referred to as network capacity) depends on the level of interference they can tolerate. It is critical to note that, if concurrent transmissions use quasi-orthogonal codes, the interference that a node creates for any of its neighboring nodes is attenuated by a factor of the CDMA codes' "spreading gain" [15]. So, while in random-access networks the interference range is often (much) larger than the transmission range, the reverse tends to hold for CDMA [25, 26]. This enables each node under CDMA to neglect the effect of the nodes that have relatively large distance from itself (and use codes orthogonal to its codes) e.g., for calculating SINR, performing power control, local scheduling or contention avoidance/resolution. Note in particular that reducing the size of contention zone aids CDMA networks with random access MAC schemes to mitigate the excessive delay issues from which 802.11 networks may suffer.

Another benefit of CDMA is that with the aid of power control, the data-rate/transmission-range trade-off that restricts 802.11 networks [27] can be alleviated. That is, by increasing the power of a certain flow's transmitters and relays (multihop flows assumed herein), we can clearly increase the transmission range and decrease the number of hops between its transmitter and receiver and, therefore, provide less delay, lower BER, and higher throughput. Note however that there is an inherent trade-off between the above merits and network capacity: as it is well known, increasing the transmission range may reduce the network capacity quadratically [28, 29]. For instance the well-known near-far effect occurs when a node receives signals from one or more interfering nodes with power level(s) larger than that of its intended transmitter. This problem is usually addressed either in MAC, by using a *guard-zone* [25] around a receiver wherein no transmission (except the intended one) is allowed, or in the physical layer with the aid of power control (see e.g. [26, 30, 31]) or a hybrid of both (see e.g. [3, 32]). When the near-far problem is addressed in the physical layer, the only restriction in scheduling the traffic in DS-CDMA MAC is to ensure that self-interference (transmit/receive conflict) is avoided. Such relaxed scheduling restrictions (in comparison with TDMA networks) contribute to the increase in the spatial reuse of bandwidth in CDMA networks. Also, note that similar to TDMA-based settings, the self-interference avoidance restriction can be relaxed when two (or more) radios are used [10, 33].

Thus, a key feature which makes CDMA advantageous for multihop ad hoc and mesh networks is the flexibility it provides for trading off capacity, end-to-end delay, reliability (related to SINR and BER) and even energy efficiency (by e.g. varying hop-count). When considering contention-free (scheduled) traffic management, it is worth noting an additional advantage of CDMA over TDMA systems that has to do with finding conflict graphs. While this task may be computationally complex in TDMA systems, in CDMA networks it is readily known (see Section 3.1.1). That is, since two signals with (even) imperfectly orthogonal codes can be concurrently transmitted without corrupting each other at their receivers as long as they cause tolerable interference, all links can conflict with each other to some degree. In other words, CDMA networks simply presume fully connected conflict graphs as SINRs are estimated e.g. for power control or the avoidance of near-far effects.

Some studies on the capacity of CDMA ad hoc and mesh networks claim capacity reduction with DS-CDMA compared to regular narrow-band transmissions (unlike cellular systems) if no guard-zone or Successive Interference Cancellation (SIC) is applied [26, 31]. However, these studies assume random-access MAC with no guard-zone considerations and either no "comprehensive" power control or only pairwise power control between transmitter and receiver (to ensure a certain level of received power without consideration of SINR). In contrast, in [3], a typical experiment on wireless settings using CA-CDMA, in which both RTS/CTS handshaking and power control (to some extent) are used, has shown almost three times the throughput that 802.11 achieved in a simplified (single-hop) setting. Also, it has been shown in [34] that applying guard-zones around every receiver to suppress interfering transmitters results in achieving higher capacity in DS-CDMA systems compared to narrow-band systems.

2.2.2 Code Assignment Issues for Multihop CDMA networks

To be able to use the merits of CDMA, we must (*i*) assign one or more distinct code(s) to each node and therefore devise a code assignment protocol and (*ii*) decide on how the transmitters and receivers use their codes to transmit data and monitor the channel in anticipation of data respectively [35]. The first problem is challenging in large networks where there may not be enough codes to be able to assign a unique code to every node [3]. In such circumstances, the code assignment protocol has to find efficient methods to spatially reuse the codes while making sure that no two nodes in each other's neighborhood are assigned the same code. The second problem is usually addressed by *transmitter Based* protocols, *receiver Based* protocols, or a hybrid version of the two [3]. In a transmitter based protocol, a transmission code is assigned to each potential transmitter. Each potential receiver node must monitor the whole pool of codes to detect possible transmission activities which requires highly complex receiver circuits but guarantees that *primary collisions* are avoided. By primary collision we mean an event in which two or more nodes concurrently transmit to a common neighboring node with the same code sequence and therefore there is no way for the receiver to decode either transmitter's data. In receiver based protocols on the other hand, the transmitters use the receiver's code to transmit data. The receivers therefore only have to monitor their own code to detect their data. One disadvantage of this method is that it may suffer from primary collisions. Also, it does not support broadcasting. That is, in order to send a message to a set of receivers, a terminal must send unicast packets to every single one of them. To overcome the difficulties involved with transmitter based and receiver based protocols, hybrid methods such as *common-transmitter-based-protocol* and *receiver-transmitter-based-protocol* [32] have been proposed. The former suggests to first spread the header part of the packet (including source and destination addresses) via a common code and then switch codes and spread the rest of the packet by the transmitter code. Similarly, the latter suggests to spread the header by the receiver's code and the rest of the packet with the transmitter's code (which still does not support broadcasting). Note that in both of these hybrid methods, the address part of a packet may still be corrupted due to collisions. However, in the receiver-transmitter-based protocol, this only happens when two nodes send to one receiver at the same time, whereas it can happen in the common-transmitter-based-protocol when a receiver node can hear two transmissions, destined to it or not, concurrently. The advantage of these hybrid methods is based on the fact that collision can only happen to a small part of a packet, i.e. its header. When used in a Carrier Sense Multiple Access (CSMA) with Contention Avoidance (CA), this scheme allows the transmitters to contend with each other (using the common code) only to send the header part of their packets. The hybrid method therefore helps saving both power and bandwidth resources of the network. The discussion above reveals the fact that in practice, CDMA-based systems are **not** delay-free. The packets may still suffer from queuing delay due to collisions. However, heuristic techniques such as the two hybrid methods above can be applied that reduce the delays significantly. To get a more clear picture, one can compare the length of header to the length of the whole packet as an indication of the delay in ALOHA and delay in CDMA systems.

Although avoiding primary collisions is necessary, measures also need to be taken to avoid secondary collisions. Secondary collisions result from cross-correlation between codes which are sometimes referred to as *near-far* effects. This happens when a receiver attempts to detect a certain transmitter's signal and there is another transmitter closer than the first one that is propagating some signal (not destined to the receiver under consideration). If there was no cross-correlation between codes, the receiver's matched filter would be able to detect the intended transmitter's signal without difficulty. However, when this is not the case, the unintended transmitter's signal, if of sufficiently higher power, can dominate the intended signal at the receiver's matched filter.

Code orthogonality is only feasible when (*i*) there is a common accurate time reference among transmitters, (*ii*) all the transmitters propagate their signals in paths of the same length and conditions (fading, shadowing, etc). Although such conditions may be available with small approximations in cellular networks (downlink specifically), in ad hoc network they are simply not. To mitigate the undesirable effects of cross-correlation, designers attempt to (1) devise low cross-correlation codes and (2) incorporate non-zero cross-correlation in network solutions. Regarding (1) it is interesting to note that perfectly orthogonal codes (when synchronous) show higher cross-correlation in asynchronous conditions than the codes particularly designed to have low cross-correlation in asynchronous conditions [15, 35].

2.2.2.1 Practical limitations in code assignment for multihop CDMA networks

In our network model, we assume each node can transmit (receive) to (from) more than one node concurrently. This assumption disqualifies the code assignment methods discussed in last section for our setting as none of them guarantees a unique code assignment per signal. Consider the transmitter-based code assignment mechanism again. When a node say A, wants to transmit to both nodes B and C simultaneously, it uses its unique code to spread both signals and it sends out $C_A \times (S_B + S_C)$ where C_A is the spreading code of node A and S_B and S_C are respectively the signals directed to nodes B and C [16]. Neither node B nor C has a way to separate its intended signal after decoding the received signal as $S_B + S_C$. A more complicated scenario happens when node A wants to transmit (or relay) two different flows (pertaining e.g. to two different applications or two different original sources) to node B. Obviously using its own code C_A for both of the flows guarantees failure. Similarly, it is easy to see that the other methods previously discussed could not succeed either. The only code assignment method that guarantees avoiding primary collisions is assigning **one code per node per flow** in a transmitter based framework. Each node must have a set of codes available and be able to assign a unique code to each one of the flows it transmits concurrently. Note that the size of this set determines the number of flows a node can transmit and relay at any time. Also, note that in such a code assignment technique, it is necessary that neighboring nodes[1] have disjoint sets of available codes. Alternatively, two neighboring

[1] Node A is in interference range of node B if A's signal is received at B's receiver antenna at a level above its sensitivity.

nodes may have common codes as long as they do not use them concurrently. The latter therefore uses the code pool more efficiently although it requires additional negotiation and additional overhead and set-up time consequently. Also, in medium or large-sized networks, spatial reuse of the codes becomes unavoidable.

For the coding schemes using one code per node, there are several algorithms and protocols discussed e.g. in [36–38] that assign one code to each node considering spatial reuse. These algorithms may be extended to settings which require a set of codes per node.

By using a common control channel, implemented by e.g. using a unique commonly known code similar to common-transmitter-based protocol decribed earlier, a transmitter-receiver pair could negotiate the code sequence that will be used in a certain session (perhaps using encryption for security purposes) [39]. Alternatively, similar to a transmitter-based design, a receiver node may monitor the code pool in anticipation of data. Note that the complexity of the receiver circuits based on such code assignment techniques can be mitigated by requiring each node to only monitor the set of codes available to its neighbors, rather than the whole code pool. Nevertheless, this mechanism may incur a significant overhead in some cases and also risk the privacy of network users.

2.2.3 Power Control for CDMA settings-Literature Review

The problem of power control in CDMA networks was initially raised in the cellular context to eliminate the near-far effect. This effect is observed in cellular networks when the signal of an interferer located close to the BS can dominate the signal of a user distant from the BS. The goal of power control in this context was therefore to choose the transmission power of all users such that their received powers at the BS are equal [40–42]. As near-far effect was the only concern, the underlying assumption in the studies addressing this problem was identical (received) SINR requirements for all users. The problem of power control was later extended to multi-class users by the authors of e.g. [43–45]. In these studies, a **distributed** algorithm was developed that, given that it is feasible to satisfy all different users' SINR requirements simultaneously, could obtain the minimal set of powers required.

Let us assume that user i attempts to transmit to BS^*, its assigned BS, and that the perceived interference at BS^* is:

$$I_i(\bar{P}) = \frac{\beta_i}{h_{(i,\mathsf{BS}^*)}} \times (\frac{1}{B} \sum_{j \neq i} P_j h_{(j,\mathsf{BS}^*)} + N_0)$$

where $\bar{P}$ is the vector of all transmission powers, $h_{(i,\mathsf{BS}^*)}$ is the path-gain from node i to its assigned BS, and N_0 is the noise level. Assume that the required SINR of each user is β_i. Therefore, the condition required on the received SINR at each node i is:

$$\frac{P_i h_{(i,\mathsf{BS}^*)}}{\frac{1}{B} \sum_{j \neq i} P_j h_{(j,\mathsf{BS}^*)} + N_0} \geq \beta_i;\ \forall i \in \{1, 2, \cdots, M\}$$

where M is the number of all nodes, and I_i is the interference level observed at BS^*. At each iteration n the algorithm developed in [43–46] suggests to update the transmission power vector according to the following rule:

$$\bar{P}^{(n+1)} := I^{(n)}(\bar{P}^{(n)}) \tag{2.1}$$

starting from an arbitrary initial power vector $\bar{P}^0$ or equivalently for each user i:

$$P_i^{(n+1)} = (\frac{1}{B}\sum_{j \neq i} P_j^{(n)} h_{(j,\mathsf{BS}^*)} + N_0)\frac{\beta_i}{h_{(i,\mathsf{BS}^*)}}; \ \forall i \in \{1, 2, \cdots, M\} \tag{2.2}$$

which simplifies to intuitive Multiplicative Increase-Multiplicative Decrease (MIMD) rule below:

$$P_i^{(n+1)} = P_i^{(n)} \cdot \frac{\beta_i}{\mathsf{SINR}_{(i,\mathsf{BS}^*)}} \tag{2.3}$$

When a solution exists, this algorithm converges to a fixed point that satisfies all users' SINR requirements [46]. Perhaps the most desirable characteristic of this algorithm is that it is distributed as each node can update its transmit power using only local information. This method can also be easily extended to the cases with a limit on maximum power at each node. At each iteration, a node updates its transmission power by finding $\min(P_i^{(n)}, P^{\max})$. Note that for scenarios where a feasible solution does not exist, the attained fixed point will be a boundary point of feasible power space [47]. With a small variation from the described formulation, the solution above was designed not only to find transmission powers but also the "best" BS amongst those available to a node. This was done by finding the required transmission power according to equation (2.1)for all accessible BSs and choosing the BS which requires the least amount of transmission power. Again, a major advantage of the above algorithm was it was distributed and could be performed by each user independently. When this condition (distributiveness) is not critical, reformulation of the above problem could be obtained in [43, 48] for scenarios with fixed BS allocations. That is, the fixed point of the above algorithm, i.e., $\bar{P} = I(\bar{P})$, could be obtained by solving a linear system of equations:

$$(J - EA)\bar{P} = b$$

In the above formula, J is the $M \times M$ identity matrix, E is an $M \times M$ diagonal matrix with β_is as its elements, A is an $M \times M$ matrix with diagonal elements equal to zero and non-diagonal elements obtained as

$$A[i,j] = \frac{1}{B}\frac{h_{(j,\mathsf{BS}^*)}}{h_{(i,\mathsf{BS}^*)}},$$

and b's elements are obtained from the noise and path-gains using $b = N_0 E H^{-1}\bar{1}$ where H is a diagonal matrix with the ith entry being $h_{(i,\mathsf{BS}^*)}$.

The conditions under which there exists a feasible solution to the power control problem could therefore be obtained from the eigenvalues of matrix EA, and the iterations were simplified to:

$$\bar{P}^{(n+1)} = b + EA\bar{P}^{(n)}$$

Power control in CDMA networks has been approached differently based on the objective of the network. Specifically, the objective of [49–51] has been to maximize the minimum SINR achievable by all users which clearly obtains identical SINR levels for all users across the network.

Later, the algorithm defined in equation (2.1) above was suggested to be applied in ad hoc context in [2]. In general, when extending to the contexts other than cellular settings, objectives such as maximum utility, maximum capacity, etc., require other decentralized and adaptive algorithms. This is the main topic of Chapter 4 of this thesis. For an extensive literature review on the issues addressed in this section, readers are referred to [47].

Chapter 3

Traffic Management Schemes and Integration Framework

In this chapter, we propose a framework for integration of different network management components such as routing, scheduling and power control in the time plane. Based on this framework we identify different time-scales for operation of these components. The time-scales introduced in this chapter will form the basis for chapters 4 and 5 (the latter only when used in the CDMA network context). That is, we assume that the MAC mechanism, based on random access and/or scheduling, and power control are performed within the time-intervals indicated by the framework proposed here.

3.1 Scheduling for Delay-Sensitive Traffic

3.1.1 Merits of Scheduling

The HCF[1] Controlled Channel Access (HCCA) function of 802.11e WLANs addresses issues such as meeting the requirements of delay-sensitive traffic, resolving the fairness issues, and enhancing the service-differentiation characteristics. Based on this function, transmissions from wireless nodes to and from BS are allowed only via a specific channel reservation scheme [18, 27, 52]. Extension of such a function to networks with multihop transmissions that spatially reuse bandwidth (and codes in a CDMA context) is a scheduling problem [52–55]. Again, in order to set up a conflict-free schedule in which

[1] Hybrid Coordination Function

concurrent signals do not garble each other, the network's conflict graph is required to be known. In the context of narrow-band systems, there are several existing methods to accurately find the conflict graph of a network with fixed transmit powers, see [10, 56] and their related references.

These algorithms require at least $O(n^2)$ measurements for stable networks with n nodes [56]. If the network pattern varies (even in the absence of mobility) due to nodes' arrival and departure or changes in the media (path-gain variations due to fading, shadowing, etc.), the network's conflict graph may vary significantly. Therefore, less complex conflict resolution approaches that can adapt to network variations and attempt to resolve conflicts only between the currently in use or **active** links (rather than finding all of the potentially conflicting links) seem to be more efficient and scalable. Among such algorithms is the one proposed in [57] that is a distributed synchronous two-level RTS/CTS-based algorithm for conflict-free MAC scheduling. This algorithm, however, assumes *fixed*-frame-lengths and does not address the infeasible scheduling scenarios which may happen particularly when traffic load increases.

Nevertheless, if a network's conflict graph is available, transmissions can be scheduled so that collisions are avoided as much as possible. Unlike random transmissions, scheduled transmissions *do not* suffer from unpredictable delays. However, in order to find non-conflicting schedules, not only do we need computationally complex operations to find conflict graphs, but also "good" scheduling algorithms. Finding an optimal link scheduling is known to be NP-hard (see [58] and its related references) and therefore heuristics are often used [2, 58–71]. Most of these heuristics require some degree of centralized knowledge and computation. While this is considered a great impediment for ad hoc networks, it is not the case for WMNs [11].

3.1.2 A scheduling algorithm for QoS Traffic in CDMA Networks

In this section, we propose to use a centralized, simple and greedy Contention-Based Ordering (CBO) algorithm, originally devised in the context of connection-level switch fabric arbitration [72], for scheduling a set of routed end-to-end flows. We apply simple modifications to this algorithm for use in CDMA systems, TDMA systems, and also for flows of different data rates. Although operation of centralized algorithms is not considered a great burden in WMNs, more localized algorithms may be found suitable for better scalability with network size. We therefore also suggest a more decentralized version of this algorithm called Incremental-CBO (ICBO) [73].

3.1.2.1 Related Work and Background

The problem of assigning channels to uplink and downlink communication in wireless ad hoc networks is relatively challenging. In a wireless network with a base station (a non-ad hoc network), Frequency Division Duplexing (FDD) or Time Division Duplexing (TDD) can be used for uplink and downlink channels. However, in an ad hoc network, in the absence of a central unit to manage the uplink and downlink transmissions, the problem seems to be more difficult. Using Frequency Duplex Division (FDD) requires two different frequency bands for uplink and downlink. However, there is no global definition of uplink and downlink in a multihop ad hoc network. When one group of nodes is transmitting (uplink channel), another group is receiving (downlink channel). In TDD, the same frequency band is used both for transmit and receive while uplink and downlink transmissions take place in turn. In an ad hoc network however, it is not possible for all nodes to transmit in the same time-slot and receive in the next one, as a node may be both a transmitter and a receiver albeit not at the same time [2, 66, 74]. That is, regardless of the implemented multiple-access media, we assume herein that it is not possible for a node's antenna to transmit and receive at the same time. Therefore, for each time-slot, a node needs to be scheduled to either transmit or receive to avoid self-interference (transmit-receive conflict). In a wideband CDMA network, by assigning different codes to different users, it is possible for a node to transmit (or receive) two or more flows at the same time. This is not feasible in a wideband TDMA system.

The term *scheduling* is used in different contexts by different authors. In [75, 76], scheduling refers to joint control of layers, i.e., link scheduling, power control, routing, etc. (other than rate control). The authors of the paper [75] consider a TDMA ad hoc network and solve a problem of joint power control and scheduling. They obtain a complex and highly centralized method to jointly solve the link scheduling, power control and routing. In their follow-up paper [76], an imperfect but simpler scheduling is suggested. However, the power levels are assumed fixed and power control is not performed along with link scheduling. Consequently, only one-hop interference is removed as in the papers of [59–65, 67–69].

One of the main objectives of this study is to find conflict-free and *minimum-length* uplink-downlink tables for all nodes of a CDMA network. We refer to the process of establishing such tables as uplink-downlink scheduling. In the following section, we propose a hybrid centralized/decentralized solution whose implementation relies on the much slower than packet-level time scale (time-slot duration) of connection set-up and release. As the routing algorithm decides on the paths that the transmitters should take to send their data to the intended receivers, "link" scheduling in general decides on the links that can be active simultaneously without violating any of the constraints of the network, i.e., non-tolerable interference or transmit/receive conflicts. There are many studies that address link scheduling in TDMA networks, e.g., [2, 59–69, 71]. Of these papers, all but [2,66,71] consider only one-hop interference, i.e., two adjacent links (with a common node) cannot be active at the same time-slot and any two nodes that are more than two hops apart are assumed to be conflict-free. *Not* assuming this, a goal of [2,66,71] was to maintain the SINR of each node above a threshold with the aid of power control. We reiterate that link scheduling in CDMA networks has significant differences with its TDMA counterpart. Similarly, in this section we will assume the interference of geographically close links are attempted to be controlled by a power control mechanism which ensures that each node has an SINR above a threshold.

Ad hoc CDMA/TDMA settings have been considered in [2]. With link scheduling and power control working jointly, one-hop conflicts and high levels of interference have been avoided in a CDMA/TDMA ad hoc network. The system model used in [2] is similar to our system model which is a time-slotted CDMA network. However, in [2], the number of time-slots of TDMA frames (the length of transmission schedules) is assumed to be fixed. In our study, the this number is a figure of merit, i.e., it is attempted to be minimized. The minimum frame-length and consequently minimum communication time can maximize the network's throughput. The other difference between [2] and our study is that routing is not considered in [2], while we consider both routing and scheduling. Similar to [2], we assume that the definition of interference is not limited to only one-hop sources and all nodes attempt to maintain their SINR above their minimum required threshold. Yet another difference between the system setting of [2] and our setting is that in their study, time-slots are of the order of the duration of one packet. In our study, the uplink/downlink time-slots are of much larger duration.

In [71], a framework similar to that of [2] is used to solve the problem of joint power control and scheduling in a centralized fashion for multicasting in ad hoc networks. The system under consideration in [71] is a CDMA/TDMA ad hoc network as in [66]. However, in [71], each node is assumed to be limited with the same constraints that apply to a TDMA system, i.e., a node can only be associated with one other node. As in [2], the authors of [71] do not consider routing.

Uplink-downlink scheduling in ad hoc CDMA networks has been addressed in [74] where a method to eliminate transmit/receive conflicts in a dynamic fashion was proposed. When a node has such a conflict due to requirements of two routes, it gives priority to the longer route. However, there is no coordination among the nodes to pack the maximum possible number of transmissions in each time-slot. In this study, the objective of the uplink-downlink scheduling is to utilize the time resource as efficiently as possible. We attempt to minimize the length of the schedules and therefore the total communication time. This is done in a static rather than dynamic fashion, i.e., we set up schedules for all active nodes and then the nodes prioritize the flows according to their tables.

3.1.2.2 Contention-Based Ordering Algorithm for CDMA networks

Given a set of R 'routed' multihop flows (possibly via e.g. a distance-vector-based algorithm such as Ad hoc On-demand Distance Vector (AODV) [77] or a tree-based one such as TBR [78]), we obtain the set W consisting of all one-hop flows (subflows) $v \in W$ where $|W| = \sum_{r=1}^{R} \omega_r$ and ω_r is the number of hops of route r. Let $s(v)$ be the source node of the unidirectional one-hop flow v and $d(v)$ be its destination node. We assume that all traffic rates are multiples of a basic rate and, therefore, each traffic flow is further decomposable into several flows each with the basic rate.

In CDMA settings, the subflows $u, v \in W$ conflict or **contend** if and only if $s(v) = d(u)$ or $s(u) = d(v)$, i.e., there is self-interference. In TDMA settings, they conflict if and only if one of these conditions holds: $s(v) = d(u)$, $s(u) = d(v)$, $s(v) = s(u)$ or $d(v) = d(u)$. Conflicting subflows cannot be transmitted in the same subframe. The degree of contention of a subflow u is determined by the number of subflows u is in conflict with. To ensure that a flow of rate k gets scheduled k times, we could assume that two distinct subflows $v \neq u$ also conflict if $s(u) = s(v)$ and $d(u) = d(v)$, or instead spread them with two different signature codes and allow them to be scheduled concurrently. Below, we show the pseudo code for CBO algorithm.

Step 0: Schedule the most contentious subflow φ in W in sub-frame t and $W \rightarrow W \backslash \{\varphi\}$.

Step 1:

1.1 Determine Z as the set of all elements of W that do not conflict with any of the subflows already scheduled in subframe t.

1.2 Select the most contentious subflow $\acute{\varphi}$ in Z and schedule it in t; $Z \rightarrow \setminus \{\acute{\varphi}\}$ and $W \rightarrow W \setminus \{\acute{\varphi}\}$.

1.3 In addition for Z, remove all subflows conflicting with subflow $\acute{\varphi}$ just scheduled.

1.4 Go back to step 1.2 if $Z \neq \emptyset$.

Step 2: $t = t + 1$.

Step 3: If $W \neq \emptyset$, go back to step 0; else stop.

The CBO ordering algorithm has a computational complexity of $O(T(\Phi^2 N))$ where T is the frame length, Φ is the number of subflows in the network and N is the number of its (active) nodes [72]. We therefore devised a simple distributed Incremental CBO (ICBO) algorithm that adjusts the scheduling table upon flow leave/joins if necessary and only periodically refreshes the table using CBO [73]. ICBO is a typically suboptimal approach wherein the link-layer schedules are only periodically refreshed, i.e., as fast as existing computational resources will allow for such a complex problem (especially in ad hoc networks). A period between refreshes could have two phases. In the first phase, a quick and feasible "incremental" modification of the schedule would occur to accommodate recently arrived connections and account for recently departed ones. In the second phase, no new connections are admitted and a "refreshed" schedule (perhaps based on a new routing table if routing tables were updated in the same time-slot) would be computed based on the existing connections at the end of the first phase of the period. Clearly, connections arriving to the network during the second phase of a period would suffer set-up delay (see Figure 3.3 and further discussion on ICBO in Section 3.3.2).

Note that even in very large WMNs or in MANETs where scalability issues are more important, the heavy computational requirements of a centralized scheduling algorithm are justified by (*i*) its being performed only periodically, (*ii*) its action on only a small fraction of traffic flows, and (*iii*) those flows will typically be of significant duration, e.g. VOIP sessions.

3.2 Random Access for Delay-Tolerant Traffic

Designing a contention-based CDMA MAC in ad hoc and WMNs is more or less similar. As previously discussed, assuming imperfect code-orthogonality, simultaneous transmissions in mesh networks can introduce high levels of interference that need to be controlled to attain reliable communication. We note that as opposed to cellular networks wherein the near-far problem may only happen at the BS, it can occur at every ad hoc or mesh node, especially in BSs and MAPs of the latter.

While in a cellular setting, the uplink power of wireless nodes are controlled by the BS to ensure equal received power among them, in wireless ad hoc and mesh networks, increasing the transmit power for one transmission can create an intolerable level of interference at the receiver of another concurrent transmission. This problem has been addressed e.g. in [3, 25, 32]. An efficient MAC for Random-Access CDMA (RA-CDMA) ad hoc and mesh networks may use some control policy e.g. handshaking (like RTS/CTS in 802.11) to completely avoid the near-far problem or alleviate it by choosing a sufficiently high processing-gain and tight power control. Note that the so-called 'guard-zone', which is the safe marginal distance between a transmitter and any other receiver (excluding its intended receiver), is itself a function of transmit power and processing gain. However, many of the works that attempt to consider guard-zones in their MAC policies usually assume they are fixed (see e.g. [25, 79]).

A MAC and power control design for RA-CDMA Mobile Ad hoc NETworks (MANETs) is proposed in [3] to address this issue. With the aid of modified RTS/CTS signal handshaking, potential transmitters and receivers measure the amount of power they require to communicate, and also consider the amount that their neighbors can tolerate before confirming a connection. As mentioned previously, their CA-CDMA MAC yields considerable improvement in throughput compared to 802.11. Note that CA-CDMA considers fixed transmission rates and does not attempt to use the full capacity available at any given SINR (Shannon's capacity). Although the handshaking measures increase the throughput of the network by drastically reducing collisions (intolerable levels of interference), they do not increase spatial reuse [25]. Inspired by the advantages of clustering in cellular CDMA networks of [80], the authors of [25] propose clustering transmitters and receivers in ad hoc networks relying on multi-scaled handshaking. As it is common for CDMA networks, service differentiation in their scheme is provided by allowing variable transmit powers (therefore variable transmission ranges) that when higher, obviously result in fewer hops and less delay. In the presence of heterogeneous service classes, the transmissions of higher QoS classes perform their handshaking signaling prior to those of lower QoS classes.

3.3 Integration Framework

One of the objectives of this study is to describe a time-scale-based integration scheme for wireless CDMA mesh and ad hoc networks in which different network management components such as admission control, routing, MAC and power control can operate only as frequently as required and in an appropriate order (e.g. flows be routed before scheduled)[2]. Such a framework in a CDMA context is indeed very important as its equivalent in 802.11-based settings is built in to its design (e.g. in duration of TXOP, TBTT, CW, etc.). To see this, recall the nonconformity of the recurrence of events such as flow joins/departures, change of routes, data packet transmissions and control message communications. Also note the difference in the occurrence period and duration of messages such as TBTT, TXOP, CF-Poll, RTS in e.g. 802.11e [18]. The goal of this section is to set a similar systematic framework in the context of CDMA. Readers are also referred to [2] in which a systematic integration scheme excluding routing for ad hoc single-hop networks has been proposed. Our scheme involves a hybrid contention-based/contention-free MAC inspired by the similar approach of multihop 802.11e.

3.3.1 Network Model

We use the term *user* to refer to (all) nodes in the ad hoc and to (only) MCs in the mesh settings. Each user can attempt to connect to the Internet either to upload or to download traffic. Each node has an omni-directional antenna. All nodes are assumed to have an accurate estimation of time. For service-differentiated traffic that is scheduled,

[2]Note that although our framework considers place-holders for routing and admission control, we do not suggest any specific algorithms for them. These topics are left for future work.

each node modulates its data using a unique signature code for every flow (end-to-end session) it transmits/relays while for best-effort traffic which is transmitted in contention, it uses one signature code per each *flow-aggregate* (which may be a composition of several applications' traffic). Therefore, the number of service-differentiated sessions each user can initiate is limited by the number of signature codes it has available. In the context of WMNS, since MRs (BS) may relay (initiate/receive) traffic from many applications simultaneously, the number of codes they have available should be larger than that of MCs. For simplicity, we do not consider code-reuse in this study. Considering a distinct virtual link for each flow that is transmitted from one node to another, the code scheduling task can be translated to a classical form of code assignment problem. The readers are referred to [28,38,81] and their relevant references for discussions about code scheduling. We assume that signature codes are not perfectly orthogonal. We further assume that all nodes have access to a power source and therefore, there is no energy scarcity in the nodes. However, transmission power limitations ($P^{\max}$) exist. Again,for WMNs, we assume that the maximum power allowed for communication (both data and signaling) among MRs and MR→BS and BS→MR is higher than the one used for MR→MC and the reverse. Finally, we assume that all nodes share the same frequency channel for communicating data, and that a common control channel (CCCH) is available for signaling and control messages via an out-of-band narrow frequency channel [3]. A discussion on the choice of CCCH access scheme will be made in Section 4.6.

3.3.2 Description of the Integration Scheme

The data plane of our suggested integration framework is depicted in Figure 3.1. Time is segmented into frames. During each frame, all of the single-hop components of the existing set of end-to-end *flows* (individual or aggregate), get at least one chance at transmission. We refer to the single-hop components of an end-to-end transmission flow as subflows.

Each frame consists of a Contention-Phase (CP) and a Contention-Free-Phase (CFP). Each phase is further divided into subframes. During each CFP subframe, a group of non-conflicting subflows are transmitted. During a CFP subframe, a moderate or large number (based on design specifications) of data packets of each scheduled subflow are transmitted. A fraction of each subframe in the CFP is dedicated to power control. At the end of the power control phase (for a CFP subframe), a set of transmit power levels are decided at which the scheduled subflows transmit their packets as described in more detail in Chapter 4. During the CP subframes, a CSMA-type random-access scheme controls nodes' behavior. CP subframes may or may not be of the same length as CFP subframes. Nodes may contend to access the channel for transmission of one or more packets. In our simulation, we simply assumed CPs whose durations are a multiple of the transmission time of a packet. Figure 3.2 depicts the two phases in both time and frequency plane for further illustration.

We call the maximum required processing time to calculate CBO tables T_C, the routing tables set-up time T_R, and the CBO refresh period $T_A > T_R + T_C$. To clarify a

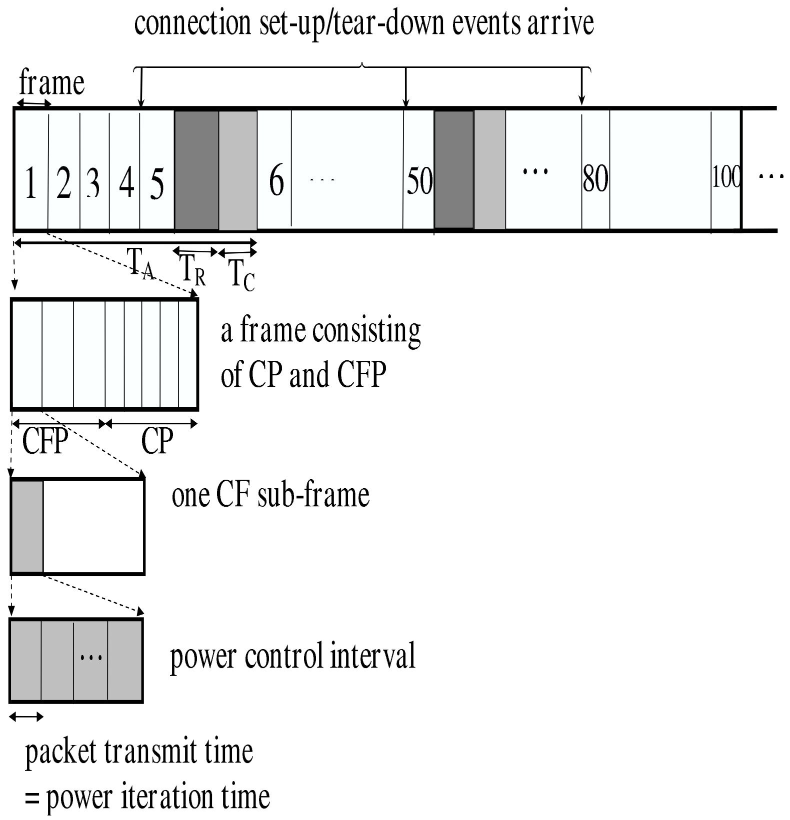

Fig. 3.1 Network architecture

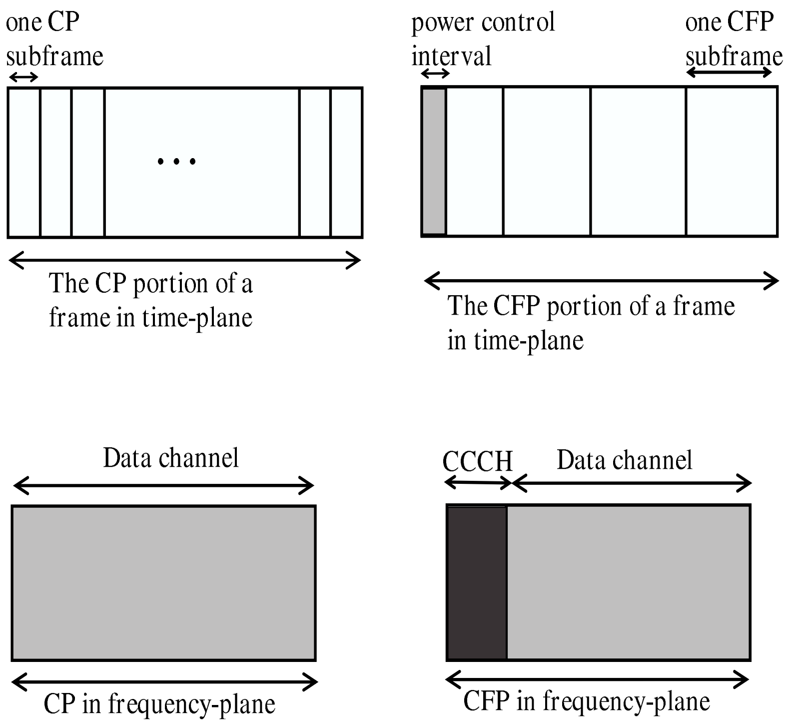

Fig. 3.2 contention and contention-free phases of the network

design choice, let us consider the following two cases, assuming there is a T_R interval at each T_A:

1. $T_C = T_A - T_R$, i.e., no ICBO, maximum (worst case) set-up delay is equal to $2(T_R + T_C)$ and minimum delay is $T_R + T_C$.

2. $T_A > T_C + T_R$, i.e., ICBO used, maximum set-up delay is $T_R + T_C$ and minimum set-up delay (ICBO delay) is negligible.

Now simply note that the average delay in the first case is $1.5(T_R + T_C)$ compared to $0.5(T_R + T_C)$ in the second case. Also note that, we may replace CBO with another scheduling algorithm and similarly make it hybrid centralized/decentralized. Figure 3.3 illustrates the ICBO hybrid scheme and the admission and computation intervals more clearly. In this Figure, X denotes the connection arrivals handled by ICBO and O denotes those queued until the next T_A period. Note that the delayed connections (shown by O) are processed using CBO (respectively, using ICBO all as a batch) at the start of next T_A period for the case when $T_A = T_R + T_C$ (respectively, $T_A > T_R + T_C$).

For WMNs, we assume that the BS is also the central coordinator and is responsible for calculating the schedules of contention-free flow-aggregates. Also that the signaling messages are exchanged between BS, MPs and MAPs for incremental scheduling and other necessary occasions again via CCCH. Each MAP performs the messaging tasks required for its clients on their behalf, except those related to itself. It is also responsible to send its clients's arrival/departure information as well as their access requests to the rest of the network (whenever necessary).

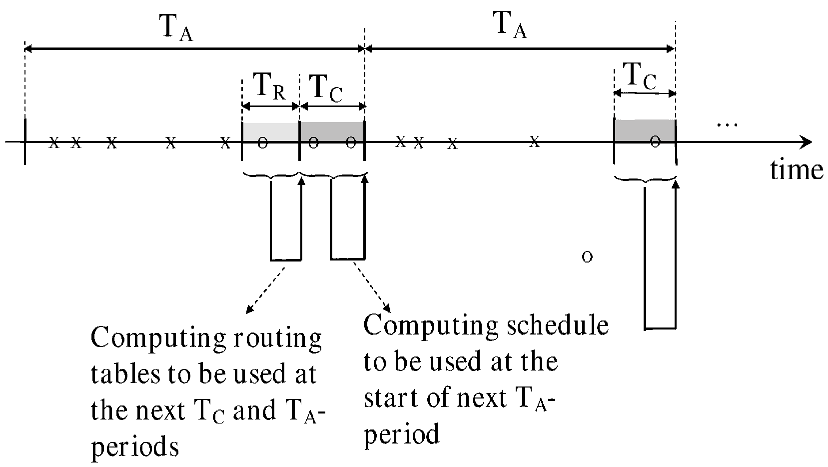

Fig. 3.3 ICBO connection admission phases

We therefore have indicated several operating time-scales for each of the contention-free and contention-based traffic:

Contention-Free traffic:

- very fast: power control iterations and associated dynamic parameters estimated (see Section 4.4)
- fast: *data* packet transmission time
- intermediate: (sustained) flow arrival/departure requiring incremental schedule accommodations in the CFP (i.e. ICBO)
- slow: routing/scheduling (periodical CBO refreshments)
- very slow: duration of a sustained flow

For the contention traffic, the fast, intermediate and slow time-scales correspond respectively to data packet transmission time, arrival/departure of (often short-lived) flows, and routing.

Chapter 4

Power Control for Multihop flows in CDMA

4.1 Assumptions and Notations

We now present a distributed power control algorithm for wireless CDMA ad hoc and mesh networks with the following characteristics:

- This algorithm is based on local optimizations of a network (global) objective that together lead to an optimized network objective.
- It prescribes the amount of transmission power any given node (MC,MR,BS in the mesh context) should use for data packets of every traffic subflow it transmits/relays (a different possible transmit power level for each subflow it transmits/relays).
- Given all nodes use these prescribed power levels, it provides an end-to-end data rate for any multihop flow in the network.
- The provided data rates are close to those initially requested but do not compromise total network utility by creating too much interference.
- The algorithm allows for "soft" Connection Admission Control (CAC) in the sense that if a user is not satisfied with the data rate the network provides for one of its flows (sessions), the MAC may simply drop it.

This Power Control (PC) algorithm is performed at the beginning of each CFP-subframe for subflows scheduled for it (shown in gray in Figure 3.1). A discussion regarding the convergence of the PC algorithm will be provided in Section 4.6. Recall that different components of an end-to-end flow may get scheduled on different subframes. For any given CFP-subframe, we identify[1] a *bottleneck subflow* of a scheduled flow as that associated with the lowest SINR (and therefore lowest data rate) it receives during this subframe, see Figure 4.1. This means that the overall end-to-end data rate a CF-flow receives depends on its minimum SINR value over all the subframes at which its subflow components are transmitted[2]. Ideally, a joint routing, scheduling and power control scheme would result in the optimal choice of all these elements. However, finding an accurate, distributed and low complexity method to perform this task is very challenging and has been an active topic of research for years (mostly in ad hoc context) [82].

Each CFP flow (user/session)[3] is indicated by $\varphi \in F$. $\tau(\varphi)$ and $\rho(\varphi)$ represent respectively the set of transmitter nodes of flow φ and its receiver nodes (obviously not disjoint) when F is the set of all flows. $\nu(\varphi, i)$ is used to denote node $i \in \tau(\varphi)$'s next-hop destination (clearly $\nu(\varphi, i) \in \rho(\varphi)$). We use W to indicate the set of all subflows (same as in Section 3.1.2) and also ω_n to refer to the subflows scheduled for subframe n. We indicate a subflow of a flow φ transmitted/relayed at node i by a pair (i, φ) (simplified from $(i, \nu(\varphi, i))$). $B(\varphi)$ is used to indicate the BottleNeck (BN) subflow of end-to-end

[1] using the signaling protocol defined in Section 4.4

[2] It is important to note that the SINR we refer to throughout this chapter is not **link** SINR which depends on the total power at which link's source transmits to its destination. Instead, SINR of a certain flow φ over a link depends on the amount of power link's source dedicates specifically to flow φ's traffic.

[3] Throughout this chapter, the term flow (subflows) is used to refer to a contention-free flow (subflow).

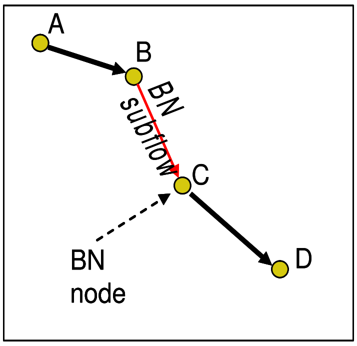

Fig. 4.1 Depiction of a multihop flow and its (single-hop) component subflows

flow φ. P_i^{φ} denotes the transmit power node i dedicates to flow φ and $\mathsf{SINR}_j^{\varphi}$ is the signal to interference and noise flow φ perceives at node $j \in \rho(\varphi)$. β^{φ} is used to indicate the end-to-end SINR (minimum SINR of a multihop flow) that flow φ desires to receive, and G is the spreading gain of the applied CDMA scheme. We assume that the utility a MC receives for one of its flows, φ, is a concave function of its end-to-end data rate. We denote this function by $\tilde{u}(\cdot)$. Since the relation between (maximum achievable) end-to-end data rate and end-to-end SINR is generally nonlinear (recall Shannon's formula), we use $\theta(\cdot)$ to refer to the function that maps end-to-end SINR to end-to-end data rate and $u(\cdot) = \tilde{u}(\theta(\cdot))$ to refer to the function that maps a flow's end-to-end SINR to its user's utility[4]. For example, $\tilde{u}^{\varphi}(\cdot)$ could be a concave nondecreasing function, e.g.,

$$\tilde{u}^{\varphi}(\theta) = \kappa^{\varphi} \log(1 + \frac{\gamma^{\varphi}}{\beta^{\varphi}}\theta) \tag{4.1}$$

[4] We note however that capacity of a link only specifies an upper bound on its data rate. The degree to which we can get close to this upper-bound depends on the design of the system, e.g. the coding scheme used, and also the measures that are taken to combat undesirable channel effects such as fading [9]. However, it is commonly used in designing wireless system [76,83] and is also used herein.

or the bounded form

$$\tilde{u}^{\varphi}(\theta) = \kappa^{\varphi} \arctan(\frac{\gamma^{\varphi}}{\beta^{\varphi}}\theta) \tag{4.2}$$

for scalars (control parameters) $\kappa^{\varphi}, \gamma^{\varphi} > 0$.

During the description of algorithm, we use the notation $\mathsf{SINR}_j^{\varphi}$ to address the ratio of the amount of power node j perceives corresponding to flow φ to the interference and noise it receives. That is:

$$\mathsf{SINR}_j^{\varphi}(n) = \frac{h_{ij} P_i^{\varphi}}{N_0 + 1/G \left(\sum_{k \neq j,i} \sum_{\psi \in F, (k,\psi) \in \omega_n} P_k^{\psi} h_{kj} + \sum_{\psi \neq \varphi, (i,\psi) \in \omega_n} P_i^{\psi} h_{ij} \right)} \tag{4.3}$$

for all $j \in \rho(\varphi), \varphi \in F$ with h_{ij} and N_0 being respectively the path-gain from node i to j and the background noise power and n denotes the current subframe index. To keep the notation simple, in the rest of this chapter we drop this index.

4.2 Power Control Algorithm

In this section, we propose a *cooperative* power control algorithm that maximizes a global (network-wide) utility [30]. In this algorithm, each node's objective function is formed based on the sensitivity of the bottleneck nodes in its interference range[5] to its transmit power levels (one per each flow it transmitted or relayed) and its own power limitations. We call the mentioned power control algorithm cooperative for two reasons. First, each node's objective is to choose its transmitting/relaying flows' transmit power such that it does not cause much interference for those nodes that cannot afford to bear

[5] The interference range of a node in CDMA settings is smaller than its transmission range due to interference suppression characteristics of CDMA.

any more, that is 'bottleneck nodes'[6]. At the network level, aggregation of such local objectives results in optimization of 'end-to-end' SINRs (and data rates). Second, nodes communicate with each other (to inform e.g. path-gain or received SINR, see Section 4.4). Although in the context of ad hoc networks such cooperative actions among nodes may seem idealistic to some extent, it is reasonable among MRs and BSs which form the mesh infrastructure. Therefore, we also propose to use this algorithm for WMNs after applying some modifications to the computational and signaling tasks different types of mesh nodes are expected to perform. More specifically, these modifications are applied both to put less computational burdens on MCs (which have lower capabilities) and to give more control to the MRs to minimize the adverse effects of MCs' possible selfish behavior. Below, we first explain our proposed power control algorithm for multihop wireless networks (ad hoc or mesh) and then describe its modifications for WMNs according to the above discussion.

The network objective in this power control is defined as:

$$g_{net}(\underline{P}) \ = \ \sum_{\varphi \in F} u^{\varphi} \left(\min_{i \in \tau(\varphi)} \mathsf{SINR}^{\varphi}_{\nu(\varphi,i)} \right) \tag{4.4}$$

subject to the power constraints of node i:

$$< \underline{P}_i, \mathbf{1} > \equiv \sum_{\varphi \in \tau^{-1}(i)} P^{\varphi}_i \ \leq \ P^{\max}_i \tag{4.5}$$

[6]A bottleneck node is the receiver of a bottleneck subflow which is the bottleneck (min SINR) of its flow.

To solve the constrained optimization problem above in an unconstrained fashion, we include the power constraints in the objective function as penalty terms:

$$L_{net}(\underline{P}) = \sum_{\varphi \in F} u^{\varphi} \left(\min_{i \in \tau(\varphi)} \mathsf{SINR}^{\varphi}_{\nu(\varphi,i)} \right) - \sum_{i} \alpha_i \sum_{\varphi \in \tau^{-1}(i)} P^{\varphi}_{i} \tag{4.6}$$

where $\alpha_i > 0$ is the Lagrangian multiplier included and enforces node i to not deviate from its power constraints.

Maximizing the above objective requires global information. Instead, we use the collection of local optimizations given below to lead the power levels to those that maximize the above global objective. Specifically, consider the optimization problem below:

$$\underline{P}^{*}_{i} \equiv \arg \max_{<\underline{P}_i, \mathbf{1}> \leq P^{\max}_{i}} g_i(\underline{P}_i) \tag{4.7}$$

where

$$g_i(\underline{P}_i) \equiv \sum_{j \in R(i)} \sum_{\varphi \in B^{-1}(j)} u^{\varphi}(\mathsf{SINR}^{\varphi}_{j}) - \alpha_i \sum_{\varphi \in \tau^{-1}(i)} P^{\varphi}_{i} \tag{4.8}$$

over the transmission powers $\underline{P}_i$ where $R(i)$ is the set of nodes in the interference region of i including i itself.[7]

Theorem: If $\alpha = \alpha_i$ for all i, distributed/decentralized joint optimization of (4.8) will

[7] As discussed previously in Chapter 2, this interference range is usually smaller than transmission range due to interference suppression by a factor of spreading gain.

also locally optimize the global objective g_{net} in (4.6).

Proof: The first-order necessary KKT conditions for optimality of g_{net} over the complete set of subflow transmission powers $\underline{P}$ are the same as those that jointly optimize (4.8) for all nodes i. Q.E.D.

This result is akin to that of [84] in a wired context. Note that in this theorem, it is assumed that user utility functions for all nodes are identical as the network's objective is to maximize social welfare[8]. In the above theorem, it is also assumed that all nodes have the same power budgets and therefore, identical power constraints apply to them. These two conditions together justify the the theorem's condition that $\alpha_i = \alpha$ for all users i.

The objective function in (4.6), in its current form, may yield significant power oscillations that happen if a certain node i does not have any bottleneck nodes in its interference range. To maximize its local objective, such a node chooses its $\underline{P}_i = \underline{0}$ and therefore creates a bottleneck itself [30]. To prevent such oscillations, we modify (4.8) to:

$$g_i^0(\underline{P}_i) \equiv \sum_{j\in R(i)} \sum_{\varphi\in B^{-1}(j)} u^{\varphi}(\mathsf{SINR}_j^{\varphi}) - \alpha_i \sum_{\varphi\in\tau^{-1}(i)} P_i^{\varphi} + \lambda \left(\sum_{\varphi\in\tau^{-1}(i)} \frac{\mathsf{SINR}_{\nu(\varphi,i)}^{\varphi} - \mathsf{SINR}_{B(\varphi)}^{\varphi}}{\mathsf{SINR}_{\nu(\varphi,i)}^{\varphi}} \right) \tag{4.9}$$

[8]If users do not have identical utilities, those who value the network service (data-rate here) more will receive better service (higher data rate) which makes the network unfair toward the others. Note that such unfairness violates the very purpose of social welfare.

where $\lambda > 0$.

Note that some other variations of the above penalty term (third summation in the above) may be used as well. Also note that, in general adding a penalty term to (4.8) may cause a slight diversion from the global objective in (4.6) at the optimal point.

The above local optimization problems may be solved possibly via simple numerical gradient ascent, i.e.,

$$\underline{P}_i \; += \; s\,\nabla_{\underline{P}_i} g_i(\underline{P}_i)$$

with step-size parameter $s > 0$ [85, 86].

Note that through the SINR terms, g_i also depends on P_j^{ψ} for $\psi \notin \tau^{-1}(i)$ and $j \neq i$. Also, for $\psi \in \tau^{-1}(i)$, the term $\partial g_i / \partial P_i^{\psi}$ involves terms

$$\frac{\partial \mathsf{SINR}^{\psi}_{\nu(\psi,i)}}{\partial P_i^{\psi}} = \frac{\mathsf{SINR}^{\psi}_{\nu(\psi,i)}}{P_i^{\psi}} \tag{4.10}$$

and, for $\varphi \neq \psi$,

$$\frac{\partial \mathsf{SINR}^{\varphi}_{\nu(\varphi,i)}}{\partial P_i^{\psi}} = \frac{-\left(\mathsf{SINR}^{\varphi}_{\nu(\varphi,i)}\right)^2}{P_i^{\varphi}}. \tag{4.11}$$

Also, the third type of gradient terms, $\partial g_i / \partial P_j^{\psi}$, appears for $j \neq i$ and is of the form:

$$\frac{\partial \mathsf{SINR}^{\varphi}_{j}}{\partial P_i^{\psi}} = \left(\frac{-h_{ij}}{P_k^{\varphi} h_{kj}}\right) (\mathsf{SINR}^{\varphi}_{j})^2 \tag{4.12}$$

where $j = \nu(\varphi, k)$. Note that the right-hand sides of the first two equations involve only terms that are assumed known by node i through its intended receiver $\nu(\varphi, i)$'s feedback, while the third display requires the third party node j (that senses i's interference) to feed back its received SINR. Also the third display requires additional path-gain information not directly measurable by node i (h_{kj}). In Section 4.4, we will explain how the power control signaling protocol allows nodes to communicate this information with their neighboring nodes.

Regarding the algorithm described, it should be noted that neither the global nor the local objective functions of (4.6) and (4.9) (respectively) are concave functions in transmit powers P_i^{φ}. However, it can be easily proved that any local optimum of this problem is regular. Therefore, the KKT conditions of form

$$\nabla_{\underline{P}_i} g_i(\underline{P}_i) = \underline{0}, \tag{4.13}$$

are necessary (but not sufficient) for optimality [87]. Consequently, the subgradient method will converge to one of the local optima which may or may not be the same as the global optimum.

Until this point, we assumed all nodes are peers, i.e., they have similar roles. We now try to modify these roles specifically for in the context of WMNs such that MCs are not required to do many computations and that they do not have enough authority to manipulate the power control. Herein, we assume that each MC is 'assigned' a Mesh Access Point (MAP) by the network (based on some criteria or routing decisions). We also assume that the transmit power updates of MCs are computed by their MAP. Each (assumed honest) MC is required to collect the identities and SINR information of all the BN nodes in its interference range and forward them to its assigned MAP (so that it is able to compute the power adjustments). The MAPs use this information to solve the PC optimization problems. They then prescribe transmit powers to their MCs. This approach involves some additional signaling that will be addressed in Section 4.4.

4.3 Deadlock Avoidance

The above power control algorithm may lead to deadlocks in some circumstances. In this section, we first explain how deadlock scenarios may happen and then propose a method to avoid them. Before explaining a deadlock scenario, we introduce one additional terms called *initial bottleneck* through the following example: Assume that node A has bottleneck nodes B, C in its transmission range and also a bottleneck node D in its interference range. Also, assume A intentionally transmits (relays) signals to nodes B and C, and that it is responsible for their bottleneck status. Finally, suppose D only receives interference from A. Thus, A's local objective (4.9) consists of B, C and D's utilities (plus the power penalty terms). When A adjusts its transmit power to e.g. node B (P_{AB}), its objective function's sensitivity to P_{AB} involves terms of type (4.10), (4.11) and (4.12) respectively addressing nodes B, C and D (which result in positive, negative and negative derivatives respectively). Now assume that there is another node E in A's interference range that is not currently a bottleneck, i.e., has "excess" SINR. However, there is no term associated with E's SINR in A's objective. Therefore, A may choose its transmit/relay powers such that it creates a high interference level at E and may gradually cause E to become a bottleneck itself. Eventually, at the optimal point, all nodes may become BN nodes. However, initially, there may be only one node that resides in a hot spot and/or has strict power limitations resulting in a bottleneck. We call such a node an “initial bottleneck”.

Now consider the following deadlock scenario: assume a node, B, is located in a congested area and is the initial bottleneck node for a specific flow φ^*. Suppose that the traffic load decreases e.g. due to some flow’s departure, and that as a result B receives less interference and therefore higher SINR. However, the other transmitting/relaying nodes residing on φ^* had previously adjusted their transmit powers such that no node receives a larger SINR than that of the bottleneck B. Therefore B’s increased SINR is considered excessive. As discussed in the above, this excess will be consumed for other flows and gradually it is driven to zero. Flow φ^* therefore faces a deadlock in that its BN SINR cannot increase. Such a deadlock can be avoided if the nodes that transmit/relay flow φ^*’s traffic react ‘suitably’ whenever their initial BN node receives excess SINR, i.e., its BN status changes. One suitable reaction could be to start the PC algorithm over which may enable the system to transition to a better equilibrium. In the following section, we will explain a signaling protocol that can be used to determine the current bottleneck nodes and disseminate the associated information required by the power control including deadlock avoidance.

4.4 Power Control Signaling Protocol

We assume that the CCCH will be used to communicate messages related to path-gain announcements, broadcast of the flows’ bottleneck SINRs (to be explained shortly), the necessary local information to calculate SINR at each node, and the required routing information. To calculate the received SINR, each node needs information about the path-gains of all nodes in its vicinity. To obtain this information, there are several possible methods, of which one is for each node to have a GPS and advertise its location periodically. Instead, each node can broadcast a probe message with a standard transmit power level so that the recipient nodes can measure received power and calculate their associated path-gains. We also assume that the $u^{\varphi}(\cdot)$ and β^{φ} attributes of a flow φ are communicated to its associated nodes by the routing algorithm. Below, we explain a signaling protocol that is performed in the CCCH along with the PC protocol to provide it with its required information.

Consider the integration-scheme of Figure 3.1. At the beginning of the PC phase in a certain frame, if there was no change in the routes and schedules, the previous frame's bottleneck and power information are used. To avoid deadlocks, at any point in the new PC phase, if a flow's initial BN's status changes, its powers are reset (to the initial power levels), its records of current BN nodes become invalid, and new records will be made. The signaling protocol indicates all initial and current set of BN nodes and informs (*i*) each transmitting/relaying node of the SINR perceived at its intended receiver and the interference it caused for its neighboring BNs, (*ii*) the source nodes about the initial BN of their flow, (*iii*) the initial BNs of their status, (*iv*) all BN nodes (initial or else) of their status, and (*v*) all the neighbors of a BN node of its presence.

The following types of packets are communicated at a certain subframe after all scheduled nodes send a "beacon" packet at the initial (or previously calculated if not the first iteration) transmit power over their assigned data channels (codes):

For each flow, all (scheduled) receiver nodes associated with that flow calculate their received SINR. They broadcast these SINRs along with the values of perceived powers from their intended transmitters on the CCCH. This "feedback" information is required by all nodes in every active node's neighborhood to evaluate terms of type (4.10), (4.11) and (4.12) (when a node is BN). Another type of control message (forward-BN-detection) is originated from each flow's source to discover BNs. In this packet, one field is considered for information of the form SINR_{BN} and one to indicate the BN nodes themselves. At the beginning of each iteration, this field contains the BN information from the past iteration. Upon receipt of this packet, it checks the SINR_{BN} field and updates this field if its current SINR is lower. As this packet reaches the final destination, the minimum SINR is determined. This message is then sent back on the reverse path (assuming bidirectional links) to the original source (backward-BN-detection). Each node with SINR equal to the minimum level updates its BN field to 1 (or 0 if not a BN any more) and passes the packet on till it reaches the source. Note that since all packets in the CCCH are broadcast, the neighbors of a BN node also get informed of its status.

The following operations and signaling are performed by each source node to identify its 'initial' BN(s) and are based on the fact that the initial BN of a flow is the first node(s) that becomes BN during a PC phase and retains its status: Each source node keeps a record of all its flows' BN nodes and also a tag to each that indicates the order in which it has become a BN. Note that if two nodes become BN at the same time, they will have the same order. A control message containing the identity of the initial BN node is originated at the source and sent to this node (initial-BN-detection packet). Finally, another type of control "reset" message is generated at a flow's source, whenever its initial BN changes status, so that all nodes residing on this flow invalidate the associated BN and power information and start over.

In summary, in the above signaling protocol, we identified one beacon packet to be transmitted via the data channel and five types of control messages which are transmitted through the CCCH, called feedback, forward/backward-BN-detection, initial-BN-detection, and reset packets. The beacon packet may be piggy-backed on the data packets (see Section 4.6, the CFP simulation). For mesh networks in which MCs' PC is performed by their MAPs (as described in Section 4.5), each MC sends its own feedback packet along with those associated with its neighboring BN nodes to its MAP. The PC signaling exchanges or "announcements" may be performed only periodically (once per every k PC-iterations) in order to avoid excessive signaling overhead. We will return to this issue in the next section.

4.5 Deployment Issues of Power Control Convergence within the Time-Scale Based Framework

We deploy the power control algorithm introduced in Section 4.2 and assume that a fraction of total available bandwidth is allocated to CCCH to convey the signaling messages described in 4.4. To ensure that convergence of power control takes place in a reasonably short duration (say less than 20% of each CF-subframe), we consider 4 different approaches as follows:

1. Letting $N(k)$ denote the number of iteration it takes PC to converge when each node performs k PC-iteration per announcement, if the cost (e.g., the amount of time required) for each announcement is high, one can choose $k > 1$ to reduce it. Also, k may be chosen non-uniformly for different parts of convergence pattern, e.g., $k = 1$ iteration

per announcement for an initial group of iterations, and $k > 1$ for the remainder. Since it may be the case that $N(k) > N(1)$ for $k > 1$, this approach may be of limited utility.

2. Spatial-reuse in CCCH may be exploited to reduce the transmission-time of each signaling-packet. This approach requires either scheduling and/or a multihop random-access scheme (which still risks collisions as for the CP data).

3. The entire duration of a CFP-subframe may be used for Power Control (PC). That is, instead of requiring PC to converge before starting to transmit data (at prescribed rates), data transmissions may be allowed at sub-optimal rates (corresponding to the current SINRs) essentially giving PC more time to converge. Since in this method CCCH and data channel can be active concurrently, each node is required to dedicate a fraction of its power budget to CCCH signaling.

4. An alternative optimization algorithm with different convergence characteristics may be used instead of gradient ascent [86].

We calculate the average end-to-end throughput of each user via the following:

$$\frac{t_D}{t_D + t_{PC}} \times \frac{1}{T|F_S|} \sum_{\varphi \in F} \tilde{C} \log_2(1 + \min_{v \in \varphi} \mathsf{SINR}_v)$$

where t_D and t_{PC} are durations of data transmission and power control respectively, T is the CFP schedule length, $|F_S|$ is the number of CFP-flows, and $\tilde{C}$ is the portion of the bandwidth C that does not include the CCCH.

4.6 Simulation Study

In this section, we present the results of a simulation study on CDMA wireless mesh networks based on the assumptions and methods explained in the previous sections. We first explain our set-up through which the different time-scales indicated in Chapter 3 will be further clarified. We then use the methodology suggested in Section 4.5 to compare the achieved throughput during the CFP and CP. The results of this comparison are indeed not unexpected since both tight power control and scheduling are mechanisms used to improve throughput performance. However, they are useful to further illustrate the different mechanisms discussed throughout the chapter. Finally, we present the results of a comparative study between the proposed power control algorithm and Multiplicative Increase Multiplicative Decrease (MIMD) algorithm [88] (described in Section 2.2.3, equation 2.3) as a variation of our study in the ad hoc context in [30].

We considered three wireless mesh networks consisting of 20, 21 and 40 nodes in a 100m×100m area, depicted in figures 4.2, 4.3 and 4.4 respectively. The first configuration was randomly generated with one BS, 5 MRs, and 14 MCs. The second configuration had a hierarchical and connected topology [9] with one BS, 8 MRs and 12 MCs . The third configuration had one BS, 8 MRs and 31 MCs. The location of the MRs were chosen as depicted and that of MCs was chosen randomly. To ensure that all MCs could access the BS either directly or using the MRs, in both the first and the third configuration, the random locations were varied until a connected topology was obtained. We address networks with out-of-range MCs later in Chapter 6.

[9] So that any MC was ensured to have a path to the BS either directly or through the MRs.

We used a simple Bellman-Ford routing algorithm for both contention and contention-free phases. We assumed that each MC had either an uplink or a downlink contention-free sustained flow (to/from the BS) and either an uplink or a downlink flow aggregate (to/from the BS) in the contention phase that always had data to send. A typical flow is shown in Figure 4.2. For conciseness, the next two subsections will be only explained under the first scenario. We will return to the other two scenarios in Section 4.6.3 wherein a comparative study between CFP and CP is described. To simplify simulation, we have assumed that two distinct subflows that share the same source and destination but belong to two different flows do not cause interference for each other (i.e. have zero cross-correlation in their signature codes). This assumption holds when the codes used are chosen to be orthogonal. Note that in such cases, the interference observed at any receiver due to neighboring communications still occur due to lack of synchronization among different transmissions (in chip-level). That is, a code is not necessarily orthogonal to the delayed version of another code, see Section 2.1. In all simulated scenarios, the utility function in equation 4.1 was used to define the mapping between a user's received utility and its end-to-end data rate.

4.6.1 Contention Phase

We assumed a bandwidth of $C = 20$ MHz similar to the available bandwidth in 802.11a. Since no power control was considered in the contention-phase, we assumed that nodes always use their maximum transmit powers, i.e., 0.5 Watts for MC$\leftrightarrow$MR and 2 Watts (4 times larger) for MR$\leftrightarrow$MR and MR$\leftrightarrow$BS. Therefore, each node was able to transmit/relay to only one other node at a time. Different outgoing subflows at a node

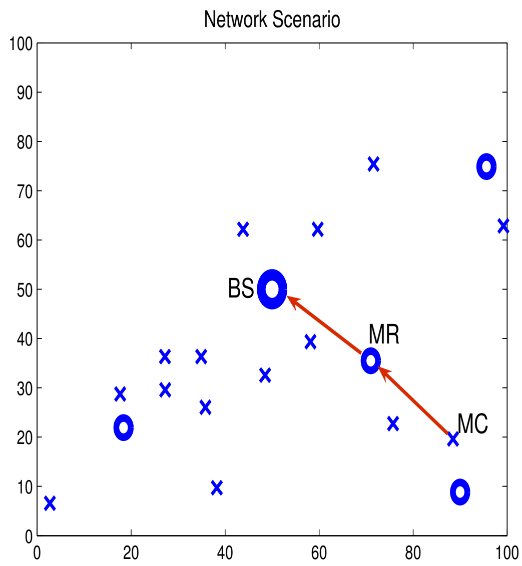

Fig. 4.2 Network scenario I and one of its flows

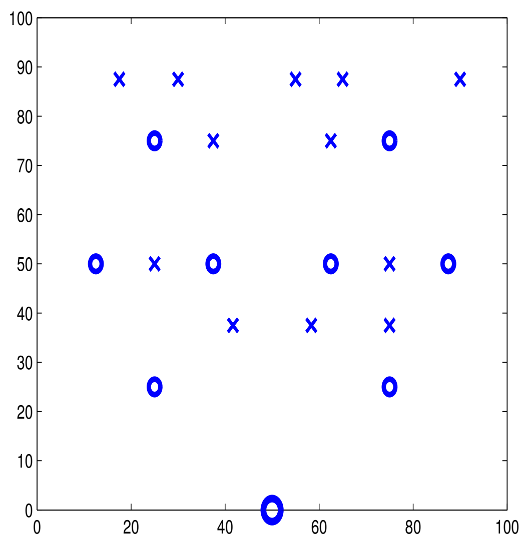

Fig. 4.3 Network scenario II

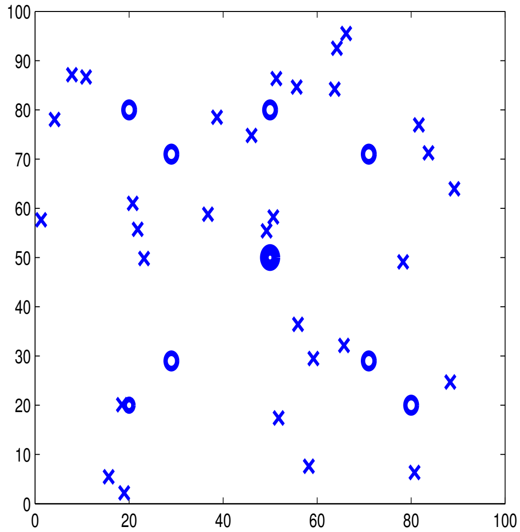

Fig. 4.4 Network scenario III

were given a transmission opportunity in a round-robin fashion. Assuming a second-order attenuation model, the transmission range of MR↔MR and MR↔BS is about 50 m and two ($\sqrt{4}$) times bigger than that for the MC↔MR.

In order to estimate the optimal transmission rate of the scenarios under consideration, we varied this value and observed its effect on average (among flows) end-to-end throughput and averaged it over 4000 trials, see Figures 4.7. The duration of the CP was chosen to be half of the duration of a frame (0.5×250 msec= 125 msec). As can be seen in this figure, the maximum average end-to-end throughputs were achieved at transmission rates of 94 Mbps for the first scenario (corresponding to SINR=25).

4.6.2 Contention-Free Phase

As with the CP, we assumed a duration of 125 msec, an available bandwidth of 20 MHz and the same maximum transmit powers (recall that in the CFP, PC is applied). During this phase, a fraction of 20% of the total available bandwidth was allocated to CCCH. With an average SNR of 3 in the CCCH transmissions, a fixed transmission rate of 8 Mbps was assumed in CCCH (i.e., $4\log_2(1+3)$ Mbps). Using CBO scheduling on the traffic pattern described earlier, the CFP's schedule-length was found to be 2. Consequently, each of the CF-subframes were 62.5 msec.

To ensure that the convergence of power control takes place within an acceptably short duration of time, for our simulation setting, we used a combination of the first two approaches introduced in Section 4.5, i.e., we assumed a CCCH-schedule of length 5 (a not small number for the network sizes simulated) and a non-uniform announcement scheme (explained shortly). Using the parameters of Table 4.1[10], we observed that the convergence of PC algorithm took at most 40 announcements and total of 60 iterations (see Figure 4.5 for a typical convergence pattern). For first and second halves of the announcements, each node performed 2 and 1 iterations respectively. We calculated the required time for transmission of all signaling messages for each announcement to be of duration 0.228 msec[11]. Therefore, 40 announcements approximately occupied less than

[10] Discussion on the choices of PC parameters can be found in [30].

[11] Assuming 7 Bytes for feedback messages, 6 Bytes for forward/backward-BN-detection messages, 3 Bytes for initial-BN-detection packet, and 2 Bytes for occasional (say 10% of times) reset-packets, each mesh node that on average transmits/relays 3 CF-flows sends 45.6 Bytes for each announcement. Given a CCCH schedule of length 5 and using 8 Mbps transmission rate in this channel, each announcement requires 0.228 msec.

15% of each subframe. To facilitate comparison between the CFP and CP and for ease of implementation respectively, we did not use the third and fourth approaches.

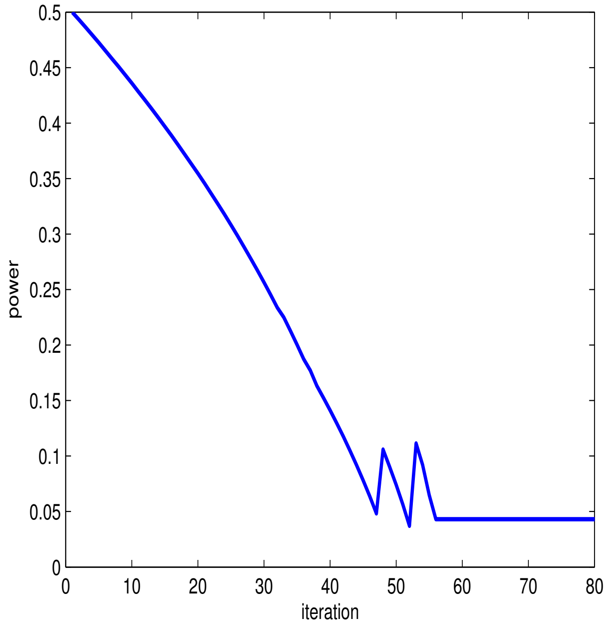

Fig. 4.5 typical convergence pattern

We assumed that all MCs request an (identical) end-to-end SINR of β although they may each receive a higher or lower value[12]. We varied the value of this parameter to estimate the maximum average end-to-end throughput a CFP flow can achieve and showed the results in Figure 4.6. As can be seen in this figure, the maximum throughput of 50.44 Mbps was achieved at $\beta = 15$.

[12]Our PC algorithm assumes elastic flows. Please refer to [30] for additional discussion.

κ_φ	β_φ
$\gamma_\varphi, \forall\varphi$	10
λ	0.01
α_φ, $\forall\varphi$	0.001
G	128
noise power	$10^{-6}W$
step-size	0.00004
interference range	50m

Table 4.1 Simulation Parameters for Power Control

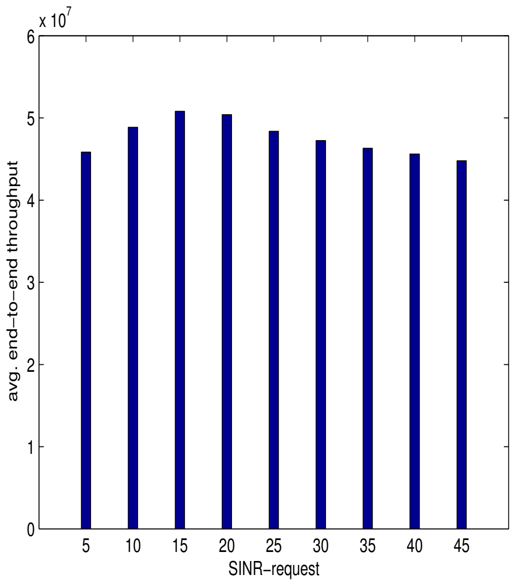

Fig. 4.6 average end-to-end throughput vs. β in the CFP

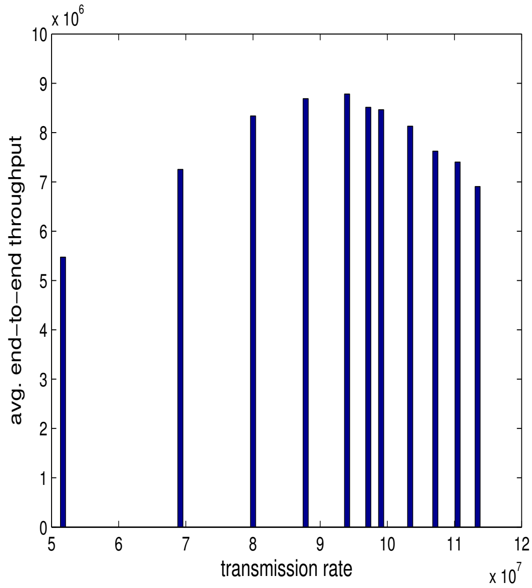

Fig. 4.7 average end-to-end throughput vs. transmission rate in the CP

4.6.3 Comparison between the Contention-Free and Contention Phases

We compared the average per-flow end-to-end throughput and the normalized standard deviation from the average end-to-end throughput values in the CFP and CP in the three network scenarios shown in Figures 4.2, 4.3 and 4.4 and summarized the results in tables 4.2 and 4.3. In all of these scenarios and for both phases, these results are obtained under the empirically estimated optimal parameters, i.e., we chose backoff parameter and transmission rate in the CP and β in CFP to optimize throughput. Note that the reported values are highly dependent on the specific network configuration. Also note that, as can be seen in these tables, during the CFP the normalized standard deviation from average end-to-end throughput was observed to be lower compared to the

CP which can be used to conclude that flows experienced better fairness characteristics during the CFP.

scenario	CFP avg. thput	CFP's norm. std. dev.	avg. hop-count
I	50.44 Mbps	0.001	1.8
II	11.44 Mbps	0.128	3.052
III	20.28 Mbps	0.074	1.968

Table 4.2 Performance evaluation of the Contention-Free Phase for the three network scenarios

scenario	CP thput	CP's norm. std. dev.
I	8.79 Mbps	0.252
II	0.876 Mbps	0.161
III	7.52 Mbps	0.19

Table 4.3 Performance evaluation of the Contention Phase for the three network scenarios

Also, to study the effect of noise on the throughput of the network, we increased its power from 10^{-6} (5×10^{-14}/Hz) to 4×10^{-6} (2×10^{-13}/Hz). The observed degradation in throughput for both CFP and CP is summarized in Table 4.4 in percentage. The observed difference in standard deviation of throughput among flows was negligible and therefore it is not reported here. Note that these small changes are in accordance with the interference-limited nature of CDMA networks and many of the studies performed in such settings ignore the role of noise altogether [9].

scenario	% CFP thput variation	% CP thput variation
I	3.2	0.84
II	10.4	3.05
III	0.81	2.33

Table 4.4 Percentage of difference in throughput for increased noise level

4.6.4 Comparison between the proposed power control algorithm and MIMD

We performed a comparison between our power control algorithm (indicated by EFPC, Elastic Flows Power Control, in the associated figures) and MIMD [88](described in Section 2.2.3). As the EFPC algorithm was particularly designed for multihop networks, similar to our results in the ad hoc context, we observed that it shows better performance than MIMD under configurations with relatively higher average hop-count between senders and receivers. For networks of low average hop-count, the performance of the two was very similar. We chose the second configuration which had the highest average hop-count and displayed the results of such comparisons on network utility (4.6) and end-to-end throughput in Figures 4.8 and 4.9 respectively.

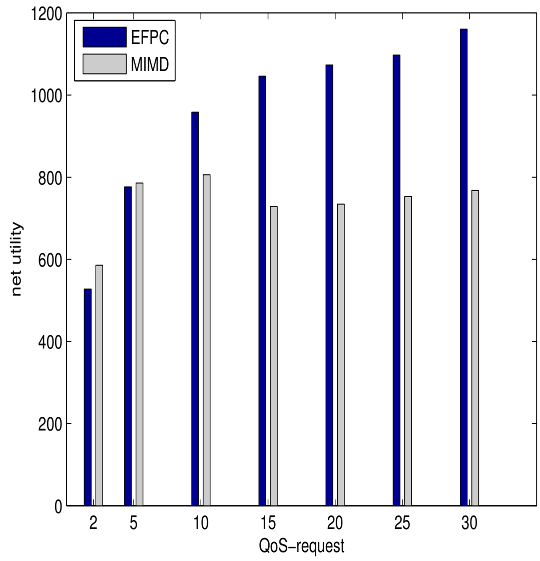

Fig. 4.8 comparison between EFPC and MIMD in achieved network utility vs. QoS-request

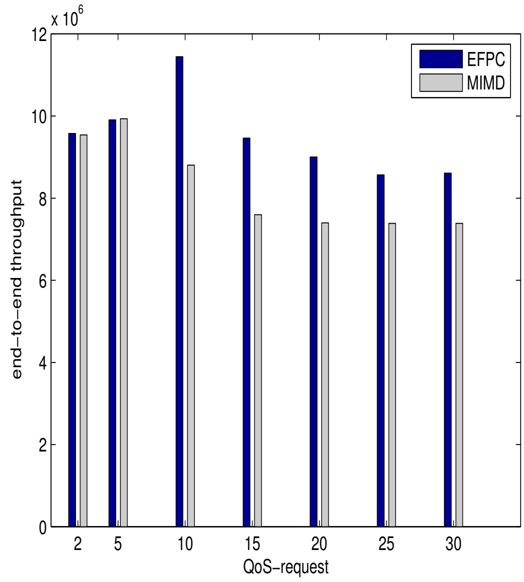

Fig. 4.9 comparison between EFPC and MIMD in achieved average throughput vs. QoS-request

4.7 Distributed Cross-Layer Resource Management in Multihop Wireless networks-Literature Review

Cross-layer design in multihop wireless networks attempts to maximize a global network objective subject to the capacity and stability constraints. Capacity constraints are imposed due to the shared medium in wireless settings and translate to the maximum durable data rates wireless links can transmit/relay akin to Shannon's capacity formula. Stability constraints mainly concern the boundedness of queues in wireless nodes.

The sum utility maximization problem has a general form as below:

$$\max_{x_s \leq Ms} \sum_s U(x_s) \tag{4.14}$$

$$\bar{x} \in \Lambda$$

where Λ is the capacity region, x_s is the data generation rate of user s and $U(\cdot)$ is a utility function chosen based on the objective of the network, e.g. fairness, minimum delay, etc. [89].

Considering a general interference model in wireless networks, in order to support the generated data by the users, network resources need to be carefully scheduled. The shared resources include transmission power at each node (that transmits or relays), the set of existing links, time, and the wireless medium. Any policy for sharing these resources is some times called scheduling [75]. Therefore, wireless resource scheduling includes power control, routing, link scheduling and load distribution.

In [75], the authors decompose this problem to a congestion-control problem, addressing user data rates, and a scheduling problem that finds a scheduling policy that is able to support the users' data-rates. Using a dual decomposition approach, they decouple these two problems and attempt to solve each one using iterative optimization methods. This decomposition leads to a simple problem to find user data rates and a very complex scheduling problem of the general form of

$$\max_{\vec{r} \in R} \sum_{(i,j) \in L} w_{ij} r_{ij} \tag{4.15}$$

When no paths are assumed to be selected a priori, the solution to this problem leads to finding the routes and a load distribution scheme that maximizes the size of the capacity region Λ. As in a wireless network the vector of all transmission powers $\bar{P}$ and the data rate of all links have a one-to-one mapping $\bar{r} = Z(\bar{P})$ (Z is in general a non-concave function), the solution to the above problem also can determine the transmission powers a node should use to transmit/relay data to any given destination.

The above scheduling problem in its general form is unfortunately shown to be very complex. Therefore, many studies have been performed addressing either special cases and simplifying assumptions that attempt to solve this problem optimally or heuristically. An example of these simplifying assumptions is that the transmission rate on a link l is proportional to its received SINR, i.e., $r_l = q\mathsf{SINR}_l$, which is rather accurate for low values of SINR [75,83]. Applying this assumption on the problem of minimizing total average power, in [83] the authors find an optimal routing, link scheduling and power control algorithm. Also, in [90, 91] the special case of high SINR conditions has been addressed in which $r_l = q \log \mathsf{SINR}_l$ leads to convex optimization. Extensive literature survey on these problems has been performed in [92, 93].

In [76], it has also been shown that applying rate control to the wireless network by solving problem 4.14 does not reduce the size of stability region studied e.g. in [94]. The stability properties of wireless networks have been extensively studied in [95,96]. In [96], a network with multi-commodity queuing system is considered. That is, each node maintains one queue for each flow it is transmitting/relaying and flows are distinguished by their destination node(s). The authors assume stationary processes for exogenous traffic arrivals at each node. At each time-slot, a servicing policy decides whether a link should service any given flow's traffic or not. Using Foster's criterion for queue backlog, the attempt is therefore to find an "optimal" servicing policy so that the queues at all nodes can be stabilized for a maximal set of mean arrival rates. The optimal policy at each link turns out to be the intuitive rule of servicing the flow which has the highest backlog pressure in its corresponding queue [97]. Also, note that when (stationary) arrival rate processes are given, Foster's criterion does not yield into a unique servicing policy, but a set of policies any of which would stabilize the queues. Extension of this work to networks including scheduling policies has also been addressed in [96]. The extension of this work to wireless networking is made in [95]. Note however that, for the purpose of cross-layer wireless network design, consideration of capacity region in addition to stability region is of critical importance. Some of the issues and difficulties involved with cross-layer network design with consideration of both capacity and stability regions have been explained in [92, 93].

Chapter 5

Routing

5.1 SINR-sensitive Routing

In Chapter 4, we proposed a power control algorithm using which the transmission power of all nodes are adjusted with specific consideration of bottleneck nodes (those with minimum received SINR). We now investigate SINR-sensitive routing in wireless mesh networks. Supplemental information about the routes (e.g., SINR information about nodes residing on each route) can be used to eliminate consideration of certain nodes that might, e.g., cause the SINR at a node to fall below its minimum acceptable value. In ad hoc settings, the residual node energy is some times used instead to filter certain nodes.

To make route selections sensitive to perceived SINR of the nodes, ideally information on perceived interference of all of these nodes should be incorporated in link metrics. However, in practice, this may impose a significant burden on the network. Therefore, a dynamic/transient routing algorithm could be instead considered which is sensitive to the perceived SINRs of only a small number of bottleneck nodes and the current imbalance of SINRs. These nodes may announce (revoke) their "status" (of being bottlenecks) to their interfering neighbors, and communicate associated details such as path-gain parameters if available.

In the light of the above discussion, in this chapter we address some of the problems in frequently used link/path selection metrics by incorporating link quality in the routing mechanism. This study is performed in the context of wireless mesh networks for Internet access which are currently being considered strong candidates for future broadband provisioning in both urban and rural areas.

Performance degradation due to interference in TDMA-based wireless mesh networks is one of the main problems that limits the usability of these networks and therefore has motivated many researchers to address it. The studies performed attempt to modify the network design across all layers. TCP in its original design has shown to be very inefficient in wireless networks for several reasons, e.g., because of its interpreting all the losses to be due to congestion and, therefore, throttling the transmission rate of the users. Together with the CSMA/CA mechanism in the MAC, this could result in very poor network performance. In particular, when packet losses due to interference happen at the MAC layer, not only does the backoff mechanism in 802.11 increase the backoff window of the interfering nodes, but also TCP decreases the transmission rate of the colliding users. A discussion regarding random loss and congestion loss can be found in the next section, Section 5.1.1. Moreover, the latter can also result in higher Round Trip Time (RTT) which in turn may cause more packet losses and even lower transmission rate. This effect is also known as a "capture effect". More complications can also happen in calculating Retransmission Time Out (RTO) as its value needs to be adjusted based on the value of RTT which is highly variant in multihop wireless environments. Modifications to TCP and 802.11 MAC have been suggested to address such issues in e.g. [98–100]. Congestion and interference are also controlled/mitigated in network layer, i.e., with routing. Our approach was motivated by persistent practical difficulties with the effectiveness of routing algorithms, despite the many routing protocols that have been suggested for multihop wireless networks [10]. These problems have been severe enough to make network designers resort to static path-selection in some of the mesh deployments. To address these issues, in some studies path selection is made more sensitive to interference and other channel conditions [10, 22, 101–105]. With the exception of [103], most of these works do not make explicit account for the network's load-level and rather focus on finding low-loss paths, where loss may be due to physical characteristics of a link in isolation (e.g., low path-gain, shadowing, etc.) or due to contention among nodes in the shared wireless medium. While this approach has proved to perform better than simple minimum hop-count metric (at least in not highly mobile settings), it is not very efficient. In highly loaded network conditions the good quality links may simply be over-used and therefore congested, while very lightly loaded links with not very high quality be simply filtered out instead of being partially used to resolve congestion.

The focus of this study is to find a better link-metric that accounts both for link quality and for link load. We investigate the effect of incorporation of SINR into the routing metric on the delay and throughput performance of the network and use a simple redemption mechanism in the SINR-based link metric to account for the link-load into our proposed metric. The objective of this study is therefore similar to that of [103] while the methodology and assumptions of our study differ from those of [103]. We describe some of these differences in Section 5.1.1 below.

5.1.1 Motivation and Literature Review

As in wireless networks the choice of 'minimum hop-count' path selection metric may result in low-quality links[1], defining a "suitable" link-metric for wireless networks has been the topic of many studies, e.g. [10, 22, 101, 102, 105]. Of all the proposed metrics, a few of them have been particularly shown to perform more effectively than the others, namely Per-Hop Packet Pair Delay (PktPair) [102], Expected Transmission Count (ETX) [101] and Expected Transmission Time (ETT) [106].

Two versions of link metrics based on probe packet delays meaning RTT [22] and PktPair [102,107] both attempt to capture local congestions and link load by incorporating the expected time for a successful transmission including MAC layer's backoff delay and nodes' queuing delay. For each node, RTT involves periodic unicast transmission of a probe packet, including a time-stamp to each neighbor, to which the neighbor immediately responds with an acknowledgment. Therefore, a node can measure the round-trip time to any of its neighbors. This metric accounts for link-loss, queuing delay (both at the node sending the probe and the intended neighbor) and channel contention (MAC delays). One of the major problems of this metric is its high sensitivity to instantaneous variations of load which could lead to path-oscillation and therefore instability. This problem is particularly exacerbated by the distortion incurred by the queuing delay the probe packets experience [22, 102]. To fix this problem, the PktPair metric is used which involves measuring the round-trip delay difference between two back-to-back

[1] e.g. with a high path-loss between the transmitter and receiver nodes

probe packets [102] the second one of which is larger than the first. This therefore discards the portion of delay that is due to queuing. In addition to incorporating local congestions (like RTT), this metric can also explicitly capture link bandwidth. That is, if a link has low bandwidth, the second packet takes long to reach the link's destination. It can be shown that even this metric suffers from some instability issues albeit less than RTT [102, 106]. Nevertheless, due to requiring each node to unicast to all of its neighboring nodes (as opposed to broadcasting in ETX explained shortly), RTT and PktPair both introduce excessive overhead (of order $O(n^2)$ in terms of the number of nodes n) and therefore might not scale well in large or high density networks [102].

ETX involves periodic broadcasting of a probe packet by each node that carries information about the number of times this node has received probe packets from its neighboring nodes (an $O(n)$ operation). By comparing this information and the record of number of times that it actually broadcast probe packets, each neighboring node can estimate the path-loss between itself and its neighbor. The expected number of transmissions required for successful packet delivery and ACK return is then calculated as $\frac{1}{(1-P_f)(1-P_r)}$ where P_f and P_r are forward and backward path-loss factors from any link-source to link-destination node respectively. Although this metric accounts for link-quality in terms of loss-rate and also implicitly for interference between consecutive hops, it does not take data-rate and link-load into consideration for selecting a path [10, 102]. This shortcoming particularly makes the routing (network layer) less sensitive to local congestions as links with heavy and light traffic loads are considered equal candidates for relaying traffic as long as they have equal path-losses. In this context, it is important to note that the higher the aggregate traffic rate on a link is expected to be, the higher should be its perceived SINR (based on Shannon's capacity formula) which suggests consideration of SINR in routing.

Another link metric commonly considered in wireless routing is Expected Transmission Time (ETT) [106] defined as:

$$ETT = \frac{Mean\ Packet\ Size}{Link\ Bandwidth} \times ETX \tag{5.1}$$

ETT is essentially a bandwidth-adjusted version of ETX. To calculate ETT, the reverse and forward link loss factors can be obtained using the same method as for ETX. The bandwidth calculation could be more complex. They may be estimated using the method proposed in [107] for PktPair: two back-to-back packets are sent to the node being probed. The first packet is of small size while the second one is large. The difference between the times these two packets are received is fed back to the probing node by the node being probed. Note that since the second packet is large, it reflects the instantaneous bandwidth of the link between the two nodes. In general, in the absence of any additional knowledge, bandwidth should be obtained empirically [106]. This metric could be modified to also include backoff delay due to CSMA/CA mechanism although it does not seem to improve throughput performance of the network and does not justify the excessive complexity it adds to the routing mechanism [106]. A variation of ETT, Weighted Cumulative ETT (WCETT), has also been proposed in [106] which mainly addresses 802.11 settings that use multiple channels. ETX, ETT and WCETT consider interference in a rather optimistic fashion. That is, as the total cost of an end-to-end route based on these metrics is considered the summation of the cost of each component link (obtained individually), an inherent assumption is that two component hops of a given path (using the same channel) cannot be active concurrently. Note that while this assumption holds for two-hop paths (to avoid self-interference), it does not necessarily hold for paths with more than two hops.

The discussion provided here suggests that a link metric with "reasonable" complexity which explicitly considers interference and also leverages quality, load and data rate characteristics of links is desired in multihop wireless networks.

One of the key factors in addressing the issues of TCP in wireless settings is to distinguish between random packet loss and congestion packet loss. Random loss in wireless networks is due to the inherently lossy characteristics of wireless links with typically time-varying quality. This problem is also exacerbated by e.g., high levels of interference and/or significantly long periods of fading. In addition to these factors, some researchers also consider all losses that occur in time-scales faster than RTT of a connection as random losses. Such short-term effects may happen for instance due to bursts of high priority traffic which results in transient congestion [108]. Congestion loss occurs when the average data rate injected to a link exceeds its capacity which eventually leads to buffer overflow and packet droppings. Note that congestion loss usually addresses **sustained** excessive loads (and not traffic bursts) which occur in an RTT time-scale [108]. Recalling that the capacity of a wireless link is determined by the SINR it receives (through Shannon's law), one can see that congestion loss occurs since the perceived average SINR (and therefore maximum possible data rate) of a link is below the level required for it to be able to carry its traffic load. Since the traffic load a link carries is determined by the data generation rate at source nodes and routing, this discussion suggests that making the routing algorithm sensitive to the links' perceived interference and therefore, SINR may be an effective way to mitigate both random interference loss and congestion loss.

In order to make explicit account for interference and local congestions, in this study we account for the links' perceived SINR in the link metric. This metric has been used before to exclude low quality links in the context of ad hoc networks [38]. Here, we use a slightly modified and load-sensitive technique in the context of mesh networks and assess its effectiveness when combined with an effective link metric such as ETX. To account for the link loads, we use a simple redemption technique in calculating the average SINR each receiver node observes. We return to this issue in Section 5.1.2.2. As explained before, in the presence of little or no mobility (the latter assumed herein), the link-breakage events mostly occur due to high levels of interference. Under such conditions, once the (average) path-gains from each node to its neighbors are assessed, they are guaranteed to remain the same for a long duration of time (before any new arrival/departure of MCs occurs).

The SINR-based path selection methods are blamed for the instability (oscillatory effects) they introduce in route selection, e.g., in reaction to short-term SINR variations [102]. This effect is less of an issue when the network is static and link-breakage does not occur very often (which is the case assumed herein). To alleviate instability, the SINR measurements may be averaged using a simple Moving Average (MA) process. More importantly, SINR could be used only as a secondary metric to exclude certain links (which is the approach taken herein). Also, path-filtering based on SINR-thresholding is believed to potentially result in elimination of links essential to maintain connectivity. To address these issues, in [109], low-SINR links (recognized as 'bad' links in their jargon) are still allowed to be used when no alternative is available. We do not use such techniques in our study. Instead, we apply thresholding on a modified version of SINR which is made also sensitive to the links' load[2] to perform better load balancing across the network. As mentioned earlier, the required SINR on a link depends on the average load it is expected to carry. Therefore, in order to make explicit account for a link's load, its SINR-threshold could be made sensitive to its load. We will discuss this issue in further detail in Section 5.1.2.2. There are some other studies that also account for interference by measuring signal strength as a link metric [105, 110]. For an extensive literature review regarding advantages and disadvantages of these techniques, readers are referred to [102] and its references.

Our study shares common objectives with those of [103] in that they both attempt to account for link-loss as well as link-load in selecting routes. In [103], the authors approximate the delay and throughput characteristics of the network through an analytical model, assuming mostly stationary traffic patterns. They use the predictions of this model to obtain a more link-loss/load-sensitive routing metric. Under structured topologies and stationary traffic patterns, UDP transport layer and a policy with no collision avoidance in the MAC (no RTS/CTS), their proposed metric yields significant improvement over more conventional routing metrics. In this chapter, we seek the same objectives using a different link-loss/load-sensitive routing metric, assuming TCP, CSMA/CA and no specific assumption on the mesh structure or traffic pattern.

[2]Note that the link sensitive metric element is used as a secondary metric to avoid path oscillation.

Also, the methodology of this chapter is different from that of [103]. A combination of the two approaches may lead to link-metrics with better load balancing properties and pursuit of this is left for future work.

We wish to acknowledge the existence of a concurrent work by the authors of [111] which also addresses the use of SINR in routing. While the main idea of that work is similar to our study, a different method (including a heuristic for measuring excess capacity instead of SINR redemption mechanism) is used to capture link load in their routing metric.

5.1.2 Incorporation of SINR in routing

5.1.2.1 Multi-Dimensional Link Metrics

When the routing algorithm pursues more than one objective, there may be a need to have more than one link metric in the network, e.g. hop-count (to address delay requirements) and power (perhaps to maximize number of simultaneous users). Denote a multi-dimensional metric for link l by $\boldsymbol{c^l} = (c_1^l, c_2^l)$. The end-to-end cost of a route r then depends on the links l residing on the route as well as the nature of each of the metrics c_i^l. That is, for instance in the two-dimensional example, c_1 may be delay or hop-count and is therefore additive, i.e.

$$C_1^r = \sum_{l \in r} c_1^l$$

while c_2^l may be residual energy and of bottleneck nature, i.e., $C^r = \min_l \{c_1^{l_i}\}$ where $\{l_i\}$ are the links that form route r [112]. More generally, a multi-dimensional link-metric may consist of one *primary* and one or more *secondary* metrics. Under such an assumption, the routing algorithm attempts to optimize the objective associated with the primary link-metric while using the secondary metric(s) only to exclude certain links [112]. In a two-dimensional metric for example, the primary link metric could be chosen as hop-count and the secondary value could be a member of set $\{0, \infty\}$, with the choice made between the two members based on comparison of one characteristic of the link with a threshold value, i.e.,

$$c_2^l = \begin{cases} 0 & ; \mathsf{SINR}^l \geq \Theta \\ \infty & ; \mathsf{SINR}^l < \Theta \end{cases} \quad (5.2)$$

where Θ is the threshold value and SINR^l is, of course, the received SINR of link l. In this study, we assume a two-dimensional link-metric with hop-count or ETX as primary and SINR as secondary metric.

5.1.2.2 Practical Issues with SINR-thresholding

Let us first assume a mesh network with one BS, a number of MRs and a larger number of MCs. Let us also assume that most MCs do not have direct access to the BS and therefore require multihop routes to communicate with it. In a uniform network with balanced load, it is intuitive to choose a single value for the SINR threshold, as all links on average carry the same amount of traffic. In a mesh network however, such a choice may not always be reasonable. That is, in a mesh setting, all MCs need to send their traffic to the BS through MRs (for Internet access) and, therefore, the average traffic load of MRs increase as we move further toward BS. This may render these MRs the natural bottlenecks of the network. This effect is known as a *funnel effect* and has also been observed and studied in the context of sensor networks [113]. Since the higher the average traffic load on a link, the higher its received SINR is required to be in order to carry this load, it may be beneficial to set the SINR-threshold of the links closer to the BS higher than at leaf links (i.e. connected to the MCs). Setting these values by such a static approach is possible by e.g. assuming that MRs (parts of infrastructure) already know their relative distance to the BS(s). Alternatively, MRs could obtain this information by examining the packets they receive (both data and acknowledgment) and extract the average number of hops that they have traversed before reaching them. Dynamic adjustments to SINR-thresholds may also be performed in order to find optimal values although in practice this may result in path-oscillations due to the sensitivity of routing to the traffic load. For simplicity however, in this study we assumed a fixed SINR-threshold identical for all MRs. To obtain a "good" threshold, we varied it and measured throughput and RTT. Further discussion is given in Section 5.1.3.

5.1.2.3 Accounting for Link Load in the routing metric

An important issue with an SINR-sensitive link metric is that, although it attempts to avoid hot-spots, it does not take link load into account. To see the problems that can be created due to this, let us consider an example in which a node, A, resides in a low density area of the network (has only a small number of nodes in its neighborhood), but is critical to maintain connectivity and carries a lot of traffic. When attempting to route a new flow using a routing metric insensitive to link-load, node A may still be preferred to an idle node that resides in a network hot-spot and therefore perceives a higher average interference. Therefore, eventually, node A will get overwhelmed and congested by excessive traffic. To address this issue, we use a redeemed version of SINR in thresholding the routes. To calculate SINR, a node measures the amount of interference it receives during its idle periods. An moving average exponential weighting rule is then used to update the perceived interference (denoted by I) at a node:

$$I(i) = (1 - \chi)I(i - 1) + \chi I_{sample} \tag{5.3}$$

where I_{sample} is the latest measured interference level during idle periods and χ is a weighting factor. Assuming a slow rate in the variation of **average** interference, this quantity is used to calculate SINR during reception periods. Accordingly, c_2^l is updated as follows:

$$c_2^l(i+1) = \begin{cases} \min(c_2^l(i) + \Delta, \Theta + \delta) & ; t \neq kT, idle \\ \mathsf{SINR}(i) & ; t = kT \end{cases}$$

where Θ is the SINR threshold explained previously, $\Delta > 0$ is the step-size of each increment, $\delta > 0$ is a small margin which ensures that c_2^l will gradually reach a level above the threshold Θ when a node does not transmit/relay for a long enough duration of time, k is any positive integer, and T is the resetting period, i.e., c_2^l is reset to (the currently assessed) SINR periodically. Note that this resetting may instead be performed in instances at which a node starts receiving relayed packets. For each node, thresholding is applied to c_2^l rather than to SINR itself. This scheme essentially helps to take the number of times a node transmits, i.e. its load level, into account. This therefore allows potential preference of an infrequently used node residing in a hot-spot over a congested node with a high perceived SINR. Alternatively, to account for the link load, one may include the fraction of times a node transmits [103] by adding it as a third dimension's element to the link metric.

5.1.3 Simulation

In this section, we present the results of a simulation study with the main objective of comparing the performance characteristics of a static wireless mesh network when the routing algorithm does/does not account for local SINRs in routing. Throughout this section, whenever we use SINR-sensitive link metric, we refer to the redeemed version of SINR as described previously in Section 5.1.2.3.

We considered a mesh network consisting of one BS, 12 MRs and 22 MCs configured as depicted in Figure 5.1 in a 100m×100m area. We assumed a second order power attenuation model. We used a simple physical layer model in which BPSK is used for modulation. We assumed that the nodes use a Carrier Sense Multiple Access-Collision Avoidance (CSMA/CA) mechanism as in 802.11 with Request-To-Send (RTS), Clear-To-Send (CTS) and ACKnowledgment (ACK) being of length 160, 160, 112 bits respectively (based on 802.11b parameters). The duration of SIFS, DIFS and one time-slot were assumed to be 10 μsec, 50 μsec and 20 μsec respectively. The data rate of the wireless channel was assumed to be 11 Mbps, and the data and (end-to-end) ACK packets were chosen to have a length of 1500 bytes and 38 Bytes respectively. The Contention Window (CW) was chosen between 64 and 1024 slot durations. No actual error correction was simulated. The maximum number of retransmissions in the link-layer was assumed to be 5 and the node buffer size was chosen to be 50. We used ETX as the primary and SINR as the secondary link metric and studied the delay/throughput performance of the network under different load conditions.

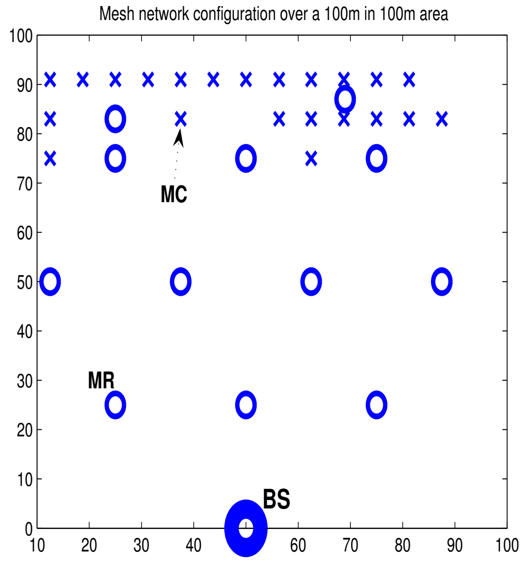

Fig. 5.1 Simulated mesh network Scenario over a 100m×100m area

We also assumed that the MCs adjust their transmission rate using a simplified version of TCP Vegas [114] in which if the value of Round Trip Time (RTT) a MC observes is above its minimum measured value, a.k.a BaseRTT, it cuts its congestion window to half and linearly increases it otherwise (within the window's boundaries). Also a threshold (equal to 2) was set on the standard deviation of RTT and deviation from it was assumed to have the same effects as deviation from BaseRTT. The contention window was allowed to vary between 1 and 10. The value of RTT was updated according to a weighted exponential model in which the weight of new values was 0.2, i.e., $RTT = 0.8 * RTT_{old} + 0.2 * SampleRTT$. We note however that, due to the unfairness observed in window sizes larger than one (which will be addressed shortly), the simulation results presented here are obtained under $W = 1$.

The basic routing algorithm used in all of the scenarios was distributed Bellman-Ford. Flows were added one by one in 3 second intervals. Once a flow's traffic path was chosen, it would remain the same throughout the simulation interval. The routing algorithm was applied *only* to newly arriving flows based on one of the metrics discussed earlier. Therefore, in the SINR-sensitive routing schemes, the new flows were routed such that hot spots were avoided.

As discussed earlier in Section 5.1.2.3, we adjusted the measured SINR of each node with an additive term to account for the link load. We chose this term small enough so that it does not fully compensate for high interference, but does take the number of times a node transmits, i.e. load, into account. In our simulation, SINR was incremented with steps of $\Delta = 5 * 10^{-5}$ at time-quanta of 10μsec (equal to one time-slot) for each time-quantum it was not receiving data packets, $\delta = 0.03 * \Theta$ as the SINR margin, and $T = 4$ second as the period of resetting (the latter chosen to be bigger than flow arrival intervals).

We assumed that all MCs generate data (uplink) for transmission to the BS according to a CBR model with data rates that were varied from 12 Kbps to 1.2 Mbps and there is no downlink traffic generated. To measure ETX, probes of length 193 Bytes were broadcast under 1 Mbps transmission rate once every 1 second to all of a MC's neighbors with slightly different starting times to avoid collision. No collision avoidance (RTS/CTS) was applied to these packets. Link path-gains were found through $\frac{1}{(1-P_f)(1-P_r)}$ (as described in 5.1.1) where P_f and P_r values between any pair of nodes A

and B were obtained by counting the number of probe packets received at node A (B) over 10 second sliding windows transmitted by B (A). Note that any node A gets to know about the number of its probe packets that were received at node B by inspecting the information contained in B's probe packets broadcasted [3]. A weighted exponential was also assumed for calculating the MRs' SINR with a new value having a weight of 0.2 again for the SINR-dependent routing scenarios. To find a suitable value for SINR threshold, its value was varied and the resulting throughput and delay were observed. Different optimal values were observed under different traffic levels. Figure 5.2 shows the network's RTT versus versus different choices of SINR-threshold when each MC generates data with a constant bit rate of 12 Kbps (aggregate traffic generation of 264 Kbps uploaded to the BS). The numbers shown next to each graph are the obtained average aggregate (collected from all MCs at the BS) throughput values. With regard to this graph we should note that the non-monotonicity effect observed in this figure is the result of different factors that affect the delay and throughput performance of the network[4]. That is, increasing the SINR-threshold helps to have a better distribution of load throughout the network although at the potential cost of an increase in the length of paths. The immediate result of this would be higher throughput but also higher latency. On the other hand, as a result of better load balancing, SINR-thresholding also helps to reduce local congestion which also decreases MAC incurred delay. In any case, SINR-thresholding to the least provides a means to trade off delay and throughput. In

[3]Each probe packet sent by a node contains information on how many probe packets in the past 10 seconds it has received from each of its neighbors.

[4]The specifics of these effects is closely dependent to the network architecture and traffic patterns.

Figure 5.2, we can see that the threshold value 150 results in delay levels even lower than those obtained under no thresholding in addition to improvement in throughput. Nevertheless, we observed that in most network scenarios even simple blocking of links with low SINR-level, i.e. low quality links, results in meaningful improvement of aggregate throughput by reducing the number of failures and wasteful use of the wireless medium. In other words, simple greedy mechanisms for data forwarding also result in throughput enhancement.

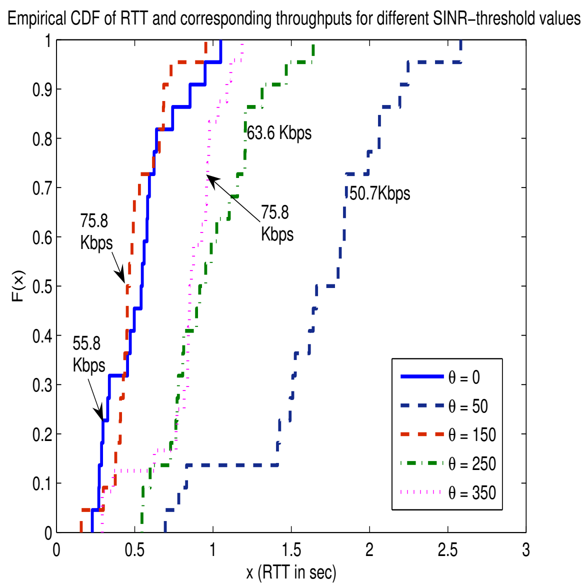

Fig. 5.2 RTT and throughput for different choices of SINR-threshold

To assess the performance enhancement due to the SINR-sensitivity of link-metrics, we varied the traffic load level from very light to very heavy and measured the RTT and aggregate throughput (of all MCs) over a time-window of 10 minutes. Figures 5.3 and 5.4 show the resulting median RTT (obtained over 22 flows) and aggregate time-averaged throughput versus the data generation rate of MCs. Both of these figures are obtained using a fixed SINR threshold of 150. Note that this was done for simplicity and the optimal threshold value is different for different network loads as mentioned previously. The values shown in these figures were obtained by averaging over 5 different traffic pattern realizations (due to the inherent randomness of CSMA/CA mechanism). Both of these figures were obtained using the same realizations. To see the effectiveness of the routing scheme, we fixed the value of congestion window at $W = 1$. In fact, in practice, due to the difference in path-lengths and interference flows experience under moderate traffic loads, varying congestion windows usually result in unfairness in the throughput among different users. This effect has been observed before [108] so that $W = 1$ is commonly chosen in presence of different wireless TCP sessions with non-identical paths. With regard to Figure 5.3, it should be mentioned that we did not draw the delay past user rate 120 Kbps since most of the MCs did not receive any throughput and therefore delay was undefined for them. However, very few users that monopolized the channel still received some throughput.

As expected, we observed only small differences between SINR-sensitive and SINR-insensitive cases in the very low load conditions and larger difference as load level was increased. It should also be noted that at very high traffic rates, only a few sessions were observed to have positive throughputs which were essentially the "winners" of the medium. Therefore, the median RTT values shown in Figure 5.3 were obtained only using these sessions.

We also tested the network performance when hop-count was used as the primary metric instead of ETX. Although for most cases the results showed a similar trend as

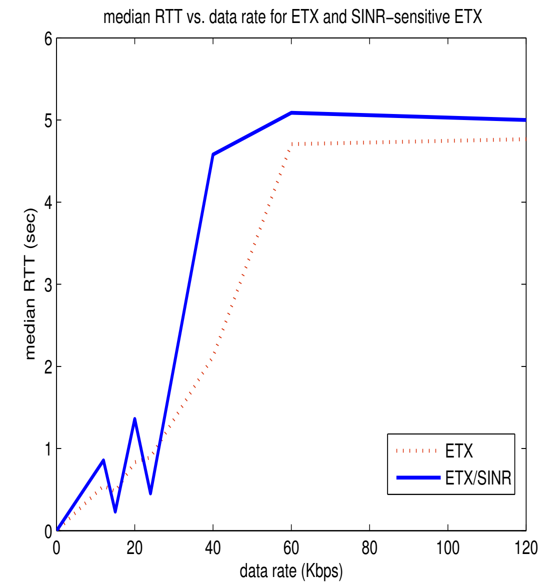

Fig. 5.3 Median RTT versus data rate using ETX and SINR-sensitive ETX

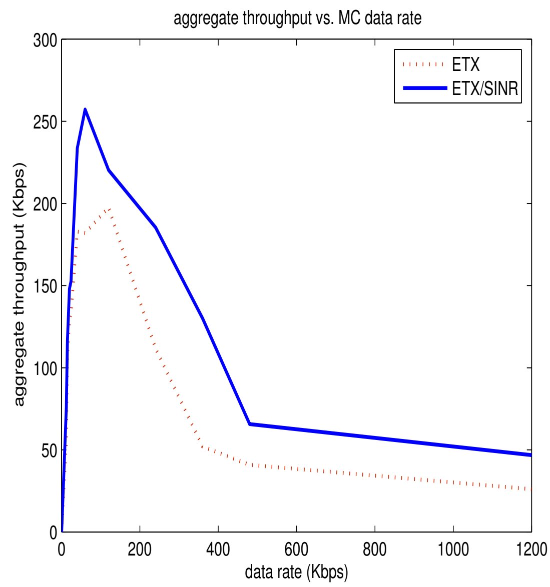

Fig. 5.4 Aggregate throughput versus data rate using ETX and SINR-sensitive ETX

with ETX, many path-oscillations were observed when using SINR-sensitive metrics, especially as the value of the threshold was increased.

5.2 Joint Routing and Scheduling

5.2.1 Routing with consideration of Scheduling

In the previous section, we attempted to incorporate the links'load and quality in selecting routes. The discussion made in that section was independent of the MAC layer scheme used in the network, i.e., random-access or scheduling. In this section, we address scheduling-based medium access (and therefore not 802.11). As in such settings the length of scheduling tables (frames) is inversely proportional to the share of the total bandwidth a certain flow can obtain, minimum frame-lengths are desired. Note however that frame-lengths are determined not only by the scheduling algorithm, but also by the paths taken by network flows. Therefore in order to maximize network resource utilization, given a certain scheduling mechanism, selecting a set of routes that result in minimum-length frames are desirable.

When, say, a source node tries to route a data flow through the network, all of the nodes on the route need to update their link schedules. Clearly, choosing certain paths may require adding new time-slots to the scheduling tables. The effect of this additional time-slot on the network throughput may outweigh favorable attributes of the path e.g. energy and delay. That is, there might exist alternative paths that require more energy and have more hops but are able to route the new flow without increasing the frame-lengths.

If the current duration of the schedule is T slots and it is increased to $T + 1$, the throughput reduction factor will obviously be $T/(T + 1)$ which is sizable when T is small and negligible when T is large. However, when the number of flows in the network is small, the length T of the schedule will typically be small and hence the allocated bandwidth B per time-slot, B/T, will be large. Thus, the reduction to $B/(T + 1)$ may still be adequate for most existing flows.

Regarding the preceding discussion, one can consider the existing uplink-downlink schedule in several ways when routing. For example, if a new route does not fit in the current schedule, the schedule can be always augmented to accommodate the flow or always reject the flow. An example compromise approach considering both scheduling and energy will now be described. Suppose there are two parameters that constitute a link metric: the energy spent per packet and the throughput reduction percentage (due to time-slot addition). Flows requiring no additional time-slots on routes that are energy rich (their "Minimum energy" is larger than some predefined threshold) are always accepted. Paths that require additional time-slots could, for example, have their energy penalized by a factor proportional to $(T + 1)/T$.

5.2.2 Simulation

In this section, we assess the performance of the CBO and ICBO scheduling and routing when performed with or without consideration of scheduling. The results presented here are based on experiments on a small network. However, the plots obtained by the current simulation are illustrative enough to visualize the effects of implementing the suggested methods on the network and to compare between the different strategies both in routing and scheduling.

In the first part of simulation, we considered a network of $N = 10$ nodes with randomly joining and leaving traffic and compared the length T of the obtained schedules. The routing algorithm used is simply distance-vector minimizing hop-counts. The network initially has a random number of traffic flows. The flows join and leave the network at the boundaries of time-slots. For simplicity, at each time-slot only one of the following three events occurred with equal probability: a random number of existing flows departed the network, a random number of new flows joined the network, or no change.

Under CBO, table refreshments occurred every time-slot, whereas CBO refreshments were performed only every 5 time-slots under ICBO-5. By comparing the length of the time-schedules obtained by CBO and ICBO-5 algorithms in Figure 5.5 (in which a typical 20 time-slot coupled sample path is displayed), we observe that the CBO algorithm results in schedules with significantly smaller length, i.e., higher per-flow throughput.

The second part of the simulation investigated the three routing strategies discussed earlier in Section 5.2.1: In the "R-AAF" (Routing/Accept All Flows) strategy, the routing algorithm chose a minimum cost path and extended the table if necessary to accommodate the flow. Under the second method, "R-RIC" (Routing/Reject if Conflict), the flow was simply rejected if its minimum-cost path conflicted with the existing schedule. In the third "R-PIC" method (Routing/Penalize If Conflict), we penalized the

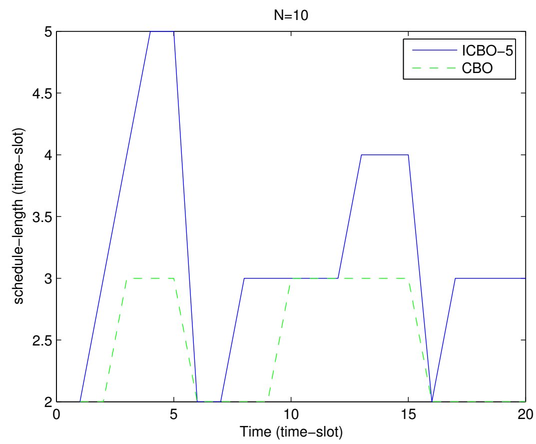

Fig. 5.5 ICBO-5 versus CBO scheduling algorithm

cost of paths that did not fit in the schedule by a factor of $(T+1)/T$ where T was the current schedule-length and then performed the minimum cost routing algorithm again.

For a network of $N = 20$ fixed nodes, we assumed for simplicity that flows only joined the network and did not leave during the time-window of interest, and applied CBO at every time-slot. We plotted the table-length obtained by the three methods in Figure 5.6. As obviously expected, the first R-AAF method has the longest schedule-length. The "R-RIC" method had the shortest schedule but had a high blocking (flow rejection) rate, see Figure 5.7. The third "R-PIC" method had a table-length longer than that of the second "R-RIC" method and shorter than the first "R-AAF" one. However compared to "R-AAF", "R-RIC" had slightly longer paths. This effect can be observed in Figure 5.8 where the percentage of the additional number of hops traveled in the third "R-PIC" method relative to that of the first "R-AAF" method is depicted. Since the number of hops of a flow is an indication of the amount of energy required to forward it, the mentioned effect reveals a trade-off between energy and bandwidth (that is proportional to $1/T$). Again, results for typical sample paths are depicted in these figures. Note that to calculate the blocking rate of R-RIC method in Figure 5.7, we attempted to add a new flow to a certain network with variable number of flows and counted the number blocking occurrences in 100 trials. The blocking rate of Figure 5.7 is obtained under the initial schedule-lengths of 2 and 3.

Several notes should be made regarding the simulation results. First, as can be seen in Figure 5.9, we observed frame-length reduction in some realizations of the network, i.e., the number of time-slots decreased despite the addition of a new flow. This phenomenon is due to the fact that CBO scheduling algorithm is not necessarily optimal. It's worth noting that joint routing-scheduling helps to reduce the effects of this event by preventing the frequent occurrence of table extensions. Second, we observed that blocking rate depends on the number of time-slots required for the transmission of the initial network flows, i.e., if the network has primarily a high flow traffic, the number of initial time-slots is also high. Obviously, the higher the initial number of time-slots, the lower is the blocking rate (at the cost of reducing the bandwidth), e.g., in a network of $N = 20$ nodes, a frame-length of 5 was high enough to schedule almost all flows and, therefore, the blocking rate at this frame-length was very small (0 in our experiment). This phenomenon occurs at shorter frame-lengths in smaller networks. Finally, note that since, to the best of our knowledge, there is no other suggested algorithm in the existing literature to perform joint routing and uplink-downlink scheduling, the R-PIC method could not be compared to any other previously suggested joint routing-scheduling algorithms.

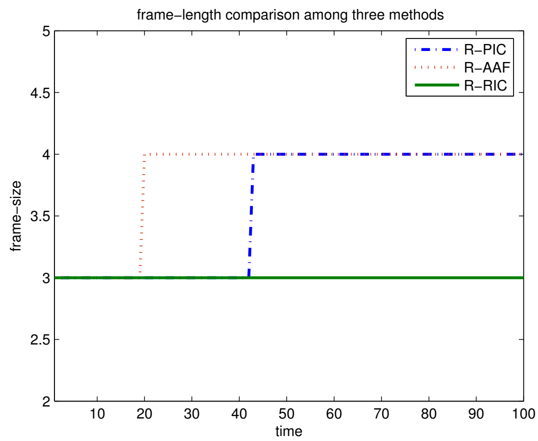

Fig. 5.6 frame-lengths of three routing strategies

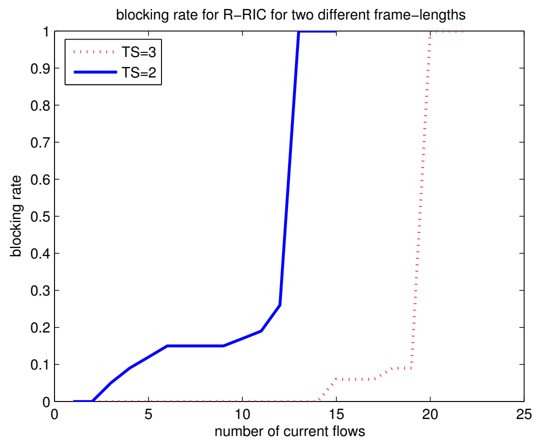

Fig. 5.7 blocking rate of the R-RIC

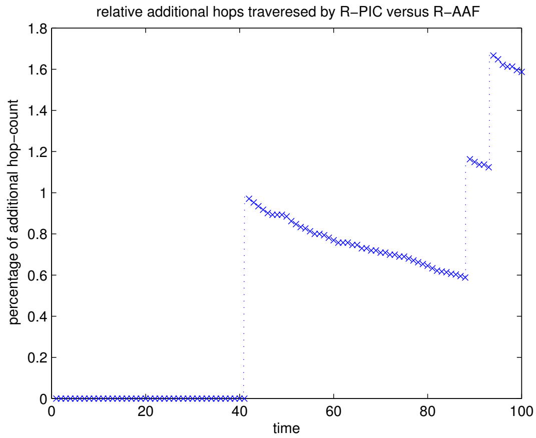

Fig. 5.8 additional hops to pass under R-PIC compared to R-AAF

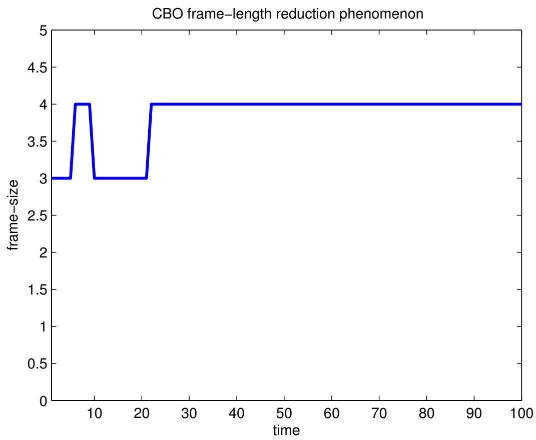

Fig. 5.9 CBO frame-length reduction effect

Chapter 6

Incentivized Relaying for Wireless CDMA Mesh Networks

In this chapter, we propose a relaying mechanism in CDMA Wireless Mesh Networks (WMNs) for broadband Internet access. We consider a portion of such network with one pivot Mesh Router (MR), a number of static Mesh Clients (MCs) in communication range with the MR, and a group of Mobile Mesh Clients (MMCs) which are out of communication range with the MR, but in range with at least one MC. Based on this structure, MCs can receive their required traffic directly from the MR, while the MMCs require a MC to relay their traffic from the MR on their behalf, and also send this traffic to them subsequently. As this relaying requires consuming their resources, MCs would prefer to avoid it unless there is a financial incentive. We therefore set up a financial model in which MCs are compensated for relaying MMCs' traffic through discounting their own traffic. For simplicity, we assume that at any given instant, an MMC only communicates with one MC, akin to a cellular setting.

Specifically, we consider scheduled CDMA with adjustable transmit powers [2, 115]. The case of scheduled CDMA with constant powers is trivial as there is no conflict, and the case of Random Access CDMA (RA-CDMA) with adjustable powers is complex and therefore not usually implemented. Regardless of the MAC and power control scheme, each node is assumed to use distinct (pseudo)orthogonal codes for each neighboring node to which it transmits, see discussion in 2.2.2.1.

6.1 System Model

For simplicity, herein we assume downlink traffic although the extension of the model to both uplink and downlink traffic is straightforward. A cluster of MMCs serviced by MC_n is denoted collectively by MMC_n. We assume that every MC_n has a strictly concave utility function $U_n(\cdot)$. Denote the average traffic rate (destined to and) received at MC_n by y_n and the average traffic rate relayed to MMC_n via MC_n by x_n.

To transmit a packet destined to a MC, the network charges an amount of M dollars. MC_n receives compensation for the traffic x_n it relays to its corresponding MMC community by the amount of $D(x_n)$. This discount function may be chosen as any differentiable and increasing function of its argument, e.g. linear $D(x_n) = dx_n$, logarithmic (subadditive) $D(x_n) = d\log(1+x_n)$ or exponential (superadditive) $D(x_n) = \exp(dx_n) - 1$ where d is a discount factor. The specific choice of a discount function depends on the requirements of the network. That is, a superadditive (subadditive) discount function motivates a larger (smaller) number of MCs to perform relaying on behalf of MMCs. The net utility of MC_n is as follows:

$$U_n(y_n) - My_n + D(x_n). \tag{6.1}$$

Assuming selfish but rational users, each MC_n therefore attempts to maximize its net utility by choosing to relay

$$y_n = (U_n')^{-1}\left(M - D'(x_n)\frac{\partial x_n}{\partial y_n}\right). \tag{6.2}$$

6.2 CDMA Dynamics

Under RA-CDMA with fixed powers, as nodes use (pseudo)orthogonal codes to transmit to their neighbors, any node is able to send to (receive from) more than one other node concurrently. In a CDMA random access setting, collisions may only occur due to a transmit/receive conflict [2, 115]. Denoting total traffic of MCs downloaded at MR by $Y = \sum_n y_n$ and that of MMCs by $X = \sum_n x_n$, if the transmission probability of any node n at a given instant is π_n, we will have

$$X + Y = \pi_{\mathsf{MR}}(1 - \sum_{n=1}^{n=N} \pi_n)$$

and

$$x_n = \pi_n(1 - \pi_{\mathsf{MR}} - \sum_{i \neq n} \pi_i).$$

The steps to find $\partial x_n/\partial y_n$ and game-based adjustment of transmission probabilities in this case would be analogous to those derived in [116] for ALOHA. Herein, we do not further discuss the dynamics of RA-CDMA as the main focus of this chapter is on scheduled CDMA.

Under scheduled CDMA, the transmissions are assumed to be scheduled in a conflict-free manner, i.e., unlike the random-access case, simultaneous transmit/receive occurrences are avoided. Considering the structure of a mesh network with only downlink data traffic, a simple scheduling scheme could have frames consisting of two time-slots the first one of which is used for transmission from MR to the MCs and the second one is used for transmission from MCs to MMCs. Note that, considering only downlink traffic, when no relaying to MMCs is performed, the MCs can use all of a time-frame to receive their own traffic, i.e., no capacity sharing is required. We assume that a fraction γ_r of the time is assigned for transmission of downlink traffic from MR to MCs and a fraction of $\gamma_c = 1 - \gamma_r$ for the downlink traffic from MCs to MMCs. Note that such division of capacity between a MC's own traffic and its assigned MMC community requires incentivization. We may model this by e.g. setting

$$\gamma_c = \mu \times d \tag{6.3}$$

where $\mu > 0$ and $\mu d < 1$.

To consider both uplink and downlink traffic, two different values may be chosen for each portion of γ_r and γ_c, i.e., γ_{ru}, γ_{rd}, γ_{cu} and γ_{cd} where the subscripts u and d are added to indicate uplink and downlink transmissions respectively. To reflect the ratio between the two communication directions, we could set e.g. $\frac{\gamma_{ru}}{\gamma_{rd}} = \frac{1}{10}$ and similarly for γ_{cu} and γ_{cd}. The extension of the following to these scenarios is straightforward. Based on the above assumptions and using the mapping between the SINR and channel data rate [15], we have

$$x_n + y_n = C \log_2(1 + \mathsf{SINR}_{\mathsf{MC}n}) \times (1 - \gamma_c) = \tag{6.4}$$

$$C(1-\gamma_c)\log\left(1 + \frac{h_{(\mathsf{MR},\mathsf{MC}n)}P_{(\mathsf{MR},\mathsf{MC}n)}}{I_{\mathsf{MC}n} + N_0}\right),$$

where: C is the frequency bandwidth available; $h_{(a,b)} = h_{(b,a)}$ (path-gain is transitive, but this is not true for P of course); and $I_{\mathsf{MC}n}$ is the interference perceived at $\mathsf{MC}n$ during the time-slot it is transmitting, i.e., it is affected only by the traffic scheduled in the same time-slot as itself:

$$I_{\mathsf{MC}n} = 1/G \sum_{m \neq n} P_{(\mathsf{MR},\mathsf{MC}m)} h_{(\mathsf{MR},\mathsf{MC}n)} + \tag{6.5}$$

$$1/G \sum_{m \neq n} \sum_{j} P_{(\mathsf{MC}m,\mathsf{MMC}j)} h_{(\mathsf{MC}m,\mathsf{MMC}n)}$$

where G is the spreading gain of the CDMA system [15]. Note that if the scheduling scheme is chosen as described in the beginning of this section with only downlink traffic, the second summation in the above expression will disappear. Finally, note that x_n and y_n are not only limited by the interference the MCs perceive, but also by the maximum transmission power available at the MR and MC, i.e.,

$$P^{\max}_{\mathsf{MR}} \geq \sum_{n} P_{(\mathsf{MR},\mathsf{MC}n)} \tag{6.6}$$

and

$$P^{\max}_{\mathsf{MC}n} \geq P_{(\mathsf{MC}n,\mathsf{MMC}n)}, \tag{6.7}$$

and the scheduling constraint $\gamma_r + \gamma_c = 1$.

Considering $\mathsf{MC}n \rightarrow \mathsf{MMC}n$ communication, we also have

$$x_n = C\gamma_c \log_2(1 + \mathsf{SINR}_{\mathsf{MMC}n}) \tag{6.8}$$

$$= C\gamma_c \log_2\left(1 + \frac{h_{(\mathsf{MC}n,\mathsf{MMC}n)}P_{(\mathsf{MC}n,\mathsf{MMC}n)}}{I_{\mathsf{MMC}n} + N_0}\right)$$

where, again, $I_{\mathsf{MMC}n}$ is the interference $\mathsf{MMC}n$ observes which is only affected by the traffic being communicated concurrently with its own traffic:

$$I_{\mathsf{MMC}n} = 1/G\sum_{s\neq n} h_{(\mathsf{MC}n,\mathsf{MMC}n)}P_{(\mathsf{MC}n,\mathsf{MMC}s)} \tag{6.9}$$

$$+1/G\sum_{m\neq n} h_{(\mathsf{MR},\mathsf{MMC}n)}P_{(\mathsf{MR},\mathsf{MC}m)}.$$

Again, note that if the scheduling scheme used consists of two subframes one for all MR→MC and the other for MC→MMC transmissions, the second summation in the above expression will disappear. In the rest of this chapter, we assume that communications occur under such a scheduling scheme.

Using equations (6.4) and (6.8), y_n can be obtained as follows:

$$y_n = C(1-\gamma_c)\log_2(1+\mathsf{SINR}_{\mathsf{MC}n}) - C\gamma_c\log_2(1+\mathsf{SINR}_{\mathsf{MMC}n}) \tag{6.10}$$

To obtain $\frac{\partial x_n}{\partial y_n}$, we can first find $\frac{\partial y_n}{\partial \gamma_c}$ and $\frac{\partial x_n}{\partial \gamma_c}$ from equations (6.10) and (6.8) respectively: $\frac{\partial x_n}{\partial \gamma_c} = C\log_2(1+\mathsf{SINR}_{\mathsf{MMC}n})$ and $\frac{\partial y_n}{\partial \gamma_c} = -C\log_2(1+\mathsf{SINR}_{\mathsf{MC}n}) - C\log_2(1+\mathsf{SINR}_{\mathsf{MMC}n})$. Using the chain rule $\frac{\partial x_n}{\partial y_n} = \frac{\partial x_n}{\partial \gamma_c} \times \frac{\partial \gamma_c}{\partial y_n}$ we therefore have:

$$\frac{\partial x_n}{\partial y_n} = -\frac{\log_2(1+\mathsf{SINR}_{\mathsf{MMC}n})}{\log_2(1+\mathsf{SINR}_{\mathsf{MC}n}) + \log_2(1+\mathsf{SINR}_{\mathsf{MMC}n})}. \tag{6.11}$$

Regarding the derivation above, note that under scheduled transmissions, y_n is only a function of independent variables γ_c and $P_{(\mathsf{MR},\mathsf{MC}m)}, \forall m$ and x_n is only a function of γ_c and $P_{(\mathsf{MC}n,\mathsf{MMC}m)}, \forall m$. Therefore, when the boundary points at which $x_n + y_n = 0$ or $y_n = 0$ are avoided, x_n and y_n are only coupled through γ_c. To see this, recall that under scheduled conditions, $\mathsf{MR} \rightarrow \mathsf{MC}m$ and $\mathsf{MC}n \rightarrow \mathsf{MMC}m$ do not occur concurrently, please refer to the simplifications to equations (6.5) and (6.9) under scheduled conditions.

We now can set the synchronous algorithm as follows using i to indicate iteration number:

Based on equation (6.4), the MR adjusts its transmit power to $\mathsf{MC}n$ in an attempt to achieve the current data rate $x_n(i) + y_n(i)$ using either a Multiplicative Increase Multiplicative Decrease (MIMD) update [47] (see Section 2.2.3, equation (2.3)), i.e.,

$$P_{(\mathsf{MR},\mathsf{MC}k)}(i+1) = P_{(\mathsf{MR},\mathsf{MC}k)}(i) \times \frac{(2^{(\frac{x_n(i)+y_n(i)}{C(1-\gamma_c)}-1)})}{\mathsf{SINR}_{\mathsf{MC}n}} \tag{6.12}$$

or the step shown below assuming that it knows the vectors of iteration i, $\bar{P}(i)$ and $\bar{h}(i)$ (in both cases):

$$P_{(\mathsf{MR},\mathsf{MC}k)}(i+1) = \mathsf{SINR}^{-1}_{\mathsf{MC}n}(2^{(\frac{x_n(i)+y_n(i)}{C(1-\gamma_c)}-1)}), \tag{6.13}$$

where $\mathsf{SINR}^{-1}(\cdot)$ maps the SINR at a receiver node to the transmit power given the interference level. If the above updates result in $\sum_k P_{(\mathsf{MR},\mathsf{MC}k)}(i+1) \geq P^{\max}_{\mathsf{MR}}$, we scale down the $P_{(\mathsf{MR},\mathsf{MC}k)}; \forall k$ as below:

$$P_{(\mathsf{MR},\mathsf{MC}n)}(i+1) = P_{(\mathsf{MR},\mathsf{MC}n)}(i+1) \times \frac{P^{\max}_{\mathsf{MR}}}{\sum_k P_{(\mathsf{MR},\mathsf{MC}k)}}$$

Using equation (6.8), $\mathsf{MC}n$ updates its transmit power to $\mathsf{MMC}j$ attempting to satisfy the current values of x_n. This can be again done using an MIMD step similar to equation (6.12):

$$P_{(\mathsf{MC}n,\mathsf{MMC}n)}(i+1) = \min\left(P_{(\mathsf{MC}n,\mathsf{MMC}n)}(i) \times \frac{(2^{(\frac{x_n(i)}{C\theta_c}-1)})}{\mathsf{SINR}_{\mathsf{MMC}n}}, P_{\mathsf{MC}n}^{\max}\right) \tag{6.14}$$

or as indicated below assuming that $\mathsf{MC}n$ knows $\bar{P}(i)$ and $\bar{h}(i)$:

$$P_{(\mathsf{MC}n,\mathsf{MMC}n)}(i+1) = \min\left\{\mathsf{SINR}_{\mathsf{MMC}n}^{-1}(2^{(\frac{x_n(i)}{C\gamma_c}-1)}), P_{\mathsf{MC}n}^{\max}\right\}. \tag{6.15}$$

Accordingly, $\mathsf{MC}n$ updates y_n using:

$$y_n(i+1) =$$

$$\min\left\{(U_n')^{-1}\left(M - D'(x_n(i)) \cdot \frac{\partial x_n}{\partial y_n}(i)\right),\ x_n(i) + y_n(i)\right\},$$

where

$$\frac{\partial x_n}{\partial y_n}(i) = \frac{\partial x_n}{\partial y_n}(\bar{P}_{-n}(i), P_{\mathsf{MC}n}(i+1), P_{\mathsf{MMC}n}(i+1)).$$

After updating, $\mathsf{MC}n$ informs MR of this value. Note that choosing γ_c according to equation (6.3) ensures that in the absence of any incentive, no fraction of the capacity is spent by the MCs to relay MMCs' traffic.

Finally, the MR updates each x_n using:

$$x_n(i+1) = C(1-\gamma_c)\log_2(1 + \mathsf{SINR}_{\mathsf{MC}n}) - y_n(i+1). \tag{6.16}$$

Regarding the above algorithm, again note that to obtain the right-hand-side of equation (6.15), each MC needs to know the complete power vector $\bar{P}$ (indeed only those scheduled in the relevant time-slot, i.e., transmission power of other MCs). However, eliminating the interference caused by relatively far nodes (with low path-gain to the MC) can give us good approximations for these terms and relax this requirement. This is because of the interference suppression in CDMA networks by a factor of the spreading gain G. In fact, unlike TDMA networks in which interference range is usually larger than transmission range, the reverse holds in CDMA networks [3, 115]. Clearly, we are assuming that the degree of mobility of the MMCs permits accurate estimation of the path-gains $h_{(\mathsf{MC}n,\mathsf{MMC}n)}$ to them. Finally, note that in the above algorithm it is assumed that the transmission powers satisfy constraints (6.6) and (6.7) which defines a closed and convex set. Applying a continuous function through iterations of the described algorithm therefore will gradually result in reaching a fixed point. This is guaranteed by Brouwer's fixed point theorem [117]. Note that there may be more than one fixed point the algorithm may converge to depending on the initial point that is chosen.

6.3 Numerical Study

In this section, we present the results of a numerical study for the proposed algorithm to investigate its convergence characteristics and the sensitivity of the resulting fixed point to the parameters in play. A simple network scenario with one MR and two MCs is considered. Each MC services a cluster of MMCs out of range of the MR. Our simple network scenario resides in a $100\,\mathrm{m}\times 100\,\mathrm{m}$ area and contains one MR (at $(50, 0)$), two MCs (located at $(25, 50)$ and $(75, 50)$) each supporting one MMC cluster (centered at $(25, 75)$ and $(75, 75)$ respectively). Herein, we model only downlink traffic and assume that users have elastic QoS requirements. The maximum available power at the MR and the MCs is assumed to be 0.5 W and 0.1 W respectively. A bandwidth of 10 MHz, and noise power of 10^{-14} W/Hz were assumed. Power decay was assumed to follow an attenuation model with decay factor of 2.5, and spreading gain G was chosen to be 256.

We assumed that all users have a utility function $U_n(z) = m_n \log_2(z+1)$ where m_n has a dimension of \$/log(unit data rate) and indicates user n's willingness to pay [84,116]. Figure 6.2 shows the convergence characteristics of the model when $M = 10$ (network's charge per unit data rate in dollar) and m_1 and m_2 (corresponding to MC1 and MC2) are 5.75×10^8 and 28.75×10^8 respectively. In the scenarios under which this figure (and Figure 6.4) are obtained, μ was chosen to be 0.0001 and a linear discount model was used, although the results were very similar to those obtained under superadditive and subadditive models ($d = 4000$ for Figure 6.2).

Figures 6.3, 6.4 and 6.5 illustrate the dependence of the ratio x/y on γ_c for $M = 1$, $M = 10$ and $M = 100$ respectively when the rest of the parameters are those under which Figure 6.2 was obtained. In obtaining Figure 6.6, we chose a different set of parameters with $M = 80$, $m_1 = 10^9$, $m_2 = 2 \times 10^9$ and $\mu = 0.01$. As can be seen, the quantities graphed in these figures are unimodal in γ_c. Note again that the aggregate traffic $x + y$ is relayed to the MCs during the $1 - \gamma_c$ portion of the schedule. Also note that a higher m/M ratio results in lower x/y ratio as expected. In these figures we do not show the x/y ratio at $\gamma_c = 1$ as at this value both x and y are equal to zero. Also note that since MC2's willingness to pay (reflected in m_2) is higher than that of m_1, the x_2/y_2 ratio is lower than x_1/y_1 in all of these figures.

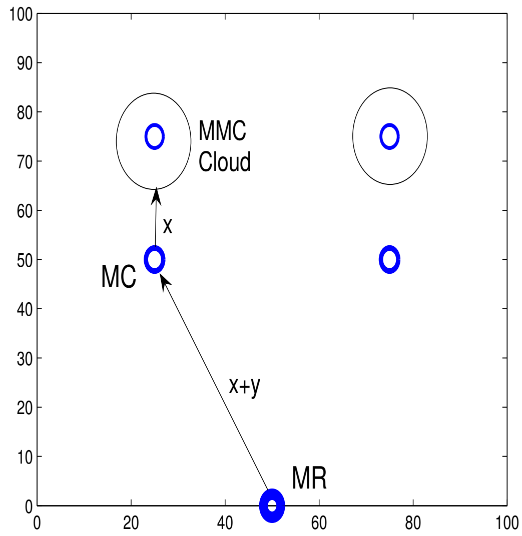

Fig. 6.1 Network Configuration

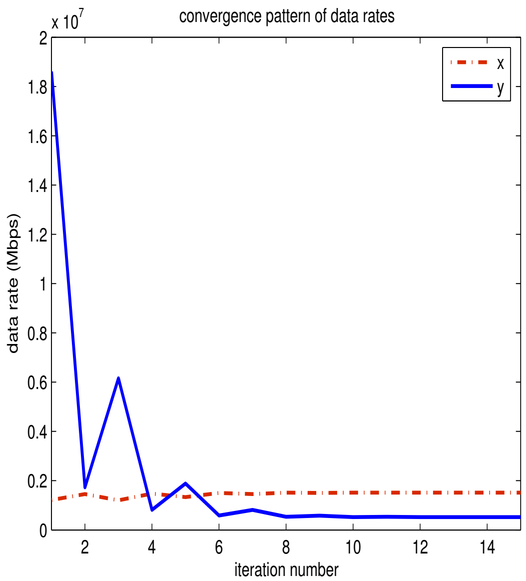

Fig. 6.2 Convergence pattern of the relaying game

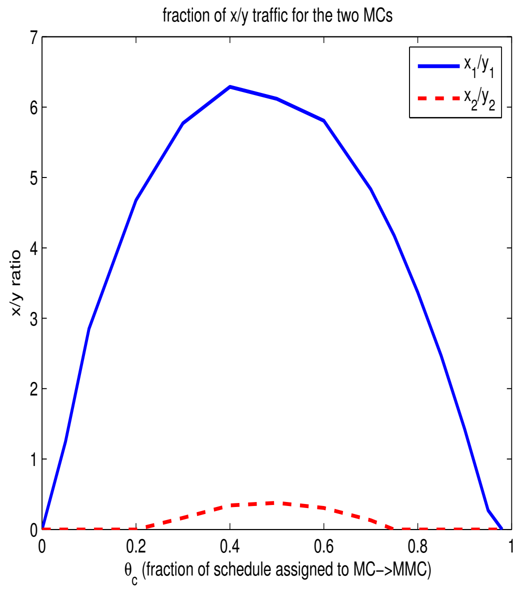

Fig. 6.3 x/y ratio versus schedule fraction γ_c for the two MCs for $M = 1$

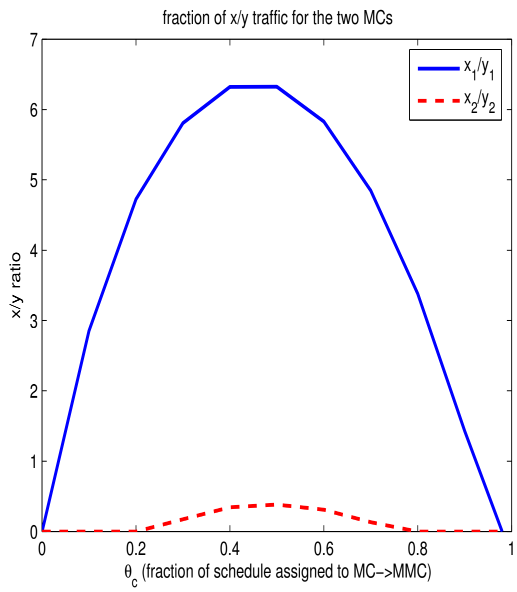

Fig. 6.4 x/y ratio versus schedule fraction γ_c for the two MCs for $M = 10$

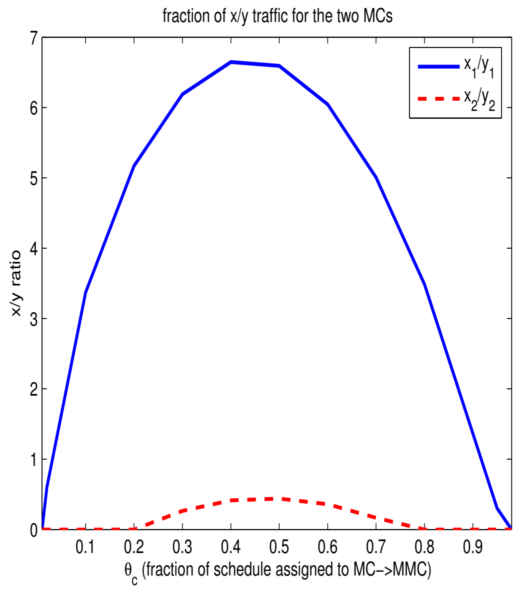

Fig. 6.5 x/y ratio versus schedule fraction γ_c for the two MCs for $M = 100$

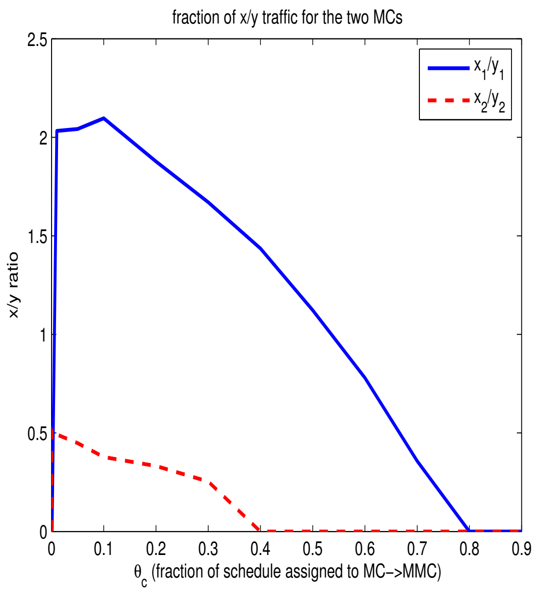

Fig. 6.6 x/y ratio versus schedule fraction γ_c for the two MCs using a different set of parameters

6.4 Summary

In this chapter we proposed an incentivized relaying mechanism for CDMA wireless mesh networks for broadband Internet access. This mechanism is designed for the network scenarios in which some users are out of access range to the mesh infrastructure due to, e.g., fading and/or mobility, but are in range with at least one other user. Using financial enticements for the in-range users (fixed MCs), we motivated them to relay traffic for their out-of-range peers. Based on this, we set up a game through which, the MR and the fixed MC elements of the network adjust their transmission power to their respective correspondents. Since in order to have conflict-free communication in the shared medium, capacity needs to be shared between MR→MC and MC→MMC transmissions, the capacity sharing ratio was adjusted in accordance to the compensation offered by the network. We implemented this game in a numerical study and showed its convergence characteristics and the dependence of relaying to the enticement rate.

Chapter 7

Summary and Future Work

In this thesis we addressed some of the challenges involved with the design of multihop wireless networks. While the main focus of this thesis was on CDMA, some of the methods proposed, especially routing, were also applicable to TDMA settings. We proposed a new integration framework for multihop wireless networks based on different time-scales with attention to the requirements of the traffic, i.e., delay sensitive and delay-insensitive traffic classes. We proposed a new distributed power control algorithm that provides end-to-end throughput guarantee to (sustained) traffic flows. We suggested a hybrid centralized-decentralized scheduling algorithm with specific regards to characteristics of CDMA networks although the algorithm may also be applied to TDMA networks as well. We designed a relaying mechanism in which in-range users are incentivized to relay traffic to the out-of-range users in their coverage area.

As a direct extension of our work in Chapter 6, we intend to explore a different pricing model wherein MRs sell portions of their bandwidth resources (through e.g. θ_c in scheduling, see equation (6.3)) in wholesale prices to a some MCs. These MCs in turn service the MMCs in retail prices. Therefore, there is a primary market in which MCs interact with MRs (or the network) and a secondary market in which MCs interact with MMCs. Note that this model is an alternative to the model described in Chapter 6 wherein servicing out-of-range MCs (MMCs) was performed via discounting cooperative in-range MCs.

The structure of WMNs incurs a funneling effect similar to that in sensor networks [113] which can degrade the network's performance. That is, as we move from the leaf nodes (MCs here) toward the BS, traffic load incurred on the links increases. In addition to load balancing through routing, this problem may be alleviated when more than one BS can be accessed by the last-hop MRs. Allowing the routing algorithm to perform anycasting by finding the least congested BS amongst all may decrease the outage probability, but may also increase the hop-count and therefore the end-to-end delay. Also it requires additional signaling between the two BSs to ensure duplicate copies of the same packet are not forwarded to the Internet in case they both receive it. As future work, we propose to investigate the performance of such anycasting schemes.

Also, when communication among MCs in geographical proximity to each other comprises a non-negligible fraction of traffic, it may be beneficial to use the MR infrastructure to exchange this data instead of referring all communications to the gateways. This problem is akin to file sharing schemes in Peer-To-Peer (P2P) networks. Using multiple BSs, we therefore may be able to further mitigate the funneling effect in WMNs for Internet access and more efficiently use the wireless medium. As another direction for future work we plan to investigate this problem and its related issues.

Finally, load balancing through multiple routing incurs packet-reordering and therefore may degrade the performance of TCP especially when re-routing happens frequently. The same problem may be found in multiple routing schemes. That is, if not carefully scheduled, this may result in frequent incidences of miss-ordered packet arrivals at the receivers. This problem may occur in both wired and wireless settings. As part of the future work, we are planning to shape the traffic at the transmitter side so that minimum re-ordering occurs at the receiver.

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Vita

Azin Neishaboori

Azin Neishaboori was born in September 1980 in Sary, Iran. She received her high school diploma in 1998 from Farzanegan school, Tehran, Iran. She then entered Sharif University of Technology, Tehran, Iran from where she received her Bachelor's degree in 2002 in Electrical Engineering. She continued her studies in Electrical Engineering at Pennsylvania State University under supervision of professor George Kesidis and earned her Ph.D degree in Dec. 2008. Her areas of interest include networking, pricing mechanisms and game theory.