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TRANSMISSION POWER CONTROL FOR ENHANCING THE PERFORMANCE OF WIRELESS PACKET DATA NETWORKS

BY

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THESIS

Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Electrical Engineering in the Graduate College of the University of Illinois at Urbana-Champaign, 2001

Urbana, Illinois

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THE GRADUATE	COLLEGE
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WE HEREBY RECOMMEND THAT THE	THESIS BY
JEFFREY PHILIP	MONKS
ENTITLED TRANSMISSION POWER CONTR	ROL FOR ENHANCING
THE PERFORMANCE OF WIRELESS F	PACKET DATA NETWORKS
THE DEGREE OF DOCTOR OF PHILOSO	ОРНҮ
N. Norrow	Director of Thesis Resear Month for Head of Department

ABSTRACT

This thesis presents several techniques that enhance the performance of wireless mobile devices that communicate without depending on a supporting infrastructure. These networks are commonly referred to as *ad hoc networks* since they operate in highly dynamic environments and, therefore, must utilize available resources.

The primary focus of this thesis is on improving the performance of ad hoc networks by controlling the transmission power to maximize the spectral reuse (capacity) and minimize energy consumption. This work starts by looking at single-hop ad hoc networks, but then extends this to multihop wireless ad hoc networks to investigate additional energy savings and capacity improvements. It is shown that the capacity of multihop data flows depends heavily on the shaping of the traffic at intermediate hops. Therefore, transport layer enhancements are also defined that adapt how nodes handle the data flows based on local environmental conditions (contention, congestion, and routing overhead).

Multiple access-based collision avoidance MAC protocols have typically used fixed transmission power and have not considered power control mechanisms based on the distance of the transmitter and receiver in order to improve spatial channel reuse.

This work proposes power control multiple access (PCMA) a wireless MAC protocol within the collision avoidance framework. PCMA generalizes the transmit-ordefer "on/off" collision avoidance model of current protocols to a more flexible "variable bounded power" collision suppression model. The algorithm is provisioned for ad hoc networks and does not require the presence of base stations to manage transmission power (i.e., it is decentralized). The advantage of implementing a power-controlled protocol in an ad hoc network is that source-destination pairs can be more tightly packed into the network, allowing a greater number of simultaneous transmissions (spectral reuse) and less average transmission power (energy consumption).

Our simulation results show that the PCMA protocol can improve the throughput performance of the non-power-controlled IEEE 802.11 protocol by a factor of 2, with a potential for additional scalability as source-destination pairs become more localized (the maximum distance between source and destination is reduced). Further, the protocol demonstrates more than a 50% average transmission power reduction and additional savings as source-destination pairs become more localized, thus providing a compelling reason for migrating to a new power-controlled MAC protocol standard. It is also shown that when intermediate hops are utilized between source and destination (to reduce the maximum transmission range between nodes) in conjunction with power control, there is an energy savings potential on the order of several orders of magnitude.

The enhancements at the transport layer demonstrate that by implementing hopby-hop control of data flows instead of end-to-end flow control (as with most transport protocols implemented today) the intermediate node flow rates can be adapted more quickly to changes in the local environment for optimum performance. Fast adaptation is particularly important in (mobile) ad hoc networks where link states and contention can change on the order of a second or less.

The power control and hop-by-hop protocol frameworks presented in this thesis demonstrate the potential for significant improvements in the wireless ad hoc environment thereby, motivating their incorporation into future working drafts and standards.

ACKNOWLEDGMENTS

I would like to thank my advisor, Professor Wen-mei Hwu, for his guidance, support, and encouragement throughout the course of my doctoral research. His support and belief in me has helped me in my research and has helped me gain the confidence needed to make contributions to my field of study. I would also like to thank Professor Vaduvur Bharghavan for his invaluable assistance in developing and refining my research and dissertation topic. His technical advice and encouragement have provided me with the skills needed to carry me through the completion of my doctoral research. In addition, I would like to extend my thanks to the rest of my dissertation committee: Professor Steven Franke, Professor Douglas Jones, and Professor Robin Kravets for their helpful comments and suggestions.

I wish to thank all my colleagues, especially Thyagarajan Nandagopal for his valuable feedback and suggestions, Prasun Sinha for his assistance in helping me to fully grasp transport and routing issues, Jean-Pierre Ebert for his insight into energy consumption issues, and the IMPACT group for their technical and nontechnical support with my research. Further, I would like to extend my thanks to Motorola for supporting my research with a UIUC Motorola Labs Research Grant and to Larry Marturano from Motorola labs for his support.

Finally, I would like to thank my parents Phyllis and James Monks for their unbounded support and encouragement and for always being there for me.

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CHAPTER 1

INTRODUCTION

In the last few years, with the Internet growing by leaps and bounds and the demand for untethered access to information, the interest in wireless packet data networks has increased considerably. Future wireless packet data networks will provide flexible access to a vast array of data applications by many users, each requiring a share of the network resources. These network resources primarily include capacity, which is the sum of the throughput provided to all users in the network. Up-and-coming mobile applications including video conferencing, playing music and videos, and surfing the Web will require an even greater amount of throughput and therefore additional network capacity. A variety of mobile devices are being exploited by consumers to access these applications including personal digital assistants (PDAs), mobile phones, laptops, and other hand-held devices, each having different power constraints or battery lifetime. The battery lifetime is becoming an increasingly important issue with mobile user desiring more compact mobile units. In additional, mobile users are demanding more frequent and even continuous (commonly referred to as "always on") access to remote information, placing an even greater demand on the mobile energy resources of these devices. Thus, a major issue in wireless packet data networks is the development of medium access control (MAC) protocols that make efficient use of available network and mobile resources. Controlling the transmission power level is one approach that provides improvements in both these

areas. The capacity of the network is improved by optimizing spatial packing of sourcedestination pairs, known as *spectral reuse*. The battery life is also extended because the senders reduce their transmission power to just reach the intended receiver (that is, they provide the receiver with a signal quality sufficient to receive a valid data packet). The benefits of implementing power control for the network topology outlined below are discussed further in Section 1.1.

There are many types of networks where power control can provide benefits in performance, although the amount of improvements provided by power control and the complexity of their implementation will vary. The improvements provided by applying power control to cellular networks and the implementation issues have been studied extensively in past years [1, 2] and are being utilized in current cellular networks. While cellular networks offer a dependable quality of service, mobile users can only communicate if a supporting infrastructure is in place. In addition, the available network resources are limited and can only be increased with significant system engineering. This requires adding additional supporting infrastructure and adjusting the configuration of existing infrastructure. Such an approach will incur a significant cost to the provider. An alternative approach to this type of network is ad hoc networks, where no preexisting infrastructure is required to support communications between mobile nodes. For this configuration no centralized control or access points are required because the nodes serve as access points (routers) for other neighboring nodes. An example of this network configuration is demonstrated in Figure 1.1, where laptops are shown with their respective communications connectivity. The communications devices connecting the mobile computers could be for example a wireless LAN (WLAN). Ad hoc networks are wireless packet data networks that do not have a supporting infrastructure. In general, wireless packet data

networks specify the type of traffic (packet data), but can refer to may different types of network topologies (those with or without base stations – centralized access control). However, for this thesis we will generally use the term *wireless packet data networks* to refer to ad hoc type topologies. Further, it is generally assumed that all nodes in the network have equal access to network resources and are provided with similar mobile resources (energy reserves). The ad hoc network scenario can be single hop, where source and destination are within transmission range, or multihop, where source and destination are out of range and intermediate nodes are needed to forward the packets. Note that the ad hoc topology does not preclude the techniques defined in this thesis from being applied to heterogeneous networks or enhancing cellular networks. Rather it demonstrates that they can be applied without depending on the support of a fixed infrastructure or nodes with extensive resources.



Figure 1.1 Example of an ad hoc configuration

The dominant wireless MAC protocol is currently the IEEE 802.11 standard, which follows the "carrier sense multiple access with collision avoidance (CSMA/CA)" paradigm. Our goal is to propose power-controlled multiple access protocols that follow the same collision avoidance principle. To the best of our knowledge, there exists no power-controlled MAC protocol that fits within the collision avoidance framework and demonstrates sufficient mechanisms for controlling the power (see the overview of related work in Chapter 9). This is due to the complex issues associated with implementing power control in ad hoc networks (they cannot depend on the support of a fixed infrastructure to regulate the transmission powers of mobiles). We show in Section 1.2 that this is due to fundamental characteristics of the handshake and collision suppression mechanisms in the CSMA/CA class of protocols, which requires (under current MAC protocols) that stations transmit all control packets at the same power level.

In addition to the mobile devices currently in use, there is also significant research efforts in progress to develop even smaller wireless devices that have considerably more energy resource limitations. Examples of such devices include watches with wireless access, wearable computers, and wireless sensors. This is prompting researchers to investigate new approaches for saving energy. One particular method that has shown some promise is utilizing intermediate nodes between source-destination pairs to relay packets. An extension of this approach is evaluated in this work and utilizes intermediate hops in combination with transmission power control for additional energy savings. Such an approach can be realized by extending the power-controlled protocol framework introduced in this work [3, 4, 5] and extending the power metrics into the routing layer. Defining the mechanisms for multihop power control into the routing layer is outside the scope of this thesis; hence, we simply present the potential of methods that extend the power-controlled framework for multihop networks.

One of the most attractive features of using power control and multiple intermediate hops together is that the number of intermediate hops can be controlled by the transmission power level. The primary benefit here is that energy savings and range between intermediate hops can be adjusted on a per-packet basis and in accordance with the mobile node density and environmental conditions. It will be shown in Chapter 5.4 that without power control the transmission power would have to be optimized off-line for the conditions existing in a particular network, otherwise the energy-saving benefits of utilizing multiple hops would not be fully exploited (since the transmission power would not be adapted to the spacing between intermediate hops). Such an approach is not feasible in most mobile networks, where the network conditions can change over a short period of time (on the order of a few packet transmissions). Therefore, power control is the preferred method for exploiting such energy savings techniques.

It is later demonstrated that the capacity of data flows traversing multihop ad hoc networks is limited by the way the traffic is shaped inside the network (i.e., at intermediate nodes). This result is also demonstrated for power-controlled networks in Chapter 5.4, where it is shown that the traffic patterns can prevent a power-controlled MAC from fully exploiting the spectral reuse in the network. That is, when some nodes in a flow are in a part of the network with high contention and congestion, downstream nodes in the flow can be prevented from utilizing the capacity gains from power control. As shown in Chapter 6.3, these problems can be further compounded by the behavior of current transport protocols. Current transport layer protocols were designed for wired networks that have constant link qualities, unlike wireless ad hoc networks. Therefore, a study is conducted on the performance of ad hoc networks, as a result of the transport layers interaction with the dynamic nature of ad hoc protocols. A protocol is then evaluated that shapes the traffic at intermediate nodes such that the flow rates are controlled based on the worst environment the flow passes through (i.e., worst link). This helps nodes to adapt more quickly to changes in the network conditions, avoiding buffer overflow and further retransmissions from causing additional congestion. This approach in conjunction with power control can be applied to ad hoc networks to provide the most efficient use of the network resources in a way that corresponds to the current network traffic conditions.

1.1 Motivating Power Control

In this section, transmission power control is motivated from two prospective benefits. The first benefit is a more efficient use of the network resources. That is, by allowing a greater number of simultaneous transmissions, power control increases the total network capacity. The second benefit is energy savings, which is achieved by minimizing the average transmission power. It is shown below that the transmission power level is directly related to the power consumption of the wireless network interface. Both of these issues are investigated further in the following two sections.

1.1.1 Capacity

Multiple access-based collision avoidance MAC protocols have made the case that a sender-receiver pair should first ensure exclusive access to the channel in the sender and receiver neighborhood ("acquire the floor") before initiating a data packet transmission [6, 7, 8, 9]. Acquiring the floor allows the sender-receiver pair to avoid collisions due to hidden and exposed stations in shared channel wireless networks (Figure 1.2 illustrates the scenario). The protocol mechanism used to achieve such collision avoidance typically involves preceding a data packet transmission with the exchange of a RTS/CTS (request-to-send/clear-to-send) control packet handshake between the sender and receiver. This handshake allows any station that either hears a control packet or senses a busy carrier to avoid a collision by *deferring* its own transmissions while the ongoing data transmission is

in progress (as shown in Figure 1.2). The top part of the figure shows four wireless nodes that have a transmission range shown by the dashed ellipses. A is the sender, B is the receiver, C is the exposed station (within range of sender, but not receiver), and D is the hidden station (within range of receiver, but not sender). Note that for a successful A-B transmission, D must not transmit to avoid corrupting the data packet being received by B, and C must not transmit to avoid colliding with the ACK that will be received at A. When A wants to send a data packet to B, it senses the channel to see if it is free. Then A sends an RTS to B. If C hears the RTS, it defers until A can hear B's CTS. If B is free to receive, it sends back a CTS to A. When D hears the CTS, it defers transmission until A finishes sending data to B. When C hears a busy carrier, it defers transmission. After B receives the data packet correctly, it sends back an ACK to A. This is the ideal operation of the protocol.



Figure 1.2 General protocol operation for multiple access with collision avoidance

While acquiring the floor to enable collision avoidance from hidden and exposed stations is certainly a fundamental requirement for the efficient operation of wireless medium access, this method precludes multiple concurrent transmissions over the region of the



Figure 1.3 Capacity enhancements observed with transmission power control

acquired floor. To optimize spatial channel reuse in a shared wireless channel network, a pair of communicating nodes must only acquire the *minimum area* of the floor that is needed for it to successfully complete a data transmission. An example is illustrated in Figure 1.3, where we observe that with the contemporary MAC protocols, the transmission from A to B would prevent C from sending to D since it is within range of B. However, if A reduced its transmission power level to be just enough to reach B, and likewise if C would send with just enough power to reach D, both transmissions would happen simultaneously. Such a power-controlled MAC could therefore provide extensive increases in capacity. These benefits are demonstrated with both theoretical studies [10] and simulations shown in [5] and Chapter 4. Further, MAC protocols are presented in [3, 4, 11] and Chapter 3, where considerable gains in throughput are shown (and correspondingly in Chapter 4). Such a protocol would allow for a tighter packing of source destination pairs within a network environment, thereby improving the spectral reuse.

The above scenarios motivate power control between a given sender and receiver in the ad hoc network (a source-destination pair that is within transmission range). However, in addition to controlling the transmission power such that it is just enough to reach the intended destination, it is also of interest to investigate the capacity of networks where intermediate hops are utilized between source and destination (multihop wireless networks). As discussed in the next section, adding hops between the source and destination will considerably reduce the total power consumption. Therefore, it is also desirable to look at the potential benefit or cost of employing multiple hops in terms of throughput.

1.1.2 Energy consumption

The mobile battery lifetime is becoming an increasingly important issue to manufacturers and consumers, as mobile devices are being used more frequently in our everyday lives. The power amplifier, as compared to other mobile device components, consumes a significant portion of the device power. The power consumed by the power amplifier is directly proportional to the strength (power) of the transmitted signal. Therefore, it is becoming of great interest to control the transmission power level such that the lifetime of mobile terminals is maximized. As an example, consider Figure 1.4, which shows a schematic of the WLAN network interface card components and their typical power levels. Notice that the power amplifier may take more than three times the power of any other individual component and consume almost half the total energy consumed by the network interface card. This ratio is expected to continue to increase for future WLAN interfaces cards, as the processing components become more power efficient. Furthermore, there will be dedicated devices such as wireless sensors, where the RF (radio frequency) output power amplification process takes the largest share of the overall power budget. Therefore, there is a significant energy saving potential in controlling the RF output power. Figure 1.5 indicates how controlling the RF output power influences the instantaneous overall power consumption of the Aironet PC4800 PCMCIA WLAN



Figure 1.4 Power distribution of a WLAN network interface card



Figure 1.5 Overall power consumption of an Aironet PC4800 PCMCIA interface for different RF output power levels and transmission rates

interface. This data was gathered by measuring (with the assistance of a volt meter) the amount of power consumed by the WLAN interface card as the transmission power level is adjusted (in software).¹ It can be concluded from Figure 1.5 that the change in the transmission power level contributes the most to the change in the instantaneous power consumption. The higher the RF output power, the higher the power consumption of the WLAN interface. In fact, an increase in the RF output power level leads to an overproportional increase in the overall WLAN interface power consumption. Our results show that the increase from 1 to 30 mW in RF output power leads to increase of about 20% in the overall power consumption. However, as stated above, future devices will greatly reduce the power consumed by the processing components in the network card

¹This data was provided by Jean-Pierre Ebert of the Technical University of Berlin.

(those other than the power amplifier in Figure 1.4), such that the power consumed by the power amplifier is several times greater than that of all other components combined. Therefore, increasing the RF output power can in the future can cause a multiplicative increase in overall power consumption. Furthermore, the graph reveals that a change of the coding scheme (transmission rate) has an almost negligible effect on the power consumption. Therefore, while the the coding scheme is directly related to the throughput, it has little effect on the energy savings. Power control, on the other hand, has a direct effect on both the throughput and energy savings, and is therefore an issue that deserves careful consideration.

To obtain a better idea of the degree of reduction in transmission power (and therefore energy savings) that power control can provide, we must look at the basic path loss model since this dictates the relationship between the transmission range and the required transmission power. The path loss typically causes the signal to attenuate with distance on the order of $1/d^{\alpha}$ [12], where *d* represents distance between transmitter and receiver, and α , the path loss factor, is typically between 2 and 6. As a result, modest differences in transmission ranges will result in significant differences in required transmission power to maintain the same signal quality (power level at the receiver). It can then be concluded that either minimizing the power to that need to reach the destination or utilizing multiple intermediate hops will produce significant savings in power consumption by the power amplifier (as much as several orders of magnitude).

Achieving the desired power savings may require that a source use one or more intermediate hops to reach its destination. As shown above, since the power needed to reach a destination increases considerably more than linearly with the distance, the benefits of using multiple hops greatly overcomes the cost of addition transmissions with respect to power consumption. The choice of the appropriate power level to save as much energy as possible is a challenging task, which depends on numerous factors. A few of these factors include: the mobile node density (number of nodes per unit area), network traffic load, the topology and distribution of mobile nodes, and available mobile node resources (battery life and link bandwidth). These factors along with others will be further explored in Section 6.1.

1.2 Problem Definition and Proposed Solution

In this section, the complexities associated with implementing power control in ad hoc wireless networks are evaluated. The basic requirements for implementing power control in a shared channel scenario are outlined. Then based on these requirements, we show how the mechanisms associated with the current MAC protocols prevent them from exploiting the advantages of power control. Finally, our proposed approach to the problem is presented that specifies (1) how to provide collision avoidance information without causing collisions, (2) how to convey collision avoidance information in a short enough time for it to be relevant, and (3) how nodes should determine the amount of power needed to reach their intended destination.

For a non-power-controlled MAC to best use the network resources in a single shared data channel scenario, it must provide a mechanism for avoiding collisions among mobile nodes competing for the channel. A power-controlled MAC adds to the complexity of this mechanism by also requiring that nodes send with only enough power to reach their intended destination. We will see later how this new requirement adds considerably to the complexity and renders the current MAC framework insufficient. Our goal is to change the "on/off fixed power" transmission model of the existing protocols to a more flexible "bounded and variable power controlled" transmission model, thereby changing the fixed floor acquisition model to an adaptive floor acquisition model for collision avoidance. Therefore, we are able to achieve power controlled multiple access by adhering to two key principles:

- 1. The cooperation principle dictates that no station that commences a new transmission can transmit loud enough to disrupt ongoing transmissions.
- 2. The *power conserving principle* dictates that each station must transmit at the minimum power level required to be successfully heard by its intended receiver under current network conditions (i.e., channel gain between source-destination pair and noise power observed at the destination).

Enforcing these two principles achieves efficient power-controlled multiple access within the framework of collision avoidance protocols. However, achieving this goal requires that two mechanisms be defined that provide a way for nodes to satisfy these two basic principles:

- 1. One mechanism that allows new transmitters (those that wish to start transmitting after the receiver starts receiving) to know the maximum power level they can transmit at without interfering with their incoming packet.
- 2. Another that allows a new transmitter to determine the power level needed to reach the intended destination.

When using a power-controlled MAC, Mechanism 1 provides transmitters with a means of calculating their upper power bound, associated with the cooperation principle, and Mechanism 2 provides transmitters with a means of calculating their lower power bound, associated with the power conserving principle.

For traditional non-power-controlled MAC protocols, such as 802.11, Mechanism 1 is implemented by carrier sensing transmissions and control packets that notify nodes in the sender and receiver neighborhood of the data transmission so they can delay sending packets that may cause a collision. This is sufficient when the interference range is the same size as the floor acquired by the source-destination pair (i.e., fixed transmission powers are used). However, the basic idea behind power control, as Mechanism 2 dictates, is that nodes acquire different size floors. This means the source-destination pairs operating in this power-controlled environment must restrict not only the data transmission power but also the corresponding source request (RTS) and destinations response (CTS). Otherwise, the source-destination pair will effectively be reserving a larger area than required for data transmission. Thus, the framework defined by current MAC protocols cannot be applied to power-controlled environments since some nodes' interference ranges are larger than other nodes' transmission ranges. This scenario is demonstrated in Figure 1.6, where a shorter range source-destination pair, A to B, have a transmission in progress when a longer range source-destination pair, C to D, wishes to initiate a transmission. Node C will not be able to hear the transmission or interpret the initial source-destination reservations (RTS/CTS). Hence, a new collision avoidance mechanism must be developed for the power control environment so that longer range source-destination pairs can avoid colliding with shorter ones.

Collisions occurs as a result of other transmitters sending with enough power that a receiver observes more noise power than can be tolerated, based on the strength of the desired signal. Therefore, by comparing the current desired signal power to the total power observed from other sources, a receiver can calculate the amount of additional noise from interfering stations that can be tolerated. Then transmitters can only know how to



Figure 1.6 Collision avoidance issues in a power-controlled environment

upper bound their transmission power if the receivers notify them of the amount they can tolerate (assuming the gain information can be calculated from the received signal power of this notification and combined with the noise tolerance to calculated the upper power). For a receiver to avoid a collision it must send a noise tolerance notification message to all transmitters whose maximum power level can cause a collision with the incoming data packet. However, the transmission power required to send this notification to all the nodes that can cause a collision can itself cause a collision at another receiver. This in fact presents conflicting requirements for a single shared data channel configuration: receivers must transmit collision avoidance notifications with enough power to reach all nodes that could potentially cause a collision and no transmission can be sent with enough power to cause a collision at a receiver. An example of a situation of where these requirements can in fact be conflicting is shown in Figure 1.7. Here, A is sending to B, and shortly after C starts sending to D. In this case, D, the receiver, must then notify all other potential transmitters that can possible cause a corruption, like E that may later wish to send to F, how to avoid a collision. Although the power needed to send the collision avoidance information to E may cause a collision with an ongoing receiver B. Therefore, a separate channel is required for receivers to notify other potential transmitters of their noise tolerance to avoid causing a collision with other receivers.



Figure 1.7 Collision avoidance notifications causing collisions in power-controlled networks

Now that it has been demonstrated that implementing Mechanism 1 in a shared access power-controlled environment requires a new collision avoidance mechanism that operates on a separate channel, we demonstrate how this can be implemented. That is, we address the issue of how collision avoidance (upper power bound) information can be conveyed by receivers to potential transmitters. One approach would be to send broadcast packets on the second channel that specifies a node's noise tolerance. This packet would then allow the transmitters to determine the gain to the receiver, providing a way for each to calculate their upper power bound. Although, this means that nodes must contend to send their broadcast packets on the second channel. However, for a dense network with high load (the type of network for which power control is intended to provide the greatest capacity improvement) the contention delay on this channel may be significant,

preventing receivers from notifying other transmitters in time for them to avoid sending at a power level that causes a collision. This problem is further compounded by the fact that receivers may have to send their noise tolerance several times during the packet reception as the noise tolerance changes due to background transmitters starting and stopping. Therefore, for the PCMA protocol we suggest a new method for conveying the noise tolerance information on this separate, collision avoidance, channel: instead of sending in the form of a conventional packet, we propose that it be encoded in the form of a power signal. This power signal would be sent at a power level inversely proportional to the noise tolerance of the receiver. The basic idea is that as a receiver can tolerate less noise power from other transmitters it "yells" louder on the collision avoidance channel, and as it can tolerate more background noise power it "yells" less loud. Then the louder a potential transmitter "hears" this power signal, the more it must restrict its transmission power on the data channel. Section 3.2 shows that when the transmitter measures this power level (which is attenuated by the channel gain) it can simply invert the measured value to bound its power such that no more power is inserted into the channel than the corresponding receiver can tolerate. These power signals can be sent in short tone bursts that are referred to as busy tone pulses. The channel that the busy tone pulses are sent on is then called the busy tone channel and the channel that the data and control packets are sent on is called the *data channel*. The layout of the data and busy tone channels is discussed in Section 2.2. The width of the pulses will be short enough that there is a small probability of multiple pulses interfering with one another at a transmitter such that the combined power level is changed considerably, resulting in an inaccurate upper power bound calculation. This result occurs only if the busy tone power received from the receiver most sensitive to this transmitters signal (based on the channel gain)

is affected. The pulses are also long enough for there power to be accurately measured by neighboring nodes (on the order of a few bits). This issue of busy tone pulse width and interference of busy tone pulses will be addressed further in Section 3.2.

Mechanism 2 can easily be implemented through a simple handshake between sender and receiver. For example a source would send a request over some maximum area since it does not initially know the power needed to reach the intended receiver. The receiver then knows the channel gain (or the equivalently needed transmission power) from a power measurement made while receiving the source's request and sends back a response at the power needed to reach the destination, which informs the source of the minimum power level required for a successful transmission. In order for Mechanism 2 to be employed in a nonintrusive manner (without causing a collision with other ongoing transmissions) on the same channel as the data, Mechanism 1 must first calculate the upper power bound. The upper power bound would then allow the transmission power of the initial request to be limited such that it avoids collisions with other transmissions. Note there are some addition issues associated with sending the initial request over a range smaller than the maximum that are discussed in Section 8.1.1.

In summary, the fundamental change that we make in the existing approach is the following: unlike current protocols that use the reception of control packets as an on-off trigger for transmission/deferral by hidden and exposed stations, our approach is to use the signal strength of a received control message to bound the transmission power of these stations.

1.3 Contributions

The key contribution of this work are in three areas: integrating power control into a MAC for ad hoc networks to define the PCMA protocol, demonstrating how a powercontrolled MAC (namely, PCMA) framework can be expanded to provide significant benefits in energy savings, and shaping traffic through hop-by-hop rate control for data flows in ad hoc networks. These areas, and the key contributions made to them are discussed below.

- We achieve transmission power control while still preserving the collision avoidance property of multiple access protocols. Our proposed protocol, PCMA (power control multiple access), demonstrates improvements in aggregate channel utilization by more than a factor of 2 compared to the IEEE 802.11 protocol standard. Further, it demonstrates a reduction in latency and reduces the average transmission power by more than 50%, proving a significant savings in energy.
- It is shown that extending the power control framework to a multihop wireless scenario can provide considerable energy savings. For various network topology scenarios the energy savings and throughput trade-offs are demonstrated. This work provides a metric for future researchers to evaluate the degree of energy savings that can be achieved for their particular configuration, and determine if these benefits justify the additional routing overhead, trade-offs in throughput, and added implementation costs.
- Finally, a transport protocol study depicts the deficiencies of current transport techniques' abilities to regulate traffic in wireless ad hoc networks. In addition, a protocol is outlined that regulates traffic at individual hops of a multihop wire-

less flow, providing the potential for faster adaptation to changes in the network conditions. The algorithm adapts to changes in contention, congestion, and routing overhead (route recomputation) not only between individual source destination pairs but also at individual hops, where changes will be observed first.

These contributions along with others will be discussed in the chapters that follow. The next section provides an overview of the structure of this thesis and highlights the contributions of each chapter.

1.4 Thesis Structure

The rest of the thesis is organized as follows. Chapter 2 discusses the channel characteristics and power constraints that must be considered when implementing a power controlled wireless MAC protocol. Chapter 3 highlights the supporting mechanisms of the PCMA protocol (e.g., control packets and the fields relevant to the protocol) and presents the algorithm. In Chapter 4, PCMA is compared to IEEE 802.11 and an ideal power controlled protocol using an implementation in the *ns2* wireless network simulator. Extensions to the PCMA protocol are proposed in Chapter 5 that increase the spectral reuse of the original protocol, improve the fairness, and decrease the average transmission power, thereby extending battery life. Chapter 5.4 demonstrates the potential for significant energy saving by utilizing intermediate hops between source-destination pairs. Chapter 6.3 outlines the deficiencies and limitations of end-to-end flow control protocols such as TCP and shows the benefits of integrating hop-by-hop rate control into an ad hoc wireless network. The implementation issues of the methods defined in this thesis are investigated in Chapter 8. Related work is presented in Chapter 9. Finally, Chapter 10 summarizes the key results and issues present in this thesis and suggests how they may be applied to future wireless packet data networks.
CHAPTER 2

THE NETWORK AND CHANNEL MODELS

The network and channel models define how nodes share a medium, what effects the medium has on the signals sent from mobile terminals, and the basic network topology. As in IEEE 802.11 and other multiple access protocols [6, 7, 8, 9, 13], we assume a shared channel model in which simultaneous transmissions in the neighborhood of the receiver will result in a collision at the receiver. In the spread spectrum physical layer environment, which is used by most WLAN cards today, this (shared channel access) model corresponds to a group of nodes accessing the medium with the same frequency hopping pattern in the frequency hopping spread spectrum technique, or the same pseudo-random sequence number in the direct sequence spread spectrum implementation. Section 2.1 demonstrates how signals sent from the transmitters are affected by the wireless medium. At the MAC layer, we do not assume a cellular model, and we do not constrain designated "base stations" to be senders or receivers of data. That is, we assume an ad hoc topology, where nodes have access to similar resources, and have similar functionality (see the network configuration presented in Chapter 1).

In the rest of this chapter, the channel propagation model is described as well as the effect it has on the protocols basic operating assumptions. Then we present the transmission power constraints required to satisfy the network model such that the basic

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operating principles known as the *power conserving principle* and the *cooperative principle* are not violated.

2.1 Channel Propagation Models

We now describe the channel propagation model that is applied to the typical wireless channel. While our focus is on the MAC layer rather than the physical layer, we have taken into account the channel propagation characteristics at a sufficient level of detail that the power-controlled MAC should work reasonably well in practice.

The amount of spatial reuse and transmission power required for a node to send a valid signal to its destination will depend on the *gain* between each source and destination, which models the *attenuation of the transmitter power over distance*. We define two path loss field regions:

- the region inside the Fresnel zone [12], where the gain drops proportional to the distance squared will be referred to as simply as the $1/d^2$ field, and
- the region outside of the Fresnel zone where the gain is proportional to the distance to the fourth power and refer to it as the $1/d^4$ field.

The distance where the mobile changes from the $1/d^2$ field to the $1/d^4$ field is called the *cross-over* distance. These basic channel effects, along with shadowing and multipath, are discussed further in Appendix A. A more detailed discussion of these various effects and different channel models can be found in [12, 14, 15]. The result of these channel effects on the performance of the communications protocol are outlined in Section 2.2.

In the protocol design, the actual gain, G_{ij} , from source *i* to destination *j* is calculated from the specified transmission power (advertised in the packet) and power measured in the received signal, measured during the initial handshake preceding the data packet. This is then used to determine the power needed to send a successful packet to the intended receiver. We then overcompensate (transmit at a power level that is more than needed to receive a valid packet under the current network and channel conditions) to account for the distortions introduced from the channel such as fast fading and interference from other transmissions in the background.

2.2 **Protocol Assumptions**

Let us now investigate the channel assumptions of the PCMA protocol, and see how they hold for the channel propagation model above. In PCMA, we assume the following:

1. The average channel gain is stationary for the duration of any complete transmission between a source and destination (for the entire control plus data packet sequence). PCMA calculates the transmission power level needed to send a successful packet to a destination through the initial handshake and uses that power level to send all packets between source and destination. Also, the protocol does not adjust the power throughout the transmission since the needed feedback for such an operation would require a significant amount of bandwidth, and in a shared channel setting without a centralized access point to manage the transmission, the feedback could not be guaranteed to reach the transmitter. Therefore, the channel must be stationary so that the initial power level is sufficient for the duration of the packet transmission. As a result, the power received will not decrease dramatically and the noise power introduced by other transmitters will not increase significantly.

- 2. Channel reciprocity holds so that the gain between two nodes is approximately the same in both directions. The information needed for senders to avoid collisions with other receivers is sent from the receiver in the form of the power signal that notifies other receivers of an acceptable upper bound transmission power. However, the receiver must then be able to assume that the channel attenuation, or gain, of the potential interfering transmitter's signal that arrives at the receiver is similar to that experienced by the receiver's collision avoidance power signal that arrives at the transmitter to properly avoid collisions (see Section 3.2 for detailed explanation of the protocol and its collision avoidance mechanisms).
- 3. The data and busy tone channels observe similar gains. It was shown in Section 1.2 that for a power-controlled MAC to avoid collisions on a shared data channel and take full advantage of spectral reuse, a separate channel is needed for receivers to advertise their tolerance to a new transmitter's signal power. As described in the previous assumption, the power signal that advertises a receiver's noise tolerance to other transmitters must experience similar channel gains to the the received interference on the data channel. This means that the data and busy tone channels must have similar gains or fade similarly such that a constant calibration factor can be incorporated to make up for any differences.

While all these assumptions will be violated to a certain extent in most environments, to what degree they hold will depend on the system engineering and design of the communications system. Therefore, in the remainder of this section we investigate some of these design issues and limitations.

There are three basic channel effects [12]: path loss, which is directly related to the separation between source and destination; shadowing, which accounts for objects be-

tween the source and destination attenuating the signal; and *multipath*, which accounts for the effects of multiple paths (between transmitter and receiver) through line-of-sight and reflecting of objects combining at the receiver. The paths and their distances are the same in both directions (i.e., source to destination and destination to source), and the objects impeding the paths are the same in both directions. However, the way the paths refract off objects and combine at the source and destination receivers may differ depending on the extent of the multipath effects (delay spread). Also, only multipath effects are generally considered frequency dependent and vary differently over time for different frequency channels. Therefore, only multipath alters the validity of these assumptions. As long as the multipath effects can be mitigated by the physical layer techniques such as orthogonal frequency-division multiplexing (OFDM) [16, 17, 18], Rake receivers [19], channel coding [20], and overcompensation at the MAC layer, these assumptions hold.

The first assumption guarantees that the channel gain measured from sending the initial request (control packet) is still valid for the duration of the data packet and the ACK that follows. Path loss and shadowing will have little effect since the distance a node moves in the duration of a control and data transmission (on the order of a few milliseconds) is small. With multipath effects the gain will not be stationary for the duration of a packet. However, the short term average gain (on the order of a few bits' transmission periods) measured for the RTS (or equivalent source request packet) is also valid in the data and ACK packets that follow since the short-term average gain is primarily a factor of path loss and shadowing effects (slow fading). Even in the cellular environment the power adjustments are not quick enough to keep up with the fast fading (multipath effects). Therefore, fast fading degradations must be overcome by physical layer techniques or be tolerated at the MAC layer with additional overcompensation

in transmission power. This argument can also be applied to the channel reciprocity assumption and the assumption that the data channel and busy tone have similar gains since, as stated earlier, only the multipath effects are different from one direction to the other. However, the third assumption presents some additional complexities that are discussed along in Section 8.2.

In Section 3, we give a detailed description of the protocol under these assumptions, but later (in Section 4.5) we show that these assumptions can be violated to a certain degree with only modest degradations in performance.¹ Further, we show that overcompensation in transmission power can help to alleviate the problems to a considerable extent. In fact, adaptive overcompensation techniques can effectively address the fast fading effects that the physical layer does not overcome. However, a detailed investigation of how these effects propagate up to the MAC layer to determine the amount of overcompensation needed for different environments is beyond the scope of this work since it depends on the particular physical layer implementation. Nevertheless, to show how PCMA would interface with a generic physical layer, Chapter 8 presents a schematic and discusses some additional implementation issues.

2.3 Power Constraints

Let Pt_Max and Pt_Min denote the maximum and minimum transmission powers for a transmitter on the data channel, respectively. Let RX_Thresh and CS_Thresh denote the minimum received signal power for accepting a packet reception and for sensing a

¹In fact, any protocol that makes the commutativity assumption (i.e., the fact that A can hear B implies B can hear A) has the same problem since fast fading can cause this assumption to be violated. We show through simulations in Chapter 4 that both PCMA and 802.11 are susceptible to this problem.

carrier, respectively. Let *SIR_Thresh* denote the "capture threshold," i.e. the minimum signal-to-interference ratio (SIR) for which the receiver can successfully receive a packet.

Given the transmitter and receiver power parameters and the channel propagation characteristics, a transmitter i must transmit a packet to a receiver j at the minimum transmission power Pt_i that satisfies the following power constraints:

- 1. The transmission power of *i* must be within its parameter range $Pt_Min \leq Pt_i \leq Pt_Max$.
- 2. The received power at j must at least be equal to the minimum received power threshold $G_{ij}Pt_i \ge RX$. Thresh.
- 3. The observed SIR for the transmission at j must at least be equal to the minimum SIR threshold $SIR_j = \frac{G_{ij}Pt_i}{Pn_j} \ge SIR_Thresh$, where Pn_j is the total noise that node j observes on the data channel and is defined as $Pn_j = \sum_{l \neq i} G_{lj}Pt_l + N_j$. The term N_j is the power of the thermal noise (the power observed at a receiver when no nodes are transmitting) observed at node j.
- 4. Let E_k be the "noise tolerance" of any receiver k that is receiving an ongoing transmission in the neighborhood of i. E_k is thus the additional noise power that k (currently receiving data from some other node) at power Pr_k can tolerate before its SIR drops below its SIR_Thresh, and is defined as E_k = Pr_k/SIR_Thresh Pn_k. Since the transmission power of i should not disrupt any ongoing transmission, Pt_i ≤ min_k {E_k } = Pt_bound_i.

If the above four constraints can be met, then i can successfully transmit to j without disrupting any ongoing transmissions. The critical issues are therefore (a) handshaking between a transmitter-receiver pair to determine the minimum transmission power that satisfies Constraints 2 and 3 (i.e., the power conserving principle), and (b) for every receiver to advertise its noise tolerance so that no potential transmitter will disrupt its ongoing reception applying Constraint 4 (i.e., the cooperative principle). These problems are addressed in the PCMA protocol section.

CHAPTER 3

THE PCMA PROTOCOL

The goal of PCMA is to achieve power control within the framework of CSMA/CA based multiple access protocols. In these protocols, there are two main components: *collision avoidance* and *collision resolution*. Collision avoidance takes place by means of a combination of carrier sensing by the transmitter and deferral of transmissions by hidden and exposed stations when they hear RTS/CTS packets. Collision resolution takes place by means of a backoff-based algorithm. In this section, an overview of the protocol is first given and then the protocol steps are described.

3.1 PCMA Protocol Overview

In PCMA, collision avoidance is generalized to power control. Conventional collision avoidance methods had an "on/off model," wherein a node can either transmit (if it is not deferring and does not sense a busy carrier) or not. However, in Section 2.3 we determined that a node can transmit to its intended receiver as long as it satisfies four constraints. Thus, the on/off model is generalized to a "bounded-power model." In order to achieve the bounded-power model, the power control component in PCMA has two main mechanisms:

- A request-power-to-send (RPTS)/acceptable-power-to-send (APTS) handshake between the data sender and receiver, which is used to determine the minimum transmission power that will result in a successful packet reception at the receiver. The RPTS/APTS handshake occurs in the *data channel* and precedes the data transmission. After the successful reception of the data, the receiver sends back an ACK packet confirming its reception.
- The noise tolerance advertisement is used by each active receiver to advertise the maximum additional noise power it can tolerate, given its current received signal and noise power levels. The noise tolerance advertisement or busy tone is periodically *pulsed* by each receiver in the *busy tone channel*, where the signal strength of the pulse indicates the tolerance to additional noise. A potential transmitter first "senses the carrier" by listening to the busy tone for a minimum time period to detect the upper bound of its transmit power for all control (RPTS, APTS, ACK) and data packets.

The packet handshake sequence on the data channel is RPTS-APTS-DATA-ACK and on the busy tone channel busy tone pulses are periodically sent while the data is received to protect the data packet. This sequence of events is demonstrated in Figure 3.1. Here we note that there is an issue in how to properly protect the ACK from collision since the noise power observed at the source cannot be updated during the data transmission. However, this is a fundamental problem associated with all power control methods since carrier sensing while transmitting is extremely expensive. This issue is discussed further in Section 8.1.2.

The collision avoidance is provided by the busy tone pulses sent from the receiver. As stated in Section 1.2, the busy tone pulses are sent at a power level that is inversely



Figure 3.1 PCMA protocol steps

proportional to the additional noise that a particular receiver can tolerates before its SIR level drops below the threshold level SIR_thresh, and its packet is corrupted. How the busy tone pulses are employed to provide collision avoidance is demonstrated in Figure 3.2. For this example, a receiver B that is currently receiving a packet sent from A broadcasts the busy tone pulse on the busy tone channel at a power level $1/E_B$ (one over the noise tolerance of B). This pulse would then be attenuated as it was sent over the channel such that a node C would hear it at G_{BC}/E_B . After C observes the power of the received busy tone pulse, it can then be inverted such that C can upper bound any future transmission power by E_B/G_{BC} , and therefore avoid a collision with B. The bound for D can be computed in a similar manner. Also the nodes would hear many receivers sending busy tone pulses and each node would bound their power level in accordance with that calculated from the busy tone pulse received with greatest transmission power. Note the greatest power busy tone pulse observed would result in the lowest upper bound power for a potential transmitter and then be the upper power bound to avoid collisions with all nodes currently receiving.



Figure 3.2 Using busy tone pulses for collision avoidance

The last major component in PCMA is collision resolution, which is backoff-based. While a simple backoff algorithm similar to 802.11 was implemented to facilitate a oneto-one comparison with 802.11 and focus on power control, we can certainly use more sophisticated collision resolution algorithms as suggested in [7, 21].

To summarize, PCMA has one-to-one analogs of the key components of standard CSMA/CA protocols. At the sender, monitoring the busy tone is equivalent to sensing the carrier. At the receiver, periodically pulsing the busy tone is equivalent to sending a CTS for collision avoidance. The RPTS/APTS handshake that precedes the data transmission is similar to the RTS/CTS handshake, except that its purpose is not to

force hidden senders to backoff. Thus, PCMA has the potential to improve efficiency of channel access without changing the fundamental MAC paradigm.

3.2 PCMA Protocol Steps

Here, we present the detailed PCMA protocol steps that correspond to the situation shown in Figure 3.1, where some source node i is sending to a destination node j and a potential interfering transmitter l wishes to transmit. The steps also reference the PCMA pseudo code algorithm shown at the end of this chapter in Figures 3.3, 3.4, 3.5 that represent the idle, transmitting, and receiving phases of PCMA, respectively.

```
1
   Start IDLE:
2
   do{
3
       Sense BT channel for max BT interarrival time
       Set Pr_BT to max BT power observed while sensing
4
   }while(no Data Generated and no RPTS Received)
5
6
   if(Data Generated){
7
       Goto TX State
8
   }
9
  else{
      Goto RX State
10
11 }
```

Figure 3.3 Pseudo code for the idle phase of the PCMA algorithm

There are three types of variables used in the PCMA algorithm: fixed variables or those that store values determined from off-line calculations, variables that store measured values (primarily from the receiver), and variables for storing the result of calculations made from measured and fixed variables. The variables in each of these categories that are referenced in the below protocol steps and the pseudo code are listed below.

```
12 Start TX:
13 while (\gamma C/Pr_BT < Pt_Min)
14
       Sense BT Channel while backing off
15
       Set Pr_BT to max BT power observed
16 }
17 backoff = rand(1, Max_backoff) * aSlot_Time
18 Sense BT channel for max BT interarrival time
19 Set Pr_BT to max BT power observed
20 Pt\_bound = min\{C/Pr\_BT, Pt\_Max\}
21 if(\gamma Pt\_bound < Pt\_Min) {
22
       Goto START
23 }
24 Pt = \gamma Pt_bound
25 Pn_S = get_noise_power()
26 Send RPTS (SenderID, ReceiverID, Packet_len, Pt, Pn_S) on Data Channel at Pt
27 Wait for APTS on Data Channel
28 if(Time-out waiting for APTS) {
29
       Max\_backoff = \beta \cdot Max\_backoff
       Goto START
30
31 }
32 Pt = extract_Pt_desired(APTS)
33 if (Pt > Pt\_bound)
34
       Goto START
35 }
36 Send data at Pt on Data Channel
37 Wait for ACK on Data Channel
38 if(Time-out waiting for ACK){
39
       Max\_backoff = \beta \cdot Max\_backoff
40
       Goto START
41 }
42 else\{
43
       Max\_backoff = Max\_backoff - \alpha
44 }
45 Goto IDLE State
```



```
46 Start RX:
47 Pr = qet_signal_power()
48 Pt = extract_Pt(RPTS)
49 G = Pr/Pt
50 Pn_D = get_noise_power()
51 Pt\_desired = \max{RX\_Desired/G, SIR\_Desired \cdot Pn\_D/G}
52 Pn\_S = extract\_noise\_power(RPTS)
53 Pt = \max{RX\_Desired/G, SIR\_Desired \cdot Pn\_S/G, Pt\_Min}
54 Pt\_bound = min\{C/Pr\_BT, Pt\_Max\}
55 if (Pt\_bound < Pt){
56
       Goto IDLE State
57 }
58 Send APTS(ReceiverID, Packet_len, Pt_desired) on Data Channel at Pt
59 while(Data incoming){
       E = \max\{Pr/SIR\_Thresh - Pn, (Pt\_Max/Pt\_BT\_Max) \cdot CS\_Thresh)\}
60
61
       Pt_BT = C/E
62
       Send a busy tone pulse at Pt_BT on BT Channel
       Wait a busy tone cycle
63
64 }
65 Pt\_bound = min\{C/Pr\_BT, Pt\_Max\}
66 if (Pt\_bound < Pt){
67
       Goto IDLE State
68 }
69 Send ACK(ReceiverID) on Data Channel at Pt
70 Goto IDLE State
```

Figure 3.5 Pseudo code for the receiving phase PCMA algorithm

- Fixed Variables: C, γ, Pt_Min, Pt_Max, Pt_BT_Max, RX_Desired, SIR_Desired, MaxBT, aSlot_Time, α, β
- Measured Variables: Pr, Pr_BT, Pn_D, Pn_S, Pr_BT
- Calculated Variables: Pt, Pt_bound, G, Pn_TX, backoff, Max_backoff, Pt_BT, Pt_desired, Packet_len

Note that unlike for the protocol steps that follow, the pseudo code does not use the i, j, k, and l subscripts because this code is run locally on a particular node so it would not make sense to use these subscripts to refer to the node itself or its destination. Furthermore, it is not necessary to know the source of the busy tone pulse to calculate the power bound, *Pt_bound*. That is, a node running the PCMA algorithm does not directly take into account any node other than its own destination and the busy tone pulses it observes (regardless of the node sending the pulses).

Step 1: A node *i* in its IDLE state monitors the busy tone channel to determine its power bound Pt_bound_i by measuring the maximum power received on the busy tone channel (Figure 3.3 lines 2-5) over a threshold time window. When *i* seeks to transmit a data packet, it waits until γPt_bound_i is greater than Pt_Min (Figure 3.4 lines 13-16), and then backs off (line 18, where $aSlot_Time$ is some mini slot representing the time to send a packet to the furthest possible node in the network) for a random interval bounded by its backoff counter to allow for contention resolution. The term γ is a constant (set to 0.9 for simulation results) that keeps the power level slightly below the threshold (Pt_bound) . The node continues to sense the busy tone during its backoff. If at the end of the backoff the transmission power bound Pt_bound is still greater than the minimum transmit power Pt_Min by a factor of $1/\gamma$, then *i* sends a RPTS control message at the transmission power level $Pt = \gamma Pt$ bound on the DATA channel (Figure 3.4 lines 20-26). The RPTS packet contains the transmission power level Pt and source noise power Pn_S_i (obtained from the air interface) placed in the packet.

Step 2: When the destination receives the RPTS, it measures the received power Pr. The channel gain G_{ij} (or just G in the pseudo code) is computed to be the received signal power over the transmitted power (advertised in the RPTS packet). The receiver then requires the data to be sent at

$$Pt_{i_des} = \max\{\frac{RX_Des}{G_{ij}}, \frac{SIR_Des \cdot Pn_D_{j}}{G_{ij}}\},$$
(3.1)

in order to satisfy both its received power threshold and its SIR threshold. Here the constraints $RX_Des > RX_Thresh$ and $SIR_Des > SIR_Thresh$ ensure the constraints from Section 2.3 are enforced, and Pn_D_j is the noise power measured at the receiver. The difference between the desired constraint levels (RX_Des and SIR_Des) and the threshold levels (RX_Thresh and SIR_Thresh) will be referred to as the overcompensation (or simply compensation as it is also referred to later). It is the amount of additional transmission power desired above that actually needed to satisfy the receiver, providing a buffer to the noise power of new transmitters. Pt_i_des is placed in an APTS control packet so that the source can be notified of the power level to send its data packet (Figure 3.5 lines 47-51). Assuming the same gain in both directions, the transmission power for the APTS packet is computed:

$$Pt_j = \max\{\frac{RX_Des}{G_{ij}}, \frac{SIR_Des \cdot Pn_S_i}{G_{ij}}\},$$
(3.2)

where the destination's noise power is replaced with that of the source (extracted from the RPTS packet). If this power is less than *Pt_bound* calculated at the receiver, then the APTS is sent at Pt_j on the *DATA* channel (Figure 3.5 lines 52-53).

Step 3: When the source receives the APTS packet, it checks if the desired transmission power is below its current power bound, and transmits the DATA packet with Pt_{i} _des on the DATA channel if the bound is satisfied. If the source times out before receiving the APTS, it multiplicatively increases its backoff bound and starts over (Figure 3.4 lines 28-36).

Step 4: The receiver starts sending busy tone pulses on the busy tone channel after starting to receive the data packet. The busy tone power Pt_BT_j sent from node jdepends on the noise tolerance E_j (see definition in the previous section) and is calculated as

$$Pt_BT_j = \frac{C}{E_j}.$$
(3.3)

The value of $C = Pt_Max \cdot CS_Thresh$ is such that a node at a distance that would add exactly E_j additional noise when transmitting at max power Pt_Max would receive the busy tone at exactly the CS_Thresh (Figure 3.5 lines 59-65). Note the busy tones only have to be received at the detection threshold since their power only has to be measured, and no data bits need be received. Also, since the busy tone's power can be no greater than Pt_BT_Max , there is a minimum noise tolerance:

$$E_{min} = \frac{C}{Pt_{BT}Max}.$$
(3.4)

This limits the ability of the busy tone to bound distant stations when the receiver is very sensitive to any small increase in noise. If there was not a minimum noise tolerance, the busy tone power could potentially approach infinity and force nodes infinitely far away to not transmit at all. Note if E_min was plugged into Equation (3.3) the resulting busy tone power would then be $Pt_BT_j = Pt_BT_Max$, which conforms to the physical limitations. The resulting noise tolerance is then

$$E_j = \max\{\frac{Pr}{SIR_Thresh} - Pn_j, E_min\}.$$
(3.5)

Step 5: When a node *l* receives the busy tone at a power of $Pr_BT_l = \frac{C}{E_j}G_{jl}$ it calculates its transmission power bound imposed by node *j* as

$$Pr_bound_j = \frac{C}{\frac{C}{E_j}G_{jl}} = \frac{E_j}{G_{jl}}.$$
(3.6)

Then node j can receive at most $Pr_j = \frac{E_j}{G_{lj}}G_{jl}$, from node l since we assume that $G_{lj} \cong G_{jl}$, and $Pr_l = E_j$. Since there may be busy tones received from multiple receivers, the transmission power bound at a node is defined by the most sensitive receiver (receiver that can tolerate the least transmission power from this node)

$$Pt_bound = \min\{\min_{j}\{\frac{E_j}{G_{jl}}\}, Pt_max\}.$$
(3.7)

The receivers periodically send busy tone pulses (as opposed to a solid tones) in order to minimize the probability of destructive interference of busy tones (i.e., collisions). The width of the pulse is based on the signal capture interval of the receiver. Sending separate pulses also allows receivers to periodically update their noise tolerance advertisement to avoid collisions with new transmitters. The needed frequency of busy tone pulses is based on the rate of change of background noise (traffic load) and is evaluated in Section 4.2, where sending a busy tone after every 128 bytes of data is found to be a sufficient update interval. The problem that may happen (particularly at high traffic loads) is that multiple potential transmitters, upon hearing a receiver's busy tone, may locally decide that it is acceptable to transmit and commence transmission simultaneously (within one period of the busy tone advertisement), thereby cumulatively creating enough noise to disrupt an ongoing packet reception. This problem is similar to contention, except that failure of contention resolution disrupts ongoing transmissions rather than the contending packets themselves. A simple solution to reduce such collisions is for a receiver to immediately pulse a busy tone whenever it sees a change in its noise tolerance by a threshold level.

Step 6: When the destination receives the entire data packet without errors, it sends an ACK at the power level needed to get back to the source on the *DATA* channel (Figure 3.5 lines 64-69).

Step 7: If the source receives a valid ACK it resets the max backoff and returns to the IDLE state. Otherwise, it increases the maximum backoff and starts over (Figure 3.4 lines 36-45).



Figure 3.6 PCMA protocol example

3.3 Example of PCMA

Following the PCMA protocol outlined above, a simple example shown in Figure 3.6 is now presented. The node locations are shown in parentheses, and the transmitted and received powers are labeled at each node. For this example we make the following assumptions: a two-ray ground reflection model with A = 1.0, $\alpha = 4$, the crossover range (distance after which the far field comes into play) is less than 25 m (to simplify the example), $RX_Thresh = 5 \cdot 10^{-10}$ W, $RX_Desired = 10^{-9}$ W, $CS_Thresh = 10^{-11}$, $SIR_Thresh = 10$ dB, $SIR_Desired = 12$ dB, $Pt_Min = 0.25 \cdot 10^{-4}$ W, $Pt_Max = 0.25$ W, $\gamma = 0.9$, and and the noise floor is 0 W. Further, assume that B is in the process of sending data to A, and D has a packet to send to C. The solid line shows the transmission in progress, the dashed line the desired transmission, the dotted lines the interference (noise power) observed at the new source-destination pair from the ongoing transmission, and the dash-dotted line the busy tone pulse observed by the new transmitter. The protocol now follows below (in steps that do not directly correspond to the protocol definition steps presented in detail above):

- If D has data to send to C, it first calculates its transmission power bound Pt_Bound = 0.0244 W with Equation (3.7). D then sets the transmission power to be a factor γ times the bound Pt = 2.197 · 10⁻² W (since we do not yet know how much power is required to reach C) and gets its noise power measurement from the air interface, Pn_S = 3.906 · 10⁻¹² W. After verifying that Pt is greater than Pt_Min, D sends RPTS (D, C, Pt, Pn_S) at Pt.
- 2. After C receives the RPTS message, it gets a noise power measurement from the air interface, Pn_D = 1.235 \cdot 10^{-11} and calculates the desired transmission power for D to send the data with Equation (3.1), Pr_desired = 3.906 \cdot 10^{-4} W, and the necessary transmission power to send back to D with Equation (3.2), Pt = 3.906 · 10⁻⁴ W. Here we notice that Pt_desired = Pt; this is because the noise at both source and destination is small enough that both are constrained by RX_Desired.

The destination (after checking Pt is less than the power bound it can transmit at) then sends back to the source an APTS $\langle D, Pt_desired \rangle$ at Pt

- 3. When D receives the APTS packet, it verifies that C's desired transmission power is below the power bound, *Pt_Bound*, D then begins sending the data at *Pt_desired*.
- 4. When C receives the data packet, it checks that the transmission power needed to send to D is still below its transmission bound and then sends an ACK back to D.
- 5. Once D receives the ACK the transmission is complete.

CHAPTER 4

PERFORMANCE OF PCMA

In this section, performance of PCMA is investigated under various network and channel conditions. The simulation environment in which PCMA, IEEE 802.11, and a generic power-controlled protocol (referred to as simply GPC, which is defined below) are implemented is first described. Then the throughput, fairness, average transmission power, and robustness properties of PCMA are compared to IEEE 802.11 (the current MAC standard for wireless packet networks). In addition, a generic power control protocol (defined below) is used to evaluate how close PCMA's performance models a power control protocol with perfect knowledge of channel and environmental conditions. It is also used to show that some of the limitations of PCMA are inherent to all power-controlled protocols employed in the single shared channel environment and not an attribute of a particular PCMA mechanism.

GPC is provided with perfect (global) knowledge of the link gain between any two nodes, the noise at any potential destination, and the upper bound on a transmitter's signal power needed to protect other receivers (maximum transmission power that neighboring receivers can tolerate). The protocol, like IEEE 802.11, follows the RTS-CTS-DATA-ACK exchange. However, all messages are sent with only enough power needed to reach the destination, and like PCMA GPC backs off if the destination requires more power than a neighboring node can tolerate. It also starts with initial overcompensated transmission power instead of making power adjustments through the transmission since in a multiple access environment the later is not practical due to contention delay. GPC is a generalized power control protocol in that it is given global knowledge to avoid defining a specific method (which will have some limitations) to extract the upper power bound and needed power to reach the destination. In this way, GPC demonstrates the upper bound on the performance of transmission power-controlled protocols for the multiple access environment.

In the remaining sections, we describe the simulation environment in which the results were generated. The results start by demonstrating the throughput improvement for large networks with multiple node neighborhoods and significant spectral reuse to exploit, and smaller ones with a single node neighborhood and significantly less spectral reuse to exploit. Some of the channel access fairness issues are then evaluated for PCMA and power-controlled protocols in general. The reduction in average transmission power is shown that implies less energy consumption. The final result demonstrates the robustness of the protocol by evaluating its performance in comparison with 802.11 as the basic assumptions stated in Section 2.2 are violated to varying degrees. Finally, an overview of the results are given.

4.1 Simulation Environment

To evaluate the performance of PCMA ns2 (a commonly used network simulator) was used and both PCMA and GPC were integrated into the CMU (Carnegie Mellon University) wireless extensions [22]. For these simulations the routing overhead was removed (since the goal of this paper is to evaluate the performance of MAC protocols and not routing protocols) and the destinations where restricted to within one hop of source nodes. Later work will evaluate the performance for multihop wireless networks.

Parameter Type	Parameter Value
Packet Size	2 KB
Data rate	2 Mbps
Channel carrier frequency	916 MHz
RTS	20 Bytes
CTS, ACK	14 Bytes
RPTS	28 Bytes
APTS	18 Bytes
Max MAC retransmissions	7
SIR_Thresh	6 dB
SIR_Des	10 dB
CS_Thresh	-78 dBm
RX_Thresh	-64 dBm
RX_Des	-60 dBm
Noise Floor	-104 dBm
Pt_min	-7.5 dBm
Pt_max	28.5 dBm
Pt	24.5 dBm

 Table 4.1 Simulation parameter settings

The parameter values used in the simulation are shown in Table 4.1. Here PCMA and GPC can send at a minimum power of -7.5 dBm and a maximum power of 28.5 dBm, and 802.11 sends at a fixed power of 24.5 dBm. The maximum power of PCMA and GPC are set to be 4 dB above the fixed power of 802.11 so that a destination at maximum transmission range for 802.11 will also be at maximum transmission range for PCMA and GPC allowing for a 4 dB compensation in transmission power. This allows the same scenario files (that determine the node connectivity) to be used for all three protocols. These parameters are reasonable and correspond to realistic settings in the hardware of a commercial wireless vendor. The traffic model is simple: sources generate arrivals according to independent Poisson processes. The source node is picked randomly from the set of all nodes, and the destination is picked randomly from the set of all nodes one hop away (in transmission range). Each data transmission between source and destination will be referred to as a *flow*, and each flow will have a specified rate that refers to the number of packets sent per second.

The channel model employed in the simulation was a simple path loss model which has a crossover point outside the Fresnel zone (86 m for the parameters chosen in these simulations) from $\lambda/(4\Pi d^2)$ to $A/(d^4)$, where λ is the wave length and A is a scalar gain the depends on the transmitter and receiver antenna gain and heights.

For the figures demonstrating the performance, the throughput is normalized by the carrier sense range and the slot time such that the total number of arrivals and departures is divided by a scaling factor sf defined as follows:

$$sf = \frac{network \ area}{carrier \ range \ area} \frac{1}{data \ slot \ size}.$$
 (4.1)

This demonstrates the utilization with respect to the non-power-controlled MAC with optimal (best case) node placement (allowing for maximum spectral reuse under the 802.11 protocol constraints). For a 1000 by 1000 m network with the parameter settings in Table 4.1, the resulting scaling factor is then $sf = \frac{1000^2}{550^2} \frac{1}{.008} = 413.22$.

The throughput and delay, fairness, and robustness performance results of PCMA is now compared with respect to 802.11 and GPC.

4.2 Throughput and Delay

In this section, we evaluate both the throughput and delay performance of PCMA as compared to 802.11. However, the majority of results are for throughput in various network scenarios since decreases in delay will follow from increase in throughput.



Figure 4.1 Throughput of 802.11 versus PCMA for 100 nodes in a 1000 by 1000 m network with 100 flows each sending 2 KB packets, and a connectivity range of 250 m

In Figure 4.1, the throughput is shown as the arrival rate is increased for a 1000 by 1000 m network where nodes are uniformally distributed over the area. The performance of PCMA is demonstrated for differing number of busy tone pulses sent per data transmission period (1, 4, 16, 64). The performance increases as the number of busy tone pulses increases (approaching the performance of GPC) since the feed back information (neighbor information) will be more up to date with more frequent busy tone pulses. However, the amount of improvement decreases and 16 busy tone pulses (i.e., sending one busy tone pulse for every 128 bytes of data since the data packets are 2048 bytes) is sufficient, and the remaining PCMA results will be for one busy tone pulse sent every 128 bytes of data. This demonstrates that the bandwidth required for the busy tone channel is small with respect to the data channel. Figure 4.1 shows that the performance of PCMA is significantly better than 802.11 if a reasonable number of busy tone pulses are sent. Notice that with power control the utilization may go above 100% since the output is normalized with respect a non-power-controlled protocol. PCMA restricts node transmissions according to variable interference region determined by the distance between source and destination (the *power conserving principle*) and busy tones (the *cooperative principle*), which can be significantly less then the fixed transmission range of 802.11.



Figure 4.2 Throughput of 802.11 versus PCMA with different RX_Thresh settings

In Figure 4.2, the results are again shown for 802.11 and PCMA (with the same settings as the last figure) though with two different RX_Thresh values. The 802.11 and PCMA solid curves labeled $RX_Thresh1$ are with the value specified in Table 4.1 (-64 dBm), and the two dashed curves labeled $RX_Thresh2$ use a value of 4 dB less (-68 dBm). From this figure we observe that the 802.11 protocol does better with the smaller threshold setting at all system load settings. However, PCMA shows improvement with the smaller setting at low loads, but at higher loads the larger threshold setting performs

better. The lower receiver threshold setting improves 802.11 at all loads because the 802.11 protocol is already overly restrictive since it utilizes both an RTS/CTS handshake and carrier sense to avoid collisions. With the original settings the carrier sense range was already more than double the receiving range. However, PCMA implements busy tone pulses from the receiver and not carrier sensing to avoid collisions. Therefore at lower loads, loosening the receiver constraint will allow more nodes to transmit with less noise tolerance without causing a significant increase in collisions, but at high loads the number lower noise tolerance results in a greater number of packet corruptions reducing performance.



Figure 4.3 Delay of 802.11 versus PCMA for 100 nodes in a 1000 1000 m network with 100 flows each sending 2 KB packets, and a connectivity range of 250 m

In Figure 4.3, the delay is shown for 802.11 and PCMA for the network described above. Again PCMA performs significantly better than 802.11 at intermediate and high loads since in 802.11 each node must backoff until all RTS and CTS messages observed expire, and the node cannot sense another transmitting station. PCMA, on the other hand, will allow for a tighter packing of source-destination pairs, allowing each node to send packets when the region around a source-destination pair is free. This allows packets to be sent sooner on average since they do not need to wait for the maximum transmission range between source and destination to be free.



Figure 4.4 Throughput for a 100 by 100 m network with 100 flows each sending 2 KB packets, and a connectivity range of 250 m

If we now consider a network where 100 nodes are distributed over a 100 by 100 m region, the resulting throughput is then shown in Figure 4.4. Here we see that PCMA and 802.11 yields almost the same throughput performance, except at extremely high loads where PCMA does only slightly better. For this type of configuration the region is smaller than the transmission range, and for 802.11 all nodes hear the RTS and CTS. As a result, there will be few collisions since there are no hidden stations. However, in this region there is also significantly less spatial reuse for PCMA to take advantage of since most nodes in the network are in the $1/d^2$ field instead of the $1/d^4$ field (see Section 2.1). In addition, PCMA does not backoff based on the carrier sense so that it may take advantage of spectral reuse, causing the protocol to more quickly reach its

maximum number of retransmissions and give up early. This is a trade-off made for not carrier sensing to improving spectral reuse.



Figure 4.5 Example of four clusters in a 100 by 100 m network

However, we argue that uniform distributions do not well define the distributions of users in a typical environment. In most situations, we expect a more cluster grouping of nodes. A simple four cluster network is shown in Figure 4.5, where nodes choose a cluster (each 25 m square and positioned in the corners of the 100 by 100 m network) at random and a random position within the cluster. Figure 4.6 demonstrates the throughput for a region containing both two and four clusters. The two-cluster case is similar to the four shown in the example depicted in Figure 4.5, but for only the top two clusters regions. The sender is chosen at random from all the nodes in the network. Then the destination is chosen at random from the other nodes in the sender's cluster. In this configuration PCMA does significantly better than 802.11. The improvement occurs because PCMA can send packets simultaneously in both clusters by reducing its transmission power, while in 802.11 each node in a cluster must always contend with the nodes in the other



Figure 4.6 Throughput for a 100 by 100 m network with nodes separated into clustered regions

cluster (in addition to its own). Figure 4.6 shows that as the network becomes more clustered the throughput increases since a greater number of simultaneous transmissions are possible and less nodes compete within each cluster.

An additional scenario for the clustered networks is that in each cluster a single node is designated as a base station that all other nodes in the cluster send their packets to and it sends packets to all the nodes in the cluster. An example of this scenario would be several businesses that provide an access point to provide information their customers. The results of this scenario are shown in Figure 4.7 and demonstrates further improvement over the case with no base station present in the clusters.

Up to this point the figures shown have been for single hop wireless ad hoc networks. However, it may also be required that source destination pairs utilize wireless links connecting intermediate nodes if the source and destination are out of transmission range or depending on spacing the routing algorithm provides based on the choices of intermediate hops. In Figure 4.8, the performance of 802.11 and PCMA is shown for a



Figure 4.7 Throughput for a 100 by 100 m network with nodes separated into clustered regions and sending to a single base station node

multihop network. For this figure the maximum transmission range for PCMA or fixed range for 802.11 was constant (i.e., 250 m, which corresponds to the power and threshold range settings shown in Table 4.1), while the routing algorithm chose next hops within the ranges shown in the legend (250, 225, and 150 m). All control packets were sent over the maximum range (250 m), but maximum distance between adjacent hops was restricted to the range shown in the legend. The figure shows that PCMA can dynamically adjust its transmission power utilizing the spectral reuse that the routing algorithm provides by limiting the spacing between adjacent hops. This allows PCMA make gains from the added spectral reuse to overcome the decrease in performance resulting from an increase in number of hops between source and destination. However, since 802.11 cannot dynamically adjust its power, it cannot take advantage of this reuse unless the fixed transmission power is manually adjusted to fit the maximum spacing between adjacent hops. Based on the theoretical results specified by [10] it would be expected that the throughput would increase as the maximum transmission range is reduced since the



Figure 4.8 Throughput for 802.11 and PCMA in a multihop network that spans 1000 by 1000 m

spectral reuse increases by a factor of four when the range is reduce by half while the number of hops only increases by a factor of two. However, these theoretical results do not assume flows, where the local neighborhoods are interdependent as occurs in true wireless multihop networks. That is the ability of an intermediate hop to send a packet depends on the previous hops ability to get a packet to it.

4.3 Fairness

In the previously mentioned figures, note that the performance of the power-controlled protocols continues to increase, even under very high loads, due to long-range transmissions being blocked by the transmission power bound allowing a greater number of shortrange transmissions. As the network load increases, the probability of a node requiring more power than the transmission power bound (set by the *cooperation principle*) also increases. The expected power for a source to reach its destination will increase as the



Figure 4.9 Destination range distribution for PCMA with $Pt_max = Pt + 4dB$

network load increases due to an increase in background noise, and the expected transmission power bound decreases as the network load increases because there will be an increase in the number of exposed receivers in the network. Then sources requiring more transmission powers (i.e., greater transmission ranges for a simple path loss channel) will be more likely to backoff, allowing a greater number of short-range transmissions. Therefore, a power-controlled MAC operating in a multiple access environment will result in unfair favoritism toward source-destination pairs sending over shorter distances. This phenomenon is particularly evident over the 250-m connectivity range for PCMA, as demonstrated in Figure 4.9, where the fraction of total packets received by destinations in five distance ranges (0-50, 50-100, 100-150, 150-200, and 200-250 m) from their sources is shown for 100 flows sending 1, 4, 16, and 64 packets per second. A perfectly fair protocol would result in a linearly increasing number of packets sent to each range since the number of destinations within each range increases as $2\pi r$, where r is the distance from the source node. Notice that for a very low transmission rate, such as one packet per second, the number of packets sent to each range is linearly increasing. However, as the network load increases, the ratio of packets sent over a greater distance decreases, and for extreme loads we observe that the majority of connections are short-range.



Figure 4.10 Destination range distribution for 802.11

The fraction of packets sent to each range for 802.11 is shown in Figure 4.10. The protocol also becomes less fair (sending fewer packets to greater ranges) as the load increase, but not to the extent that a power-controlled protocol like PCMA does. The 802.11 protocol has an equal probability of sending packets to destinations at any distance since the transmission power is not taken into account while contending. However, because all transmissions are sent at a fixed power level, there is less noise protection for destinations further from their sources, resulting in a greater number of lost packets at greater network loads. Further, 802.11 has a fixed interference range that is determined by the range over which other nodes can hear RTS or CTS packet, and the range over which other transmitters can sense the transmitters' energy. However, this range should really be increased as the distance between source destination pairs is increased because they
receive less desired signal power and also increase as a receiver is more greatly exposed to other transmitters energy. Therefore, at high loads the aggregate background noise will cause receivers that obtain less signal power from their corresponding transmitter to have more packet corruptions. PCMA, on the other hand, has the same amount of protection (the compensation factor) for destinations at all ranges; however, the probability of sending a packet to farther destinations decreases as the network load increases, as described above. In summary, for PCMA the contention phase favors nodes contending with less power (shorter range source-destination pairs), but once the nodes do contend, they all receive the same signal quality; however, in 802.11 the contention phase does not favor any particular nodes, but once a source contents successfully, source-destination pairs that are further apart receive a lower signal quality.

This biasing against longer range transmission protocols is an artifact not of the PCMA mechanisms alone but of all power-controlled protocols that fit in the collision avoidance (shared channel) framework. To demonstrate this, the fairness curves are again shown for different traffic loads for the GPC protocol defined at the beginning of this chapter (and shown in the initial throughput curves). Recall that this protocol has complete knowledge of the network power levels and gains so that it does not rely on any specific mechanisms to achieve power control. Here, it is again evident (see Figure 4.11) that a similar trend is observed for GPC. Since this protocol uses global topology and transmission power level information (known link gains and node noise tolerance levels) to transmit and backoff (instead of any specific exchange mechanism), we can conclude that this trend is present in all such power-controlled networks.

If we now increase the maximum transmission power to be 8 dB more than is required (Pt for 802.11) for a node at maximum transmission range instead of 4 dB, we see from



Figure 4.11 Destination range distribution for GPC with $Pt_max = Pt + 4dB$

Figure 4.12 that the fairness is improved over the flows shown in Figure 4.9. In particular, the 4 and 16 rate flows are now almost ideal (linearly increasing for increasing ranges) for all but the farthest range, and for the greatest flow rate the middle ranges are improved. The idea here is to increase the range distributions while still limiting the transmission ranges to the same distance. This has the effect of stretching out the fairness plots and limiting transmissions in farther ranges where a significant throughput disparity would be observed. This is a way to improve the fairness for power-controlled MAC protocols. However, it will also reduce the spectral reuse (throughput) and will demand additional power from the transmitters reducing the node's lifetime (power reserves). Whether additional compensation is used or the scheduling algorithm is changed under heavy loads, more work is needed to investigate techniques that overcome the fairness implications for power-controlled protocols.

The above figures looked at the ratio of packets sent to each range to demonstrate the PCMA at high loads PCMA provides less fairness than 802.11 as compared to the ideal



Figure 4.12 Destination range distribution for PCMA with $Pt_max = Pt + 8dB$

fair packet distribution. Another method for analyzing the throughput is to evaluate the number of packets sent to each of the corresponding ranges. If the number of packets sent to all ranges is greater for PCMA but only slightly greater for the largest distances (i.e., ranges), then the protocol is better than 802.11 for all situations, even though it does not provide ideal fairness. This is unfortunately not the case for high loads as observed in Figures 4.13 and 4.14, which show the number of packets sent to each of the five ranges stated earlier for the two highest flow rates (16 and 64 packets/s). Although PCMA performs better for most ranges, its performance at the greatest range is worse (particularly so at the highest rate). Notice when comparing the two fairness distribution bar graphs that as the rate increases, the number of packet sent over short ranges also increases, while the number long-range transmissions decrease.

The figures in this section demonstrated that PCMA can deliver more packet than 802.11 to all source-destination pairs, except those requiring significant transmission power (which spaced far apart) when the network load is high.



Figure 4.13 Number of successful packets sent to different ranges from source for a flow rate of 16 packets/s





4.4 Average Transmission Power

The PCMA protocol is now evaluated in terms of the average transmission power used for sending packets. Several parameters are investigated, such as the overhead of the busy tones pulses and the change in transmission power as the rate of packet transmissions is increased. The average transmission power is used as a metric for evaluation instead of energy because this requires that we know the power usage for the various processing units at each node, which will vary dramatically from one node to another. Assuming a particular type of mobile node would limit the applicability of this work to future mobile architectures, whose individual components are expected to take a smaller portion of the total energy compared (i.e., the power amplifier that controls the transmission power is expected to consume a larger and larger portion of the total energy budget. Therefore, simulating the average transmission power makes evaluating the PCMA protocols performance in later mobile architectures possible.

In Chapter 5.4, these results will be extended to account for the protocol overhead of retransmissions under both power-controlled and non-power-controlled protocols (802.11). Also the throughput improvement versus energy savings is investigated for multihop wireless networks of differing topologies.

The transmission power for 802.11 is fixed at 281.8 mW, while the transmission power of PCMA is varied in accordance with that needed for a particular source to reach (send a successful transmission to) its destination. This power will increase as the compensation factor is increased since we require a greater initial power from the source to satisfy the destination as the compensation is is increased. This behavior is demonstrated in Figure 4.15, which shows the average transmission power for both MAC protocols. The 802.11 results form a straight line since it does not implement compensation to protect



Figure 4.15 Average transmission power for 802.11 versus PCMA at 2 packets/s with respect to the compensation range

its nodes (i.e., it has a fixed transmission power). The results from the PCMA curve are also show in Table 4.2. Note that beyond 4 dB of compensation, PCMA requires more average transmission power than 802.11. Furthermore, with 16 dB of compensation PCMA requires over 3 W of transmission power, which would significantly reduce the lifetime of mobile nodes and is above that currently allowed by the FCC in the frequency spectrum where WLAN cards typically operate. However, this is not an issue we will focus on since we do not anticipate this amount of compensation would be needed, and these power levels will change with the RX. Thresh and CS. Thresh settings. The original ns2 threshold settings used for the results in this chapter and in Chapter 5 are based on some of the earlier WLAN devices; furthermore, newer WLAN cards use significantly lower threshold setting such that the maximum transmission power of PCMA and the fixed power setting of 802.11 would be considerably less. Therefore, the important part of these results are understanding the relative difference in power requirements for 802.11 and PCMA using different degrees of compensation.

2 dB	4 dB	8 dB	12 dB	16 dB
115 mW	239 mW	538 mW	1450 mW	3080 mW

Table 4.2 Average transmission power for PCMA



Figure 4.16 Average transmission power for 802.11 versus PCMA with 4 dB of compensation and varying flow rates

Another area to investigate is how the average transmission power changes as the network load (packet arrival rate) is increased. As the load increases, the average number of transmitters in the background increases, causing an increase in the background noise level and requiring more transmission power. Figure 4.16 displays transmission power for PCMA and shows how power varies with respect to the fixed transmission power required for 802.11, which is obviously a straight line since its power is fixed. The results show that the transmission power decreases as the rate increase. This may seem to be a counterintuitive result. However, this phenomenon can be explained if we look at the distribution of packets sent to different ranges as the network load is increased shown in Figure 4.9. We see that as the load increases, some of the longer-range source-destination pairs are being blocked by several shorter-range source-destination pairs. Therefore, as

the rate increases the average throughput for source-destination pairs that are further apart decreases, though, as discussed in Section 4.3, this is due to the inherent unfairness of power-controlled protocols in general and not just an artifact of PCMA alone. This graph leaves us with two conclusions:

- The background noise does not force nodes on average to send at a significantly higher transmission power to reach their destination than would be required a lower loads.
- Evaluating the energy consumption or power levels of lower network loads should be used to determine the the average transmission power so that similar sourcedestination distributions are observed for both power-controlled and non-powercontrolled protocols.

The previous figures showed the average power assuming the busy tone pulse was on the order of a single bit in width. In the curve in Figure 4.17 labeled "PCMA BT1" shows the average transmission power (for PCMA) again compared to 802.11. Notice the average power actually drops as the busy tone width increases. This is because the average power of the busy tone pulse is much less than that of the data signal since data signal must be received at RX. Thresh, the receiving threshold, while the busy tone pulses must only be received at CS. Thresh, the carrier threshold, (see Section 3.2) an order of magnitude less. However, if we specify that the busy tone pulses are to be received at the the carrier threshold, the results are shown in the curve labeled "PCMA BT2" in Figure 4.17. This figure verifies that, for reasonable busy tone pulse widths, the busy tone pulses require little energy as compared to the data transmission.



Figure 4.17 Average transmission power for 802.11 versus PCMA with two different busy tone powers with respect the busy tone pulse width

4.5 Robustness

Thus far we have demonstrated the performance of the PCMA protocol under ideal situations, where the channel gains are similar from one sample to the next and reciprocity holds. However, in many environments where we have multipath fading these assumptions may not hold, so we will demonstrate the robustness as these assumptions are relaxed. Implementing multipath fading into the simulation (a) is very complex since this would require sample-by-sample deviations and (b) is difficult to generalize over all types of environments. Therefore, we alter the gain (degrading the channel) on a per-packet basis by a factor χ (dB), where χ takes on the values $-\lambda$ with a probability 0.25, a value λ with probability 0.25, and a value of 0 (dB) with a probability of 0.5. The gain distortion factor λ will be referred to as the *distortion amplitude*. While other methods for introducing distortion are more appropriate for specific environments, this method shows the distortions that may be observed by the *MAC layer* and is sufficient to demonstrate the protocol's performance as the assumptions are violated. Here we

wish to evaluate the performance of PCMA as compared to 802.11 when the gain on the data channel is different in each direction. This is intended to test PCMA's dependence on channel reciprocity and gain stability. Then PCMA is evaluated when the busy tone channel and data channel gains differ. This will test the protocol under the situation where neighboring nodes' received signal levels are not accurately estimated.



Figure 4.18 Throughput for different amounts of gain distortion with varying compensations in a 1000 by 1000 m network

The throughput curves are shown in Figures 4.18 and 4.19 for both a distorted data and busy tone channels, respectively. For both cases the arrival rate is fixed to 32 packets per second and varying amounts of overcompensation (0, 4, 8, 12, 16, and 20 dB) points are plotted with different distortion amplitudes (0, 4, 8, and 12 dB for the data channel distortion and 0, 4, 8, 12, and 16 dB for the busy tone channel distortion) for each plot. Figure 4.18 shows that both PCMA and 802.11 degrade with increasing distortions in the data channel. However, PCMA (with some overcompensation) outperforms 802.11 up to 8 dB and after which it does slightly worse. Note that 802.11 does not have an overcom-



Figure 4.19 Throughput for different amounts of busy tone distortion with varying compensations in a 1000 by 1000 m network

pensation factor so the plots shown for the protocol are straight lines. Both protocols have reciprocity and stability assumptions, but PCMA depends on these assumptions to make the correct power level settings. That is 802.11 assumes if A can hear B, then B can hear A, and PCMA assumes if A can hear B, then B can hear A at the same power level (or actually within the overcompensation factor), making it more sensitive to gain distortions. In Figure 4.19, PCMA outperforms 802.11 (with some overcompensation) up to about 12 dB and does slightly worse with additional distortion to the busy tone channel. There is no busy tone channel in 802.11, so PCMA is compared to a single 802.11 plot. The distortion figures together show that PCMA can handle modest deviations from the assumptions stated in Section 2.3, demonstrating that it can operate under various channel conditions.

4.6 **Results Summary**

The figures presented in this chapter demonstrated that for dense networks with a spatial reuse to be exploited PCMA performs significantly better than 802.11. When users generally communicate locally we observe that the protocol provides improvements in throughput and increases scalability. In addition, when the amount of required compensation is low PCMA requires significantly less average transmission power, which translates into energy savings. This demonstrates that there are compelling reasons for integrating power-controlled MAC protocols into ad hoc networks.

The channel access fairness results demonstrates that in a heavily loaded network power-controlled protocols discriminate toward stations contending with less transmission power. This issue along with additional improvements in capacity are demonstrated in the next chapter.

CHAPTER 5

PCMA EXTENSIONS

In this section, several extensions are presented for PCMA that demonstrate that with some slight modifications the performance of PCMA can be improved further with respect to throughput, fairness, and energy. From this point on the original PCMA method presented in Chapter 3 will be referred to as PCMA Method 1 or simply Method 1. We start with two new methods (referred to as Methods 2 and 3) that improve the throughput and energy efficiency by dynamically changing the compensation (see Chapter 3 for a description of compensation in the PCMA protocol) based on the noise tolerance of neighboring stations. Another method is then presented that forces senders to contend (send the RPTS message) over a constant contention range (with fixed power) regardless of the power needed to reach the destination, but only send the following sequence of packets (APTS-DATA-ACK) with the power needed to reach the receiver. The psuedo code for PCMA Methods 1, 2, and 3 is shown in Figures 5.1, 5.2, and 5.3, respectively.

As mentioned above, Methods 2 and 3 vary the conpensation based on the amount of power that other stations in their area can tolerate. The range over which a station can vary its compensation is defined by an upper and lower range value, *comp_min* and *comp_max*, respectively. For PCMA Methods 2 and 3, if a station can send at the needed power (the least power that satisfies the constraints specified in Section 2.3 for a partic-

```
1 if(Pt\_needed + comp \le Pt\_bound) {

2 Pt = Pt\_needed + comp

3 }

4 else {

5 backoff

6 }
```



```
if(Pt\_needed + comp\_max \le Pt\_bound and
1
Pt\_needed + comp\_max \le Pt\_range + comp\_min) {
       Pt = Pt\_needed + comp\_max
2
3
   }
4
   else if(Pt\_needed + comp\_min \le Pt\_bound) {
       Pt = Pt\_needed + comp\_min
5
6
   }
7
   else {
8
       backoff
9
   }
```

Figure 5.2 PCMA Method 2: $comp = \{comp_min, comp_max\}$

ular source to send to a paritcular destination, and is now refer to as Pt_needed) plus upper range value (in decibels so it is actually multiplication when dealing with linear, nonlogarithmic-based, power levels) without causing a collision at other stations (i.e., it is below the transmission power bound Pt_bound), then it sends at this power. If on the otherhand, a transmitter's needed power plus the lower range value is above the maximum transission power value to avoid a collision with other receivers, it backs off and tries again later (like Method 1). Both Methods 2 and 3 also restrict the maximum transmission power to be Pt_needed for the maximum range, Pt_range , plus comp_min. That

```
if(Pt\_needed + comp\_min \le Pt\_bound) {
1
2
       Pt = Pt\_bound
       if(Pt > Pt\_needed + comp\_max) {
3
4
           Pt = Pt\_needed + comp\_max
5
6
       if(Pt > Pt_range + comp_min)
7
           Pt = Pt\_needed + comp\_max
8
9
   }
10 else \{
11
       backoff
12 }
```

Figure 5.3 PCMA Method 3: $comp = [comp_min, comp_max]$

is, the maximum power, Pt_max is the fixed power of 802.11 (for the same transmission range – maximum distance between source-destination pairs) plus comp_min.

What happens within the above specified range differs for Methods 2 and 3. Method 2 transmits with *comp_max* additional power (compensation) if it is allowed (i.e., will not corrupt other stations, based on the busy tones pulses recently observed, and is below Pt_max); otherwise, it sends at with only *comp_min* if allowed. However, Method 3 transmits at the maximum power allowed within this range. That is, Method 3 transmits at γPt_bound (refer to Section 3.2) if this value is valid power plus range of compensation, whereas Method 2 transmits at the lower range value only if γPt_bound is below the upper range value. Therefore, in Method 2 nodes transmit at either the power level $Pt_needed + comp_max$ or $Pt_needed + comp_min$, whereas in Method 3 nodes may send at any power within this range.

The following sections investigate the throughput and transmission power levels of the 802.11 and the orginal PCMA method, and then compare them to the new Methods. Finally, the fairness of these methods is investigated and another new PCMA method that demonstrates improvements. The results are again generated with the ns2 simulator and parameter settings defined in Section 4.1.

5.1 Throughput Performance of PCMA Methods

In this section, the throughput is investigated of the two new methods introduced above. Here, we expect both methods to demonstrate improvements since they can dynamically adjust the compensation to increase the packing of source-destination pairs and still provide the most protection that will not cause new transmissions to interfer with ongoing transmissions.



Figure 5.4 Througput of 802.11 versus PCMA Methods 1-3 with compensation ranges of 2 dB, 2-6 dB, and 2-6 dB, respectively

In Figures 5.4 and 5.5, the throughput curves versus network load are shown for 802.11 and PCMA Methods 1, 2, and 3. For both figures the protection provided for Method 1 is 4 dB. However, Methods 2 and 3 are provided a protection range of 2-6 dB in Figure 5.4 and a 0-4 dB in the second. The first throughput figure shows that Methods 2 and 3



Figure 5.5 Througput of 802.11 versus PCMA Methods 1-3 with compensation ranges of 2 dB, 0-4 dB, and 0-4 dB, respectively

can provide an additional 20 to 25% improvement in throughput when the compensation is allowed to be increased or decreased by 2 dB from the constant level of Method 1. Looking at the second thoughput figure, we observe that if the amount of compensation is allowed to not only increase when the network area is available, but also decrease when the 2 dB range was more than neighboring receivers can tolerate, then further gains are demonstrated. This, however, also allows the shorter-range source-destination pairs to be packed into practically every available area of the network, significantly restricting the longer-range source-destination pairs' ability to contend (as demonstrated in Section 5.3). The two new methods (2 and 3) therefore provide improved throughput because they can provide a higher level of protection when the desired share of the "floor" is available, but do not block the transmission from going forward unless the minimum quality level (compensation) cannot be acheived.

Note that in both cases Method 3 does slightly better than Method 2. This is because Method 3 allows sources to send with the maximum amount of compensation allowed for a given power bound, whereas Method 2 sends with only the minimum compensation if the maximum compensation is above the bound. Notice, as the compensation range is reduced from 2-6 dB in Figure 5.4 to 0-4 dB in Figure 5.5, that the difference between the throughput in Method 2 and 3 is reduced because the maximum compensation level is reduced so that more nodes can send with maximum compensation without interfering with other receivers.

We will also see in the next section that on average these new methods also consume power at a level that is proportional to sending with a constant compensation equivalent to thier lower compensation range value.

5.2 Transmission Power Requirements

The above protocols are now evaluated in terms of the average transmission power they require. The average transmission power is again used as a simple metric for evaluating the power consumption of the the power-controlled protocols.

The average transmission power is now shown in Table 5.1 for all three PCMA methods described earlier. The table shows Method 1 with compensation of 2, 4, and 6 dB; Methods 2 and 3 with minimum compensation of 2 dB and maximum 6 dB; and Methods 2 and 3 with minimum compensation of 4 dB and maximum of 8 dB. The results demonstrate that both Methods 2 and 3 provide an average transmission power on the order of the minimum compensation with respect to Method 1. This makes sense because at distant ranges, which account for the greatest contribution to the average power, the compensation is restricted to the lower side of the compensation range value. Method 2 here requires slightly less transmission power on average because it sends with minimum

Method 2 at 0.25-4 dB	42.7 mW
Method 3 at 0.25-4 dB	43.2 mW
Method 1 at 2 dB	115 mW
Method 2 at 2-6 dB	122 mW
Method 3 at 2-6 dB	135 mW
Method 1 at 4 dB	239 mW
Method 2 at 4-8 dB	241 mW
Method 3 at 4-8 dB	258 mW
Method 1 at 6 dB	538 mW

Table 5.1 Average transision power for PCMA Methods 1, 2, and 3

compensation when the maximum compensation cannot be acheived, whereas Method 3 will send at the maximum allowed by the power bound.

5.3 Fairness of PCMA Methods

In Figures 5.6 and 5.7, the fairness of all PCMA methods is compared with that of 802.11. These figures show the corresponding fairness distributions for the setup demonstrated in Figures 5.4 and 5.5 (the 2-6 dB compensation range and the 0.25-4 dB compensation range, respectively). The two new methods provide an increase in the number of packets successfully sent over short and intermediate ranges and about the same performance at the longest ranges for the first figure (2-6 dB range). This is because these methods provide short-range source-destination pairs with the maximum protection (power) that allows them to send without causing a collision, and limits the transmission power of long-range source-destination pairs to make up for the increase in short-range source-destination pairs that are allowed. However, the performance at the furthest range is still worse than 802.11. For the second fairness figure that uses a 0.25-4 dB range for Methods 2 and 3, it can been see that there is a large increase in the number of short-range



Figure 5.6 Comparing fairness of 802.11 to Methods 1, 2, and 3 using compensation ranges of 2 dB, 2-6 dB, and 2-6 dB, respectively, and each data flow having a rate of 16 packets/s



Figure 5.7 Comparing fairness of 802.11 to Methods 1, 2, and 3 using compensation ranges of 2 dB, 0.25-4 dB, and 0.25-4 dB, respectively, and each data flow having a rate of 16 packets/s

source-destination pairs at a great cost to the number of far range source-destination pairs. This results because the longer-range source transmissions must wait for a large area of the network to be free that closely spaced source destination pairs will contend in before an area large enough will be freed (as a result of other sources transmissions ending). Therefore, it would be benificial in throughput with little cost in fairness. However, when the minimum range is dropped down to almost no protection (0.25 dB of compensation), there is a significant fairness trade-off for the added throughput, which may make it less attractive. Also notice that Method 3 does slightly better when sending to closer destinations, while Method 2 does better when sending to further destinations. This is again because Method 2 is reducing its compensation to the minimum level when it cannot achieve the maximum level. The result is less protection for shorter-range sourcedestination pairs than Method 3 (which sends with the maximum compensation that the upper bound allows), but a greater restriction of the shorter-range source-destination pairs transmission power such that they are less likely to interfere with a longer-range source-destination pair.

We now define an additional PCMA dirivitative, Method 4, that is designed to reduce the biasing in contention toward short-range transmissions. This method works like Method 2, except that it imposes an additional requirement on the contention process; Method 4 allows a node to contend only if it is can send over its maximum transmission range, at power level Pt_max . This way, all nodes, regardless of the area over which they must transmit to reach their destination, wait to send until the maximum (fixed) "floor" is open. However, nodes use the same mechanism described in Method 2 to send to their destination. Therefore, a constant "floor" area must be free to contend, but nodes only send over the "floor" area needed to reach their destination. This will prevent nodes that require a small "floor" size (to reach their intended destination) from continually "stealing" a "floor" area that could be used by another node requiring a larger "floor" area.



Figure 5.8 Througput of 802.11 versus PCMA Methods 1, 2, and 4 with compensation ranges of 2 dB, 2-6 dB, and 2-6 dB, respectively

We start by looking at the trade-off (amount of performance we are giving up) in throughput for the improved fairness in contention. Figure 5.8, shows the throughput of PCMA Method 4 as compared to 802.11 and PCMA Methods 1 and 2. Here, we leave out Method 3 to avoid cluttering the figure, and since Method 2 already does significantly better than the newest method, it would not add to the results. Notice that Method 4 does slightly worse than Method 1 and considerably worse than Methods 2 and 3 (as inferred from the previous figures) because it restricts the cases under which PCMA can send data. However, if we look at the distribution of packets sent to each range as show in Figure 5.9, we observe that this method can send slightly more packets than 802.11 to the farthest ranges and still significantly more the closer ranges. This presents significant improvement over the other PCMA methods in the number of packets sent to the farthest range. However, this benifit in performance source-destination pairs that are far appart is provided with significant costs to source-destination pairs that are closer.



Figure 5.9 Comparing fairness of 802.11 versus PCMA Methods 1, 2, and 4 with compensation ranges of 2 dB, 2-6 dB, and 2-6 dB, respectively, and each data flow having a rate of 16 packets/s

5.4 PCMA Methods Overview

The new PCMA methods introduced in this section demonstrate the potential for significant performance improvements over the initial PCMA protocol (referred to as Method 1) presented in Chapter 3 and [3, 4]. Methods 2 and 3 show considerable improvements in network throughput and energy efficiency, without reducing the number of packets sent between source-destination pairs that have a greater spatial separation (for the 2-6 dB range), but still slightly worse than 802.11 at the farthest range. Method 4 shows improvement over 802.11 at all ranges, though with less overall benifits in thoughput. Therefore, the most suitable method will depend on the system design constriants and goals. This chapter demonstrates with some alterations PCMA can demonstrate improvents in performance, but the amount of improvement will depend on the system constraints.

CHAPTER 6

POWER CONTROL IN MULTIHOP WIRELESS NETWORKS

It was shown that controlling the transmission power can offer many benefits in performance. These benefits, including capacity and energy savings, were motivated in Section 1.1 and demonstrated in Chapter 4. However for these cases, the degree of energy savings is limited by the choice of source-destination pairs and their respective distances (link gains). That is, if sources frequently send to destinations that are farther, and therefore require more transmission power, then gains can be observed by controlling the transmission power. Further, in routing protocols currently designed for multihop wireless ad hoc networks, the goal is to minimize the number of hops. For dense mobile networks this will result in the distances between intermediate hops being on the order of the transmission range such that the transmission power required to send to the next hop is close to the maximum power. Therefore, little power will be saved by just implementing power control.

In this chapter, we take the wireless ad hoc power-controlled protocol framework and extend it to evaluate the performance of multihop wireless ad hoc networks, where the distance between adjacent hops is limited. Utilizing multiple intermediate hops to reduce the transmission range can provide extensive energy savings since transmission signals attenuate on the order of $1/d^4$ in most networks. This chapter evaluates the energy savings and capacity improvements and trade-offs of power control in a multihop wireless packet network with different maximum ranges between adjacent hops. The goal here is not to define the mechanisms for choosing the best intermediate hops between source and destination pairs since this would require the implementation of a new routing protocol; instead we evaluate the trade-offs and benefits that a power-controlled MAC such as PCMA can provide in multihop wireless networks that utilizes different maximum ranges between adjacent adjacent hops.

6.1 Network Topology Scenarios

This section outlines several network topologies that dictate how nodes communicate (their communications hierarchy) and the placement of certain nodes. We considered infrastructureless and logical infrastructure network topology scenarios. The networks with a logical infrastructure are those in which nodes are grouped into clusters with designed forwarding agents relaying packets between clusters.

The motivation for implementing forwarding agents is to reduce the complexity of the routing algorithm and take advantage of nodes with greater capacity and energy resources. Using specific nodes in a cluster for forwarding packets can greatly reduce the amount of routing overhead since the routing discovery would then require only that packets be sent to the forwarders (as opposed to every nodes in the network). This would reduce the complexity of the routing algorithm to the order of the number of clusters, instead of the order of the number of nodes in the network. It has been demonstrated [23, 24] that the overhead associated with ad hoc routing algorithms can account for more than 50% of the total packets sent in the network (depending on the average number of hops between source and destination and the mobility of mobile nodes). Therefore, limiting the nodes that send and receive routing information by designating some nodes as forwarders can limit the degree of routing overhead. Also if we consider a network consisting of heterogeneous mobile nodes (with differing available resources) such as cell phones, PDAs, laptops, vehicles, and fixed access points, it would be advantageous to use the nodes that had greater resources to send over longer distances.

Another factor to consider for forwarding agents is whether their position can be controlled. Depending on the type of network, the position of the forwarding agents may or may not be able to be controlled. If the network can control the position of the forwarding agents, they can be placed such that any nodes distance to the forwarder is upper bounded or can be placed in accordance with the mobile density in certain areas.

The different types of networks considered are evaluated in Section 6.2 in terms of their energy savings and throughput improvement or trade-off. Each of the network scenarios evaluated is now defined, and an example is given to show how they apply to real network:

• Infrastructureless networks: This type of network assumes that all nodes have equal resources, and routing is computed in a totally distributed fashion. That is, any node can be a forwarder, so the routing requires that some sort of control packets be sent between every reachable node to find the best route. An example of this would be a sensor network where every node is equal (has equal resources). An advantage of such an algorithm is that every possible route is considered such that every source-destination pair is provided with the shortest route. However, as stated above, such an algorithm would require significant overhead if there is even a modest amount of mobility in the network since routes will often become disconnected so that new ones must be found.

- Clustered networks with forwarding agents whose positions can be controlled: Here nodes are classified into clusters that form around designated forwarding agents (based on locality). The placement of these forwarders can be controlled to provide coverage and reachability. In Section 6.2.1 this scenario is tested with uniform placement, where the distance between forwarders is such that full connectivity is maintained. An example of such a paradigm is one where wireless nodes (like base stations) are placed to support a set of users with PDAs. Further, we investigate two cases within this scenario. The first case is where the power resources of the forwarding agents is unlimited such as a vehicle or a node with a fixed power supply, and the second case is where the energy of the forwarding agents is limited such as a mobile powered by batteries.
- Clustered networks with forwarding agents whose positions are not controllable: This scenario is similar to the last except that the location of the forwarding agents can not be controlled and are random. Such a configuration may result if vehicles or other nodes with greater resources that have purposes other than to serve as supporting infrastructure for mobile nodes with lesser resources. An example of this paradigm may be where a public safety officer's handheld radio communicates through the closest public safety vehicle, which would then relay the corresponding packets to other vehicles, and then to the intended receiver. One problem with this scenario is that outages may have to be tolerated since the placement of forwarding agents. Also like the previous scenario we consider forwarding agents that do and do not have limited power resources.

The next section now evaluates performance of the above scenarios in terms of energy consumption and capacity with a non-power-controlled MAC, 802.11, and a powercontrolled MAC, PCMA.

6.2 Performance of Multihop Topology Scenarios

In this section, the performance of the network topology scenarios discussed in Section 6.1 are evaluated. For each case, the throughput is shown in terms of total number of successful packets sent per second, and the signal energy per successfully transmitted bit. Signal energy refers to the transmission power level of each packet times the duration of the packet summed over the total number of packets sent (successfully and unsuccessfully) multiplied by the total time transmitting for all nodes. The signal energy per successfully transmitted bit can then expressed as

$$\sum_{i=1}^{K} \frac{Pt_i T_i}{S},\tag{6.1}$$

where K represents the total number of packets sent (including control packets) for the duration of that simulation (from all nodes including intermediate hops), S is the total number of successful data packets between source and destination, Pt_i the transmission power of packet *i*, and T_i is the time to transmit packet *i*. Note that Pt_iT_i is the energy used to send a given packet (or packet energy). The total successful packets S are calculated from source to destination and not between intermediate hops, while the packet energy is summed over all packet transmissions. Therefore, it accounts for the aggregate energy used by all hops to send a bit to the final destination so that the single hop and differing number of multihop cases can then be fairly compared.

The signal energy expenditure is used here (instead of the total energy used by the network interface) because accounting for total energy usage would require that we make assumptions about the power consuming levels of each of the components in the network interface card (as shown in Figure 1.4). This would make the measurements only relevant for a particular device. Rather, we wish to measure just the energy of the transmitted signal (which is related to the average transmission power level) such that these results are relevant for any current or future wireless network interface cards. The signal energy is divided by the number of successfully sent bits so that the overhead incurred as a result of retransmissions is taken into account.

The results in this section will show the throughput of the previously defined topology scenarios for the current wireless MAC standard IEEE 802.11 and the PCMA protocol (Method 2).

6.2.1 Simulation environment and parameter values

To evaluate the performance of these MAC protocols in the different network topologies scenarios, the *ns2* was again used with the CMU wireless extensions [22]. The data rate for this configuration was set to 2 Mb/s, the packet size was 2 KB, the transmission power range for PCMA was between -5 dBm and 22 dBm, the fixed transmission power level of 802.11 was fixed to 20 dBm. Note that the maximum power level of PCMA was again set to be above the fixed power level of 802.11. The fixed range for 802.11 and the maximum transmission range for PCMA are setup such that source-destination pairs could be a maximum distance of 500 m apart to receive a valid data packet. The nodes for these scenarios (100 for these experiments) were uniformally distributed in a 350 by 350 m network. Note with this size network and a 500 m maximum transmission range a source reach the furthest possible destination (in opposite corners).

The traffic model is the same as outlined in Section 4.1: some number of sourcedestinations were picked randomly (according to a uniform distribution) off-line. When the simulation started, these sources would generate packets according to independent Poisson processes. The results bellow are for 100 flows (source-destination pairs) generating 16 packets per second. This rate of packet generation is to keep the sources busy such that the nodes in the areas where spectral reuse can be exploited have packets to send.

For the multihop case, a simple routing algorithm is implemented that chooses the route requiring the fewest number of intermediate hops (i.e., shortest path) for the given range settings. We note that this may not be the best way to choose intermediate hops for a power controlled protocol since we would ideally also want to take into account spectral reuse. However, we used this simple method so that the same routes were used for both 802.11 and PCMA and so that we can neglect the effects of the routing algorithm.

The focus in this section is on investigating the energy and throughput performance for differing numbers of hops (or transmission ranges) between source and destination and also comparing non-power-controlled and power-controlled MAC protocols for these differing transmission ranges. The simulation results were gathered for nodes having transmission ranges of 500, 250, 166, 125, 82, and 62.5 m. For Scenario 1, these ranges correspond to a maximum number of hops of 1, 2, 3, 4, 6, and 8, respectively, based on the size of the network the (350 by 350 m) the nodes were distributed within. For Scenario 2, the corresponding maximum hops are 1, 4, 6, 8, 10, and 12 since the packets can



Figure 6.1 Average number of hops between source-destination pairs having different transmission ranges

only be relayed through the forwarding agents. For Scenario 3, the forwarding agents are placed randomly. This means that connectivity cannot be guaranteed unless the transmission range covers the entire network area (500 m or the diagonal of the 350 by 350 m network). Therefore, for this case the transmission range set to 500 m and the number of forwarding agents are set to be the number that corresponds to those needed to ensure full coverage in Scenario 2, uniform node placement (see Section 6.2.2). For Scenarios 1 and 2 the results are demonstrated as the maximum number of hops between source and destination increased or transmission ranges decrease. These are the respective maximum hops, and of course, the averages will be less than this since the source-destination pairs are chosen at random from the nodes in the network area. The corresponding averages are shown in Figure 6.1 for the basic infrastructureless topology. Note that in Scenario 3 that the maximum hops between a forwarding agents is at most one since the transmission range covers the entire network area, as discussed above. Also, the forwarding agents themselves can also have traffic so average hops decrease slightly when the number of forwarding agents becomes a significant portion of the total nodes. This trend is an artifact of the network topology and communications pattern and can be observed in Figure 6.1, where the average hops for the Scenario 3 curve drops slightly for the greatest number of forwarding agents (corresponding to the 62.5 m range shown on the x-axis).

6.2.2 Results

Following the structure introduced in Section 6.1, we start by by investigating energy savings potential and throughput of 802.11 and PCMA for an infrastructureless ad hoc network, Scenario 1. The performance is shown as the transmission range is decreased and therefore requiring a greater number of average hops (see Figure 6.1)

Figure 6.2 shows the energy savings as the transmission range is decreased. As we anticipated in Section 1.1.2, there is a significant savings in energy as the transmission range is decreased. The power-controlled MAC protocol, PCMA, shows additional improvement of over the non-power-controlled MAC protocol, 802.11. However, the amount of improvement decreases with transmission range. This is because as the range decreases, there is less spectral reuse to take advantage of, particularly since the smallest range (62.5 m) is within the Fresnel zone, where the signals attenuate proportional to $1/d^2$ instead of $1/d^4$ as they do outside of this region. Therefore, the difference between near and far destinations is less significant.

Figure 6.3 now shows the throughput for 802.11 and PCMA for the same ranges as the energy savings figure was presented. Observe that the throughput actually drops as the number of hops is increased (transmission range is decreased). This may be counterintuitive if we refer to the theoretical analysis presented in [10] since, as the range is halved, the maximum hops increases by a factor of 2, but the area of the transmission decreases



Figure 6.2 Signal energy per successfully transmitted bit for an infrastructureless network with different transmission ranges



Figure 6.3 Number of successfully transmitted packets per second for an infrastructureless network with different transmission ranges

by a factor of 4. Conceptually, this should allow for more simultaneous transmissions than the cost of requiring additional time slots to send the packet to the destination. However, this analysis does not take into account the fact that packet flows with multiple hops can only be sent at the rate allowed by the slowest (highest contention) link. The analysis for this theoretical study assumes that each link can send packets independent of the last hop (i.e., that each hop has a sufficient number of packets buffered such that it has packets to send when the network area becomes free). This is obviously not the case in a true scenario, where only the slowest link can take full advantage of the extra spectral reuse offered by the decreasing transmission ranges.

Another characteristic to note is that the throughput curves do not decline smoothly with decreasing transmission range. Particularly, the transition from 500 m to 250 m is more gradual than the next. This is because even at 250 m most nodes are still within one hop of each other since only nodes at opposite corners are actually 500 m apart. Furthermore, nodes near the center are in range of all other nodes. Therefore, the throughput drops more gradually than with the later ranges, where a greater number of nodes require multiple hops to send packets to their destination. A final property to note is that at very small ranges both curves start to level off again. The gain in spectral reuse by limiting the transmission starts to overcome some of the losses incurred by increasing the number of transmissions (hops) needed to reach the destination.

The benefits in throughput (number of packets successfully delivered) provided by power control over non-power-controlled MAC protocols are also decreased as the range is reduced for the same reason that energy benefits of implementing power control decrease for smaller ranges. That is, the amount of spectral reuse that can be exploited in the network decreases as the maximum range is reduced. Another thing to take into consideration here is that the routing protocol used to generate these results (see Section 6.2.1) chose the routes based on the minimum number of hops between source and destination, so the best-case scenario for 802.11 is also employed in the power-controlled case (for unbiased comparison at the MAC level). A better choice for power-controlled networks would be to use a series of metrics that take into account number of hops, aggregate path power consumption (summed over the power required at each intermediate link), and spectral reuse gains that account for node densities in various areas of the network in order to make the best path decisions. This, however, is a topic that is outside the focus of this discussion, so we will stay focused on the power control at the MAC layer and leave routing-level power control issues to future researchers. We mentioned this to highlight the fact that additional benefits are still possible when utilizing transmission power-controlled protocols.

Let us now distinguish between the two spectral reuse benefits specified in the proceeding two paragraphs. The first spectral reuse provided to both 802.11 and PCMA is due to the decrease in maximum transmission range and utilizing intermediate hops. This range dictates the number of intermediate hops that must be used between a given source-destination pair. The second additional spectral reuse benefit is from reducing (or controlling) the transmission power to that needed to reach the intended receiver (next hop) that must be chosen from the nodes within the fixed maximum range, which varies between 500 m and 62.5 m. The first case can only be realized in 802.11 if we manually adjust (restrict) the transmission power of all nodes, whereas a power-controlled MAC protocol (like the ones presented in [3, 11]) will dynamically adjust the transmission power so that the routing protocol only needs to restrict the nodes that can be used for the next hop to restrict the transmission power. Therefore, approaches that implement
power control in the MAC can exploit the potential energy savings of a particular node topology without manually adjusting the transmission powers of the individual nodes. In accordance with the limitations of current non-power-controlled MAC protocols (like 802.11) presented in Section 1.1, it can be concluded that even if the transmission power levels of 802.11 can be adjusted to satisfy the intended destination, such an adjustment is still not sufficient since it would violate the collision avoidance framework set forth by the communal structure of shared channel ad hoc networks. Therefore, even though the added benefits of exploiting power control decreases with increasing hops (decreasing transmission range), the ability of power-controlled protocols to dynamically adjust their power will continue to make them an attractive alternative to fixed transmission power MAC protocols.

The next network topologies that are studied are those which designate a subset of the nodes as forwarding agents for a cluster of nodes (chosen either for strategic reasons or because they have a greater degree of resources). Nodes send directly to nodes in the same cluster, but go through the forwarding agent to send to nodes in other clusters. The forwarding agents send a packet to the next forwarding in the route to the destination until the packet reaches the forwarding agent that is in the destinations cluster. All nodes including the forwarding agents communicate on a single shared channel.

For this type of network topology we start with the case where the forwarding agents positions can be controlled. A simple method would be to place some number of forwarding agents uniformally within the network area, Scenario 2 from Section 6.1. However, instead of placing a specified number of forwarding agents in the network area, the maximum transmission range is specified, and a minimum number of forwarding agents are then placed such that every location in the network is in range of a forwarding agents and every forwarding agent is in range of its adjacent forwarding agent. The number of forwarding agents then required to cover the network area for the previously stated transmission ranges (500, 250, 166, 125, 82, and 62.5 m) is then 1, 4, 9, 16, 25, and 36, respectively.



Figure 6.4 Signal energy per successfully transmitted bits for uniform forwarding agent placement with different transmission ranges

In Figure 6.4, the signal energy per successfully transmitted bit is shown for both 802.11 and PCMA for two different cases. The first case does not account for the energy consumed by the nodes designated as forwarding agents (assuming they have infinite resources such as a vehicle or node with a continuous supply of power). In the second case, the power of the forwarding agents is taken into account (they may have greater resources such as a laptop as compared to a PDA or remote sensor that has less sufficient resources, but their power must still be considered). The results shown in the figure demonstrate again that there is a significant power savings as the transmission range is decreased and additional intermediate hops are utilized. Also as expected the power-controlled protocol saves energy over the non-power-controlled protocols though again the degree of benefit decreases as the maximum transmission range is decreased. For greater

transmission ranges with few hops, there is a small difference in energy consumption between the cases that accounts for the forwarding agents' energy expenditure and those that do not. However, as the transmission range is reduced and the number of hops increases, this difference becomes more pronounced because the number of forwarding agents between source and destination increases. The results demonstrate that the energy consumed for the uniform placement of forwarding agents is less than for the scenario with no infrastructure enhancements (Scenario 1) when the energy of the forwarding agents is not taken into account. Therefore, forwarding agents are most desirable in heterogeneous networks where mobile nodes have a great variance in energy resources.



Figure 6.5 Number of successfully transmitted packets per second for uniform forwarding agent placement with different transmission ranges

The throughput for this scenario is shown in Figure 6.5. The throughput for this case drops significantly more than for the previous scenario shown in Figure 6.3. This result occurs because all packets are forced to communicate through a single access point (forwarding agent) to all nodes in other clusters, and the number of nodes in other clusters increases as the range deceases because the cluster size decreases and there are more clusters. If we consider the point on the figure corresponding to the

250 m transmission range, we see that considerably fewer packets were delivered than for the infrastructureless case. This is because the forwarding agent employs the 802.11 distributed MAC algorithm, which provides equal access rights to all nodes including those that were designated as the forwarding agent. Therefore, when N-1 sources are all trying to send through a single forwarding agent that must relay the packets to N-1destinations, the one forwarding agent will be competing with the N-1 sources to send to the N-1 destinations, but only receive 1/N share of the network resources. This will severely limit the number of packets that are allowed to reach the destinations, which is why the throughput is severely reduced when using the distributed 802.11 MAC with forwarding agents. As the number of forwarding agents is increased and the transmission range is reduced, the rate initially declines because it takes more hops, but later starts to increase because the number of nodes the forwarding agent is competing with decreases.

In addition, the power-controlled protocol provides a considerable improvement when the greater transmission ranges are used, but deceases as the range is decreased since, similar to Scenario 1, there is less spectral reuse to exploit.

The next figure is again for predesignated forwarding agents though this time the placement of these forwarding agents is random (Scenario 3 from Section 6.1). The motivation behind using forwarding agents under this scenario is that we want to take advantage of nodes with greater resources as forwarders when they are within range. For each range the number of forwarding agents placed was made equal to the number of uniformly placed forwarding agents required to cover the graph for that corresponding range. Since the placement of the forwarding agents was not controlled and was therefore random, it could not be guaranteed that all nodes where reachable from all other nodes. So, as mentioned when discussing the simulation setup, the maximum transmission range

for this topology scenario was kept constant at 500 m, but the number of forwarding agents was set to 1, 4, 9, 16, 25, and 36. Then the x-axis corresponds to the transmission ranges shown in the previous figures. Note again that the transmission range shown in Figure 6.1 corresponds to these number of forwarding agents for the random forwarding agent placement curve in this figure.



Figure 6.6 Signal energy per successfully transmitted bit for random forwarding agent placement with different transmission ranges

The signal energy used per successful bit for this scenario is shown in Figure 6.6. The energy consumed by 802.11 actually increases as the number of forwarding agents increase. This is because the cluster size decreases on average with the number of forwarding agents, but the non-power-controlled 802.11 protocol is not able to reduce its power to the size of the cluster distance to the forwarder. Although, PCMA's energy consumption decreases because the power is reduced as the average distance to the forwarding agent is reduced. Notice the energy consumed by both protocols changes at first dramatically because the average distance to the nearest forwarding agent decreases significantly as the first few are added, but the average distance to the forwarder decreases less significantly as the number of forwarders is further increased. For the last points the energy consumption decreases for both protocol (particularly those neglect the forwarding agents power consumption). This is due to the number of forwarding agents becoming a considerable number of the total sources such that the average hops decreases (see Figure 6.1) without changing the distance between forwarding agents, or forwarding agents and regular nodes. Therefore, the number of successful packets is increased without changing the average transmission power; thus, the energy per successful bit drops. The energy consumed for the random placement of forwarding agents is more than for the uniform case even though the distance between a node and its forwarding agent and between the forwarder agents is on average the same as the uniform case by the law of large numbers. This is because the random case does worse when the forwarders are spaced farther apart than average and does better when the forwarders are closer than average, but the combination of these two situations does not average out due to the gain being super-linear (a convex function).



Figure 6.7 Number of successfully transmitted packets per second for random forwarding agent placement with different transmissions ranges

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The throughput for the network with random placement of forwarding agents is shown in Figure 6.7. The throughput for this scenario drops as the number of forwarding agents are increased. The are several factors contributing to this. First, as the number of forwarding agents is increased, the cluster size decreases, and therefore, the number of nodes in the same cluster decreases. Also, the number of other clusters increases, so the a greater number of hops are required on average. In addition, the number of access points available for sending to other clusters is limited by the number of forwarding agents in range. Furthermore, as discussed in the uniform placement case, all the nodes in the cluster are contending with the forwarding agent such that the number of packets that can be sent to other clusters is limited by the nodes contending in the cluster. This effect becomes less significant as the number of nodes in the cluster decreases, but the dependence on the forwarding agent increases as the cluster size shrinks. These factors cause the throughput to continue to decrease with increasing number forwarders, until the case where the forwarders become a considerable number of the total nodes such that the average hops are suddenly reduced (see Figure 6.1).

The throughput of the random placement case is better than that of the uniform placement case because the average hops are considerably less as can be observed in Figure 6.1. If the number of hops were the same for both cases the uniform case would also do better in terms of throughput. Finally, we observe that power control provides the greatest benefits over non-power-controlled protocols when the distance between source and destination are least limited and the average number of hops are small.

6.3 Multihop Results Summary

This work evaluated the energy savings and throughput of power controlled protocols in multihop wireless packet networks. It was shown that there are extensive benefits in energy savings by utilizing both intermediate nodes (between source and destination) and a power-controlled protocol when sending between those hops. The throughput (capacity) was shown to increase when implementing power control though the throughput typically decrease as more intermediate hops are used between source and destination.

From this study it can be concluded that using power control can always provide benefits. However, using shorter range transmissions with a greater number of hops between source and destination will be most useful for devices with extensive power constraints, while for devices with less significant power constraints sending directly to the destination would be the best choice.

Using a logical infrastructure with designated forwarding agents sending packets between clusters on single shared wireless data channel will further limit the capacity as the number of clusters is increased. However, as discussed in Section 6.1, when the routing overhead is taken into account with mobility the capacity infrastructureless scenario may decrease more significantly than when specified forwarders are used. In addition, if forwarding agents can be utilized that do not have limited energy resources then the additional energy savings may further justify their use. Finally, when the position of the forwarding agents is not fixed or controllable by the network, it is less beneficial to use them unless the transmission power can be dynamically adjusted since the non-powercontrolled protocol's power cannot be adjusted off-line to extract the locality benefits in this case.

CHAPTER 7

TRAFFIC SHAPING IN MULTIHOP AD HOC NETWORKS

In this chapter we present our studies on the transport layer in ad hoc networks, along with our proposal for a new congestion control mechanism. We argue that these issues are particularly important when multihop power control is implemented on the lower layers because the flow of the traffic in different node neighborhoods can dictate how much spatial reuse can be truly exploited. The studies presented in this chapter are based on simulations on the ns2 simulator. This chapter is organized as follows. Section 7.1 introduces the problem of congestion control and presents some of the issues that arise at the transport layer, specifically due to the nature of the ad hoc networks. Section 7.2 presents several studies where the problems of the environment show up at the transport layer. Based on these studies, the new congestion control mechanism is designed and presented in Section 7.3, followed by performance evaluation of our proposal in Section 7.4. Section 7.5 concludes the chapter with pointers to future research.

7.1 Introduction

The congestion control issues deal with controlling the number of packets entering the network in order to avoid congestion at intermediate hops. For congestion control in wired networks, the Transmission Control Protocol (TCP) [25] was designed assuming very low random packet loss probability (up to 1%). In addition to performing congestion control, TCP also provides reliable data delivery.

In an ad hoc network, the channel is a broadcast medium and hence is shared among devices. The shared nature of the medium and the mobility of nodes cause heavy contention and large variations in the available bandwidth. These properties of the channel in ad hoc networks, along with the increasing bandwidth requirements of wireless applications, have instigated research on the transport layer in the recent years.

To deal specifically with the problem of frequent link breakages in ad hoc networks, several TCP enhancements have been proposed [26, 27, 28, 29, 30]. However, there are other issues left unaddressed by TCP and TCP-based mechanisms, leading to their performance (throughput and fairness) limitations in ad hoc networks, which are summarized below.

• Large RTO¹ values: Link failures are frequent and happen either due to the nodes moving out of range of each other, or due to heavy contention which is perceived as a link breakage on repeated failures to deliver a packet. These breakages lead to route failures which then result in frequent route recomputations. As different routes may have different round trip times (RTTs), measurements of RTT on different routes result in large variance in its estimate, resulting in large RTO values (the formula is usually written RTO = $(\overline{rtt}) + 4 \times \Delta(rtt))$. Variance in RTT is also caused by large variations in available bandwidth due to poor channel characteristics as well as changing neighborhood and, therefore, contention in neighborhood arising due to mobility. These large RTO values cause the TCP sender to stall transmission for long periods of time upon timeouts.

¹Retransmission time out.

- TCP's ACK-clocked nature: The congestion control mechanism of TCP uses the reception of acknowledgments as a trigger to send more data. Therefore, TCP is said to be ACK-clocked. Thus, the forward traffic for flows that have heavy contention in the ACK path will be affected, even though the forward path may not have any contention. Moreover, TCP flows that have the same data and ACK paths may be affected as follows. Because the MAC layer (IEEE 802.11) requires all nodes within one hop of a sender-receiver pair to remain silent for the duration of transmission, the contention characteristics of the forward and the reverse channels between two nodes are similar. As a result, heavy contention in the forward path also causes heavy contention for the ACKs in the reverse path, and thus, the flows are further penalized.
- Effect on whole flow due to bandwidth variations: The shared nature of the medium, and mobility of nodes causes varying levels of contention, resulting in large variations in the available bandwidth. A flow is only able to send as many packets from source to destination as the slowest link can maintain. TCP adapts the source rate based on end-to-end throughput information. This rate adjustment information can take a considerable amount of time to propagate back to the source. Therefore, TCP will not keep up with the variations in the slowest link's available bandwidth, thus resulting in the loss of packets as the bandwidth of the slowest link decreases, and an underutilization of the network resources as the bandwidth of the slowest link increases, causing a reduction in throughput.

To study these problems, we present performance studies of TCP on various ad hoc networks. For all of our simulation studies, we have used the ns2 [31] simulator and its ad hoc extensions provided by the Monarch [22] research group at Carnegie Mellon University. Like related work on transport layer in ad hoc networks [26, 27, 30], we have also used the dynamic source routing (DSR) [32] protocol for routing in our simulations. Our tests are based on static as well as mobile scenarios. The version of TCP used for our studies is TCP-Reno since it is the transport protocol most widely deployed in current systems. The packet size used is 1460 bytes of data. The raw channel bandwidth is 2 Mb/s and the transmission range of the nodes is 250 m. The random *waypoint model* is used for mobility that has two key parameters namely the maximum speed and the pause time. In this model, every node picks up a random point in the given area and then moves to that point with a speed uniformly distributed between zero and a given maximum speed. After reaching that point, it pauses for a given pause time and then repeats the process by choosing another random destination. Several experiments are based on a network of 50 nodes in a 1500 by 300 m area with a pause time of 0 and a maximum speed of 20 m/s. Note that this particular network is never disconnected, and hence, there is always a route between any pair of nodes.

Based on these studies, we propose and evaluate a congestion control mechanism which uses hop-by-hop rate control with back-pressure, and addresses the problems mentioned above. Performing rate control prevents packet bursts, which requires larger buffer sizes and also leads to unfairness among flows. The back-pressure component of our mechanism, ensures that upstream nodes do not overwhelm the downstream nodes. Our congestion control algorithm also includes the explicit link failure notification (ELFN) [26] mechanism, which was originally proposed as an enhancement to TCP for ad hoc networks. Based on studies on the ns2 simulator, we show that our protocol has higher efficiency compared to the ELFN-enhanced TCP² under various network loads.

²We will refer to it as TCP+ELFN in the rest of this thesis.

7.2 Limitations of Existing Congestion Control Mechanisms

The current proposals for congestion control in ad hoc networks [26, 27, 28, 29, 30] attempt to alleviate the problem arising due to frequent link failures by extending TCP. In Section 7.1 we presented various reasons for the limitations of protocols based on TCP. This section further elaborates the claim by presenting simulation studies of TCP, and an enhanced version of TCP (TCP+ELFN).

The ELFN approach requires the sender to freeze the TCP state (congestion window, timers, and RTT estimate) upon reception of a link failure notification. This message is originated upon a link failure and sent to senders that are using the link. Once in the frozen state, the sender periodically ([26] suggests a time interval of 2 s) probes the receiver until a full handshake is completed between the sender and the receiver, indicating the existence of a valid route. Upon a successful handshake, the sender leaves the frozen state and resumes normal TCP functionality. This proposal also bears similarities with several other proposals such as the TCP-F approach [29] and the bad state notification approach [30]. Thus, study of ELFN-enhanced TCP gives insight into these enhancements and also brings out limitations inherent to TCP-based approaches. Our congestion control protocol (described in Section 7.3) is designed based on studies of the limitations of TCP, though it also incorporates ideas similar to these enhancements.

The high level description of the set of experiments performed, along with the key observations, are as follows:

- The inter-TCP problem: In this experiment, the aim is to characterize the behavior
- of a sequence of one hop TCP and best-effort³ flows. The network is a chain of 3 All best-effort flows used in our studies are backlogged flows; i.e., they always have data to send.

20 nodes, with adjacent pairs separated by the transmission range. For best-effort flows, we observed that every fourth one-hop flow had a considerably large data delivery, and for TCP flows this effect was even more pronounced. Studies using the best-effort flows isolate the behavior for all the layers up to, but not including, the congestion control layer. Contrasting these studies with TCP studies clearly isolates the effect of the TCP layer. Based on these studies, we find that the ACK clocking mechanism of TCP may cause heavy unfairness among TCP flows.

• *Relay problem:* The MAC 802.11 protocol prohibits nodes within one transmission range of the sender and the receiver of an ongoing transmission from participating in any transmission or reception. Furthermore, the range for which a transmission can cause interference at other nodes is usually larger than the transmission range; that is, the interference range is more than twice the transmission range in the ad hoc extensions to the ns2 simulator, which are based on the specifications of the Lucent WaveLAN 2Mbps IEEE 802.11 card [33]. This means that only a few (characterized later) hops on a multihop flow could be involved in transmission at the same time. Thus, contention induced by packets of the same flow is a typical characteristic specific to the ad hoc environment. We have observed that in case of multihop flows beyond 6 hops, the throughput for best-effort or TCP flows drops to about $\frac{1}{7}$ th of that for a one hop flow. The relevance of rate control for multihop flows has been depicted by an experiment with a 10 hop best-effort flow with varying sending rates. The received data rate peaks for a certain sending rate, and the peak is about 25% higher than the case where data is sent at the fastest possible rate. This shows that sending at the appropriate rate will result in high throughput.

- Fairness issues: We study the end-to-end behavior of TCP+ELFN, which gives a user's perspective of the effect of congestion control mechanism. End-to-end behavior is studied by analyzing the sequence number progression for multiple flows. We bring out several fairness issues for multiple flows in static as well as dynamic networks. In several scenarios, some flows do not get any service from the network. The extreme unfairness toward certain flows is attributed to the inadequacy of end-to-end mechanisms for the ad hoc environment. This study thus motivates the use of hop-by-hop rate-control-based mechanisms for congestion control in ad hoc networks.
- Network buffers: We study the behavior of TCP+ELFN from the network's perspective. Study of network buffers gives an understanding of the protocol from the network's perspective. The network buffers need to be optimally occupied so as to avoid congestion, without resulting in underutilization of network resources. We study the behavior of TCP+ELFN flows, which do not have any mechanisms for buffer control at intermediate hops, but have end-to-end congestion control mechanisms. We bring out several queueing related issues for multiple flows in static as well as dynamic networks. We find that data might get stalled at intermediate nodes for prolonged intervals (tens of seconds) due to a significant number of routing packets, which have higher priority over data packets in our environment. Based on these studies we motivate our congestion control mechanism that uses hop-by-hop rate control.
- Comparison with best-effort traffic: This study is aimed towards characterizing the performance improvements that one may expect out of congestion controlled traffic, as opposed to best-effort traffic. We present studies on various scenarios

ranging from static to dynamic networks. We observe uniformly in all experiments, though to varying degrees, that using no congestion control is better than performing TCP's congestion control. This clearly shows that TCP's congestion control mechanisms, when applied to ad hoc networks, worsening the problems associated with congestion rather than solve them. Thus, new mechanisms are needed.

The following sections present these experiments in full detail and show various results that support the conclusions drawn in the above overview.

7.2.1 The inter-TCP problem

In this experiment, a sequence of 20 nodes was created, where the distance between adjacent nodes was set to be equivalent to the transmission range (250 m). Then 19 besteffort flows were initiated at the first 19 nodes, each sending to their adjacent node in the sequence, thus creating 19 one-hop flows in sequence. The number of packets received at each destination during a 100 s simulation is shown in Figure 7.1. We repeated the experiment with TCP flows in place of best-effort flows, and the results are shown in Figure 7.2.

In Figure 7.1, we find that about every fouth hop in the sequence has a high data delivery. The scenario is illustrated in Figure 7.3. If we analyze this scenario starting from node 1, we find that the transmission on the first hop (i.e., from node 1 to node 2) competes with the minimum number of flows (as there are no flows to its left). So the best-effort flow on the first hop has a higher chance to access the channel. The CTS and ACK from node 2 to node 1 for this transmission would cause node 3 to defer its transmission, as the RTS and DATA transmission from node 1 would cause enough interference at node 3 for it to reduce its channel access. Note that the interference region



Figure 7.1 Inter-TCP problem: 19 one-hop best-effort flows on a 20-hop sequence of nodes



Figure 7.2 Inter-BE (best-effort) problem: 19 one-hop best-effort flows on a 20-hop sequence of nodes



Figure 7.3 Inter-TCP problem: Effect of multiple one-hop flows

for a transmission is more than twice the transmission range in our simulator. Similarly, the interference caused by the CTS and ACK packets at node 4 would influence the flow from node 4 to node 5. As a result, the 1st hop shows better throughput compared to the next three hops. From the perspective of node 5, the scenario is very similar to node 1, as there is very little contention from the nodes to its left, and the same argument can be repeated to understand the peaking at about every fourth hop. Note that in Figure 7.1 the 9th and 11th hops have high best-effort delivery because of similar effects rippling from both ends of the sequence.

We observe a similar effect but even more pronounced in case of TCP flows (see Figure 7.2). Every fourth hop transmission has much higher throughput compared to other hops. The result is a combination of the effects of the MAC access pattern, as depicted in case of the best-effort flows, along with the ACK clocking mechanism of TCP. As a result of TCP being ACK clocked, the forward channel transmission depends also on the characteristics of the reverse channel. In ad hoc networks, the forward and reverse paths have similar characteristics when the flow traverses a single hop. For successful transmission in either direction (data packet or ACK) all transmissions within one hop of the source or destination have to be deferred. This results in every fourth hop having good forward and reverse channel characteristics and, hence, a much higher throughput compared to other hops. The lower forward data rate, as well as the lower ACK reception rate, doubly penalizes flows other than every fourth flow. Note that this behavior not only applies to this particular long chain scenario but will be a characteristic of networks with multiple one-hop or short flows. This shows that even barring the unfairness that exists due to MAC and the location dependent nature of the network (as captured by the studies using best-effort traffic), TCP's ACK-clocked nature can significantly worsen the unfairness.

7.2.2 The relay problem

For this study, we evaluated a simple network that consisted of a chain of nodes, where adjacent pairs were again separated by the transmission range. However, here a single flow was initiated over an increasing number of hops. Figure 7.4 shows how the throughput of a best-effort flow and that of a TCP flow decreases with an increasing number of hops, and then stabilizes after a certain point. A transmission on one hop can prohibit transmission in three to five other hops, which can be observed in Figure 7.5. As illustrated in the previous section, deferring transmissions due to overheard RTS/CTS packets and the interference caused by the data and the control packet transmissions prohibit simultaneous transmissions in a few neighboring hops. Thus, every fourth, fifth or sixth hop could be transmitting at the same time and therefore, the throughput for long chains should drop to between $\frac{1}{4}$ and $\frac{1}{6}$ of throughput for one hop flows. However,



Figure 7.4 Data delivery for single TCP and best-effort flow

all stations do not contend at the same time (are not synchronized) because the backoff



Figure 7.5 Relay Problem: Data transmission every fourth, fifth or sixth hop in a single multihop flow

values are randomized so the observed throughput for multihop transmissions is further reduced. We observe that compared to the throughput of a 1-hop flow, the 10-hop flow receives about $\frac{1}{7}$ of the bandwidth. The reduced throughput of a TCP flow compared to that of a best-effort flow is due to TCP ACKs occupying a portion of the channel bandwidth, in addition to the extra contention introduced by the reverse ACK traffic.

Figure 7.6 shows the result of a best-effort flow with different sending rates over a 10 hop sequence of nodes, where each adjacent node is separated by the transmission range. The curve with the unchanged MAC in Figure 7.6 shows that the receiving rate increases linearly with the sending rate, up to a data rate of about 25 packets/s, and then decreases to about 20 packets/s for sending rates of 40 packets/s and beyond. Since there are no other flows in the network, this clearly illustrates how a flow at very high rates contends with itself. Beyond a certain sending rate (40 packets/s), the receiving rate does not vary significantly, and only the first few nodes (about six as inferred from Figure 7.4) are

primarily involved in the intraflow contention, reducing the data rate enough for it to be sustainable by the remaining sequence of nodes. This study indicates the need for rate control, which can improve the throughput by as much as 25% for best-effort traffic in ad hoc networks.



Figure 7.6 Relay problem: Resetting the contention window

To alleviate the problem of reduced throughput due to intraflow contention, we propose a MAC-level enhancement. As described earlier, while contending for a channel after a successful transmission, the number of slots that a node defers for is based on a random value between zero and the contention window (cw). Hence, nodes with higher cw contend less aggressively. If a node can somehow learn that a packet being sent will be forwarded by the next hop, then it can contend less aggressively by using a higher value of cw than other nodes, thus providing the next hop with a greater greater probability of success. For a source routed packet, the routing information can be extracted and used to learn if the packet will be forwarded by the next hop node. Alternatively, the indication of whether the next hop needs to forward the packet can be sent in 1 bit of information in the MAC layer ACK from the next hop. We tried various values of cw when nodes decide to contend less aggressively. Three improvements are shown in Figure 7.6 that correspond to different *cw* settings for less aggressive contention. The figure shows that the technique of contending less aggressively when the next hop node is known to be contending improves the throughput, and this technique is not particularly sensitive to the exact *cw* value used by the forwarding node. This mechanism lowers the buffer length requirements at the intermediate nodes and reduces the end-to-end delay jitter by forwarding packets before they can be delayed through competition with preceding nodes sending packets corresponding to the same flow. Although we used the simple topology of a sequence of nodes to illustrate the relay problem, this problem also appears in more complex topologies because the node will always compete with at least the immediate next hop for a given flow.

7.2.3 Comparison with best-effort traffic

This study is aimed towards understanding the performance improvements that one may expect out of congestion controlled traffic as opposed to best-effort traffic. We study the performance of TCP+ELFN under the following scenarios:

- Static network with background traffic: We observe that the performance of TCP+ELFN is better than that of TCP, but best-effort delivery is even higher than that of TCP+ELFN.
- Dynamic network with no background traffic: Once again, the TCP+ELFN is better that than of TCP, but best-effort delivery is much higher.
- Dynamic network with background traffic: TCP+ELFN performs slightly worse than TCP, but best-effort delivery is still higher than TCP delivery.

We observe that for many scenarios TCP and TCP+ELFN are worse than best-effort traffic in terms of delivery. This shows the inadequacy of TCP and TCP enhancements such as TCP+ELFN that restrict the number of packets sent over a given time period based on end-to-end feedback information, that is frequently outdated. These studies are presented in detail in the remaining section.

7.2.3.1 Static network with background traffic

We evaluated the performance of TCP+ELFN, TCP and best-effort flows with three different experiments implemented in the ns2 simulator and run for 100 s. Each of the above flows are tested in a static network with background traffic generated by two best-effort flows. Figure 7.7 shows the sequence number sent for TCP and TCP+ELFN flows. In addition, the figure confirms that the source has a valid route for the duration of the simulation. As expected, the performance of TCP+ELFN is better than TCP (about twice in this case). Note that in this scenario, there is no mobility but the congestion caused by the background traffic results in transmission failures which are mistakenly interpreted as link failures. TCP+ELFN stops sending packets during these heavy congestion periods and hence can improve on the total throughput. When we have a best-effort flow running between the same hosts with the same offered load, we observe that the best-effort receiver can receive 2871 packets. This is significantly more than TCP+ELFN, which can send less than 400 packets, demonstrating that the congestion control mechanisms of TCP-type methods actually worsen the situation rather than improve it. Therefore, TCP's end-to-end congestion control method is not suited for the ad hoc environment.



Figure 7.7 Performance of TCP+ELFN and TCP flows in a static network with background traffic

7.2.3.2 Dynamic network with no background traffic

Figure 7.8 shows the results of running best-effort and TCP+ELFN flows together at the same source-destination pair for a 1500 by 300 m scenario with 50 nodes, each having a pause time of 0 and a maximum speed of 20 m/s. Similarly, Figure 7.9 presents the results for another pair of end hosts. Note that the lower slope of the best-effort curve indicates that it does not overwhelm the MAC layer, blocking the TCP+ELFN traffic. We observe that the performance of the best-effort flow is better than TCP+ELFN in both cases. Once again, the total number of packets delivered to the destination is more for best-effort than for TCP+ELFN. This indicates that the inadequacy of TCP+ELFN's congestion control mechanism.

The throughput graphs presented in Figures 7.10 and 7.11 are for the same experiments as presented in Figures 7.8 and 7.9, but with TCP flows in place of TCP+ELFN flows. This again shows that TCP does considerably worse than the simple best-effort flow for an ad hoc networks. If we look at Figure 7.8 we see that TCP attempts to send a large number of packets within a small period of time. It then retransmits several



Figure 7.8 Mobility: TCP+ELFN and best-effort flows between 2 nodes in a 50-node network where the best-effort receiver receives a total of 609 packets



Figure 7.9 Mobility: TCP+ELFN and best-effort flows between 2 nodes in a 50-node network where best-effort receiver receives a total of 645 packets



Figure 7.10 Mobility: TCP flow between 2 nodes in a 50-node network where the CBR receiver receives a total of 146 packets



Figure 7.11 Mobility: TCP flow between 2 nodes in a 50-node network where the CBR receiver receives a total of 610 packets

packets many times, causing its backoff timer to increase. The flow can then send a small number of additional packets for the remaining simulation time, even though the source has a valid route for the majority of the simulation. The significant number of packets sent for the initial phase of the simulation causes congestion, and the periodic outages (where a new route needs to be computed from the source) causes TCP backoff multiplicatively. These effects in concert cause TCP to perform particularly bad for this case. Note that for the same case (Figure 7.8), TCP+ELFN does considerably better by freezing its backoff timers and periodic probing for a valid path. This allows it to contend more aggressively when the channel conditions (connectivity) allow, however it still performs worse than the simple best-effort traffic flow as shown above.

For the dynamic scenarios with no background traffic, we also studied the RTO values. In Section 7.1, we presented the reasons that large RTO values can result in the ad hoc environment. Figure 7.12 and Figure 7.13 show the RTO values corresponding to Figures 7.10 and 7.11. RTO values of 20s are not uncommon in these scenarios, which leads to stalling of the TCP sessions upon timeouts. This results in a low observed throughput, as shown in Figures 7.10 and 7.11, due to TCP under-utilizing the network resources.

7.2.3.3 Dynamic network with background traffic

We tested the performance of TCP+ELFN, TCP, and best-effort flows in three different experiments of 100 s with background traffic of two best-effort flows in a 50-node network, each having a maximum speed of 20 m/s and pause time of 0. Figure 7.14 shows the sent sequence number for TCP and TCP+ELFN. The performance of TCP+ELFN is slightly worse than TCP in this case. For the best-effort flow, we obtained a total data



Figure 7.12 Mobility: RTO values corresponding to Figure 7.10



Figure 7.13 Mobility: RTO values corresponding to Figure 7.11

delivery of 1736 packets, which is again considerably greater than the number of packets delivered for TCP+ELFN, further confirming that TCP-based congestion control is not well suited for the ad hoc environment.



Figure 7.14 Performance of TCP+ELFN and TCP flows in a dynamic network with background traffic

7.2.4 Network buffers

As discussed in Section 7.1, the amount of buffering in the network affects the RTT and RTO estimates, which in turn affects the period of timeouts and thus, the network throughput of TCP connections. Studying the network buffers also helps in understanding the conditions that cause buffer overflows. This can lead to improved protocol designs and may in some cases justify the need for provisioning more buffer space at nodes. We study network buffers for both static and dynamic scenarios. These scenarios consist of 50 nodes randomly placed in a 1500 by 300 m area. The mobility model for the dynamic scenario has a maximum speed of 20 m/s and a pause time of 0. For all simulations presented in this section, 10 TCP flows between randomly chosen source and destination pairs were simulated.

In the *ns2* simulator, separate prioritized MAC queues are maintained for various packet types with highest to lowest priority queues being routing, real-time, low-delay, and normal packets. A packet is selected from a queue only when its higher-priority queues are empty. For our simulations, the real-time queue was not used. The routing packets (DSR in our case) are stored in the routing queue, ACK packets are considered low-delay, and address resolution protocol (ARP) and TCP data packets are classified as normal packets. The graphs presented in this section show only the routing and the normal queues (labeled the data queue for the figures), where the routing queue has higher precedence. The maximum queue size is 50 for all queues.

Figure 7.15 shows the routing and normal queue sizes of the intermediate node with highest average normal queue size for a static network. In this figure, the queue sizes never exceed the maximum capacity because the routing packets arrive in short, infrequent bursts. Note that even for static networks, routing packets are generated during data transmission as a result of extensive packet delays (for reasons such as contention caused by different packets from the same flow or different flows competing at neighboring nodes), causing nodes to assume link breakages. The static case shows that the network can



Figure 7.15 Routing and normal queues during a simulation of a 1500 by 300 m static network with 50 nodes and 10 flows



Figure 7.16 Routing and normal queues during a simulation of a 1500 by 300 m mobile network with 50 nodes and 10 flows

handle the traffic level without congestion or packet drops. A similar result is presented for the dynamic scenario in Figure 7.16. Although the graph corresponds to an ad hoc network that is always connected, the routing and normal queues are filled for a considerable period of the simulation because of congestion, contention, and changes in node connectivity. Note that the number of packets in the normal queue continues to grow as long as routing packets are present and are not dequeued until no routing packets remain. The fact that the static network can handle these 10 flows without causing overflow at any node in the network indicates that it is mobility that causes congestion as a result of link breakages and significant routing overhead. High mobility of nodes causes frequent route disruptions, resulting in large numbers of routing packets, which force the TCP packets to reside in the network buffers for significant periods of time. This, in turn, causes many timeouts, followed retransmissions that waste network resources. Therefore, intelligent management of queues is even more critical for mobile networks, where data packets can be significantly delayed or dropped due to changes in network configuration, than in static networks. To reduce the incidences of queue overflows, congestion control mechanisms are needed that avoid bursting of packets and adapt more quickly to the changes in the channel conditions incurred by mobility. Unlike TCP, mechanisms based on rate control do not burst out packets and keep the buffer size low. Further, varying the transmission rate at the individual nodes composing a flow based to changes in link quality at intermediate hops can allow for faster adaptation avoiding buffer overflow. A method that incorporates both of these approaches is introduced in Section 7.3. However, we first look at fairness issues associated with competing flows.

7.2.5 Fairness issues

In wireless networks, users frequently receive an unfair allocation of system resources due to one node taking control of the channel or one flow reducing its congestion window, thus allowing another to maintain a larger window and send more packets. This problem was demonstrated in TCP [34] and will also be present in TCP+ELFN because it also relies on a similar congestion window method for controlling packet transmissions. Here, we study fairness properties for static and dynamic scenarios. Both of these scenarios consist of 50 nodes randomly placed on a 1500 by 300 m area. The mobility model for the dynamic scenario has a maximum speed of 20 m/s and pause time of 0. For all simulations presented in this section, 10 TCP flows were initiated between randomly chosen source and destination pairs.

In Figures 7.17 and 7.18 the sequence number progression is shown for a static and dynamic network, respectively. The figures show only the two flows receiving the highest and the two receiving the lowest service from the network. They demonstrate that in a mobile network with multiple flows, the throughput can be significantly different for

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Figure 7.17 Packet sequence numbers for a simulation of a 1500 by 300 m static network with 50 nodes and 10 flows (only two best and two worst shown)



Figure 7.18 Packet sequence number for a simulation of a 1500 by 300 m mobile network with 50 nodes and 10 flows (only two best and two worst shown)

competing flows. This is particularly evident when comparing short range flows (those requiring only a few hops like flow 1) to longer range flows (those requiring a larger number of hops like flow 4). The short range flows have fewer timeouts and a larger congestion window causing them to contend more aggressively. In the static figure, flow 1 (requiring one hop) sends significantly more packets than flow 4 (requiring five hops) as a result of short range flows contending more aggressively, which causes longer range flows to backoff and further reduce their contention window. Here both flows 3 and 4 require only one hop between source and destination; however, their performance is substantially below that of flow 1 because they reside in an area of the network where a greater number of nodes are competing for the channel. Noting that the graph corresponding to the dynamic network is always connected. We see that flow 1 (requiring one hop on average) sends considerably more packets than flow 4 (requiring four hops on average). Even if we take into account the fact that multiple flows are contending, we have observed that both TCP+ELFN and TCP result in an unfair network resource distribution due

to the congestion at intermediate hops. Notice that in the mobile case, flows 2, 3, and 4 maintain the same level for some periods during the simulation while ELFN freezes the TCP timers and sends probe packets in search of a valid route. In all these studies we observe that large bursts from one flow can cause other flows to assume congestion and backoff. Mechanisms based on rate control attempt to avoid bursts of data and, therefore, would be more suited for ad hoc environments.

7.3 Our Congestion Control Mechanism

In this section we first present an overview of our congestion control mechanism followed by a detailed description of the rate control component.

7.3.1 Overview

In wireless multihop mobile networks, packets must often be relayed by many intermediate nodes to reach their final destination. The capacity of the links connecting these intermediate nodes can vary greatly. This may result in queue overflows at some of the nodes along the path if the capacity of an incoming link is greater than that of an outgoing link. This problem is further compounded by multiple source-destination pairs sending packets simultaneously over intersecting paths such that some of the nodes become bottlenecks (points of congestion). Most current methods for handling congestion rely on end-to-end flow control. However, due to the slow response in rate adjustments of end-to-end protocols in reacting to congestion, many packets will be dropped by intermediate nodes. Implementing rate control at each hop, on the other hand, can reduce the response time and prevent dropping packets that have already traversed multiple hops. These methods are referred to as *back-pressure based*, since they require feedback to relieve the downstream congestion.

Our congestion control algorithm is based on hop-by-hop rate control with backpressure. Here, every node maintains an outgoing rate for every flow (defined by a source-destination pair) passing through it. The sending rates are adaptively adjusted for each node traversed by a flow. These rates are updated every epoch (a constant time interval chosen off-line), based on a rate control algorithm that will be described in detail later in this section. The rate control uses two metrics, namely the number of packets received during the epoch, and the number of packets successfully transmitted to the next hop during the epoch. These two metrics are used to perform a variant of LIMD (linear increase multiplicative decrease) to update the sending rates for each flow at each node. Nodes have per-flow queues. Every node informs the upstream node (with respect to a particular flow) of its outgoing rate by piggybacking on the MAC layer ACKs corresponding to a packet sent from the upstream node. To ensure that a node does not overwhelm the downstream node, the rate of a flow is never allowed to exceed the outgoing rate of the downstream node. Similar to the proposed ELFN [26, 27] mechanism, we also use explicit link failure notification to avoid sending any data in the network for the period during which the route is known to be broken. Various components of our congestion control mechanism are described as follows:

• Rate control: As discussed in Section 7.2, bursting packets into the network may cause reduced throughput and unfairness, which we observed for TCP-based mechanisms. From the perspective of the network, bursting leads to large buffer requirements and causes high and variable RTT, which results in large RTO estimates. This means that TCP estimates the round trip time to be larger than it actually

is such that it takes even longer to adjust to changes in available rate (based on network conditions). We also studied the unfairness can result due to a few flows congesting the network because of their bursty nature. Rate control paces out packets and, therefore, avoids large RTO estimates and unfairness observed due to TCP's bursty nature. g

- Hop-by-hop: Our proposed mechanism maintains rates at every hop for a flow. Hop-by-hop rate control, thus attempts to do rate control in the network, as opposed to end-to-end. Based on studies summarized in Section 7.2, hop-by-hop is preferred mainly for three reasons. First, end-to-end mechanisms such as TCP have fairness problems due to their inability to control the flows at the intermediate hops. Second, bursty channel access patterns may cause queues to become very large in the network, even though the TCP flows are controlled in an end-to-end fashion. Third, in end-to-end mechanisms, the control information has to travel all the way to the source before the rate can be updated. However hop-by-hop mechanisms are more responsive since the previous hop needs to update the rate rather than the end host.
- Back-pressure: The information about congestion is propagated back towards the source by piggybacking the outgoing rate on the ACK corresponding to packets received from the upstream node. This is used to detect incipient congestion and ensures that a node never gets overwhelmed by packets from the upstream node.
- Explicit link failure notification (ELFN) [26]: This mechanism was originally proposed as an enhancement to TCP when used in ad hoc networks in order to handle packet losses due to link failures. ELFN prevents the sender from reacting to losses

due to link failures. Also, it does not allow the sender to start using a route until it has been verified to be correct. These properties make it very useful for scenarios where link breakages due to mobility are frequent. The original proposal suggested its use with TCP, but in Section 7.2 we discussed several limitations of TCP-based mechanisms for ad hoc networks.

We adapt ELFN to work with our congestion control mechanism. When a link failure is observed while forwarding a data packet, an explicit link failure notification message (may be same as route error message in DSR [32]) is generated and sent back to the source. Upon receiving of a route failure notification message, the flow is frozen (rate is set to zero) at the transport as well as the link layer, and the sender enters a *standby* mode. In the *standby* state, the sender sends out a probe packet every 2 s, which is the unacknowledged packet with the lowest sequence number. On receiving of an ACK for a probe packet (the probe packet and the corresponding ACK are specially marked), the source leaves the standby mode, sets the rate to the values it had before freezing, and resumes normal operation.

 In-band signaling: Introducing extra packets can add to the congestion in ad hoc networks, which already have considerably limited network resources. So the protocol was designed so as to not require any extra signaling packets.⁴ The MAC layer DATA and the ACK packets for a flow are used to piggyback congestion control related signaling information for updating the rates at the intermediate nodes.

There is, however, a design issue related to rate control that require further investigation. Maintenance of per-flow state at every hop is expensive in terms of memory

⁴Note that reliability mechanisms usually require end-to-end acknowledgments; however, we are focusing on congestion control mechanisms in this dissertation.

requirements. Mechanisms not requiring per-flow state, such as mechanisms based on per neighbor state need further study.

7.3.2 Rate control algorithm

The rate control algorithm is executed at the end of every epoch for each flow passing through a node. The rate may also change on reception of MAC layer ACKs containing the outgoing rate of a downstream node. If the current rate (at the node receiving the ACK) exceeds the downstream node's outgoing rate, then the rate is reduced to match that of the bottleneck node downstream.

We now present the pseudo code shown in Figure 7.19 that relates to the backpressure algorithm discussed above that controls the outgoing rate of intermediate hops in a flow based on local and downstream state information. Lines 1 through 8 describe the flow specific state that is maintained at every node. The expressions $recv_f$ and $sent_f$ represent the number of successfully received and successfully sent packets for flow f in the current epoch. The expression $recv_f$ is measured based on the number of incoming packets for the flow which are stored in the queue during the current epoch. The expression $sent_f$ represents the number of packets successfully delivered at the next hop during the current epoch. The successful queueing of the packet is represented by a 1-bit flag in the MAC layer ACK. On reception of the flag on the ACK, the $sent_f$ value is incremented by 1 and is reset at beginning of every epoch. Thus, when the link is congested or the next hop queue does not have available space, the number of successfully sent packets does not increase. We show how the algorithm uses this information later in the algorithm. The term r_f is the flow's computed rate. The terms r_up_f and r_down_f are the rates of the upstream and the downstream nodes respectively. The variable inc_f represents
1 Variables at each node per flow f: 2 // # packets received during epoch recv_f 3 $sent_{f}$ // # packets sent during epoch 4 // sending rate r_{f} // Upstream node's outgoing rate 5 $r_u p_f$ $r_{down_{f}}$ // Downstream node's outgoing rate 6 7 $inc_f \leftarrow \alpha //$ Additive amount to increase rate by 8 $dec_f \leftarrow \beta$ // Multiplicative factor to decrease by 9 At the end of each epoch: 10 foreach $f \in \{flows traversing this node\}$ $exp_pkts_f \leftarrow \min\{recv_f, r_f \times epoch_interval\}$ 11 12 $if(recv_f = 0)$ 13 Do not change r_f 14 else if $(send_f \approx exp_pkts_f)$ 15 $r_f \leftarrow \min\{r_down_f, r_f + inc_f\}$ 16 $dec_f \leftarrow \beta$ 17 else 18 $r_f \leftarrow \min\{r_down_f, r_f \times (1 - dec_f)\}$ 19 $dec_f \leftarrow \min\{\beta_{max}, 2 \times dec_f\}$ 20 On receiving a MAC layer DATA packet: 21 Extract $r_u p_f$ from ACK packet 22 if $(r_u p_f)$ is much lower than r_f 23 $inc_f \leftarrow 0$ 24 else 25 $inc_f \leftarrow \alpha$ 26 On receiving a MAC layer ACK packet: 27 Extract r_down_f from ACK packet 28 $r_f \leftarrow \min\{r_down_f, r_f\}$

Figure 7.19 Pseudo code for backpressure algorthm

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the increment step that can take two possible values: zero or a constant α . The initial values of the rates at every hop are set by the first data packet on a route after route (re)computation. As described in Section 7.2, the throughput of a TCP connection goes down with increasing number of hops. We use this ideal throughput to initialize the rates based on the length of the route. Lines 9 through 19 describe how this rate is updated based on the rate control algorithm. At the end of an epoch, the rates of all the flows passing through the node are updated. Based on the duration and the rate of a flow, the expected number of outgoing packets is computed, which cannot exceed the number of packets received (line 11). There is no reason to update the rate if there were no received packets in the epoch (line 12). If the number of packets sent out is almost same as the number of packets expected to have been served from the flow, then the flow can probe for more bandwidth, but the rate should not exceed the downstream node's rate (line 15). Otherwise, the rate is decreased by a multiplicative factor dec_f (line 18). In order to achieve higher throughput efficiency than TCP, which drops outgoing rate by 50% on observing losses, we start with a more genial decrease factor (lines 8 and 16). However, reduction of rate in successive epochs is an indication of sustained congestion, which is handled by doubling the decrease factor dec_f (line 19) up to a certain maximum value (typically 0.5).

In case the upstream node has a very low rate compared to the node's current outgoing rate, further increase in r_f is of no use. Furthermore, if the rate is much higher than the upstream node, then it may burst out packets rather than pacing them out. So for low values of upstream node's outgoing rate, we set the probe parameter inc_f to 0 instead of the constant α (lines 22 through 25). Similarly the downstream node's rate is extracted from every MAC layer ACK, and the rate is constrained by the downstream node's rate (lines 26 through 28) in order to avoid overwhelming the downstream node.

7.4 Performance Evaluation

We compare the performance of our congestion control mechanism with TCP and TCP+ELFN. Congestion control is concerned with *how many* rather than *which* packets are transmitted. So we implemented our congestion control mechanism using best-effort sources that always have data to send. To be fair to TCP's congestion control measurements, we introduced dummy acknowledgment packets in our best-effort mechanism, and for TCP, we measured the total number of packets received at the destination rather than the largest packet sequence number. Thus, duplicate packets were counted as separate packets. We study the progression of the number of packets received at the destination, for all the three congestion control mechanisms for the following scenarios:

• Static network: Linear sequence of nodes: To understand the behavior of the three mechanisms, we first studied this simple network consisting of 10 nodes in a sequence, with adjacent nodes separated by the transmission range. There were two flows, one from node 1 to node 10 and another from node 2 to node 9. In the case of TCP (see Figure 7.20), the flow with fewer hops takes over the resources for most of the time and the other flow goes through several timeouts. There is large unfairness between the two flows. In the case of TCP+ELFN (Figure 7.21), the unfairness is reduced. The fewer-hop flow enters the frozen state multiple times due to failed transmission of data packets, which are mistakenly assumed to be indications of link failures. The other flow attempts to take over the channel during

those brief time periods, thus reducing the unfairness gap. However, the combined efficiency of the two flows is reduced compared to that of TCP. For rate-controlled flows (Figure 7.22), the results show improved fairness compared to Figures 7.20 and 7.20. The total throughput is also close to that of TCP.



Figure 7.20 Static 9-hop sequence of nodes with two TCP flows



Figure 7.21 Static 9-hop sequence of nodes with two TCP+ELFN flows



Figure 7.22 Static 9-hop sequence of nodes with two rate-controlled flows

• Static Network with 50 nodes: For this scenario, we took 50 nodes randomly placed in a 1500 by 300 m area with no mobility. Figure 7.23 shows the throughput for

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two TCP flows in this scenario. We observe that one TCP flow stalls for a long period of time. As described above, transmission failures indicate false link failures, which cause packet drops. These packet drops may cause timeouts and stall the TCP sender, while the other TCP flows take over the channel completely. This problem is avoided by TCP+ELFN (Figure 7.24), as the TCP sender does not react to losses resulting from link failures. We observe similar net throughput, and highly improved fairness properties in this case. In addition, using rate control (Figure 7.25), we are able to further improve the total throughput at the cost of slight unfairness, though the throughput of the individual flows is higher than that of TCP+ELFN.



Figure 7.23 Static 50-node 1500 by 300 m network with two TCP flows



Figure 7.24 Static 50-node 1500 by 300 m network with two TCP+ELFN flows

• Dynamic network with 50 nodes: To test the performance our protocol under mobility we took 50 nodes in 1500 by 300 m area with maximum speed of 20 m/s and 0 pause time. Once again we studied two flows for a period of 100s. For TCP flows (Figure 7.26), we observe high unfairness resulting due to one flow taking over the channel completely and the other flow stalling for long periods of time. The total



Figure 7.25 Static 50-node 1500 by 300 m network with two rate-controlled flows

throughput is improved in case of TCP+ELFN (Figure 7.27). Although only one flow is able to transmit and the other flow is able to transmit only few packets. Thus, the fairness worsens in case of TCP+ELFN, though with an improvement in net throughput. Figure 7.28 shows improved fairness properties between the two flows when rate control is employed. The net throughput of the two flows is, however, close to that of TCP.

Thus, we see that our protocol has better fairness properties compared to the congestion control mechanisms of TCP and TCP+ELFN in various scenarios. In static scenarios, we also improve the total throughput. However, the combined throughput in dynamic scenarios is slightly reduced.

7.5 Conclusions

The problem of congestion control deals with controlling the number of packets entering the network so as to avoid congestion. For congestion control in wired networks, the



Figure 7.26 Dynamic (20 m/s) 50node 1500 by 300 m network with two TCP flows



Figure 7.27 Dynamic (20 m/s) 50node 1500 by 300 m network with two TCP+ELFN flows



Figure 7.28 Dynamic (20 m/s) 50node 1500 by 300 m network with 2 rate-controlled flows

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transmission control protocol (TCP) [25] was designed assuming very low random packet loss probability (up to 1%). In an ad hoc network, the channel is a broadcast medium and, hence, is shared among many devices. The shared nature of the medium and mobility of nodes cause heavy contention and large variations in the available bandwidth. These properties of the channel in ad hoc networks cause the TCP sender to maintain slow transmission rates. The ACK-clocked nature of TCP is also shown to be bad for such environments. Further, large RTO values (due to reasons related to the dynamic nature of the network as explained in Section 7.1) maintained by TCP senders in these scenarios affect the performance of TCP flows by reducing the protocol's ability to adapt to changes in the network. We study these behaviors of TCP using the ns2 simulator.

In an attempt to solve these problems experienced by TCP in this environemnt, we proposed and evaluated a congestion control mechanism based on hop-by-hop rate control with back-pressure. Based on studies on the *ns2* simulator, we show that our protocol has better fairness properties compared to the congestion control mechanisms of TCP and TCP+ELFN in various scenarios. In static scenarios, we also demonstrated a considerable improvement in the total throughput. However, the combined throughput in dynamic scenarios is slightly reduced. This may be overcome by adding a short signaling message to the MAC that conveys congestion information without waiting for a data packet to be sent from the upstream node so that it can be piggybacked on the ACK. This will allow a congested node to immediately notify an upstream node to slow its rate. Regardeless, further studies are needed to provide a complete congestion avaidance method for ad hoc networks. However, such work is outside the scope of this thesis so we proceed discuss some of the implementation issues of the approaches defined through this research.

CHAPTER 8

IMPLEMENTATION ISSUES

In this section, some of the issues pertaining to implementing the protocols and methods proposed in this dissertation are reviewed. Here we discuss several pertinent issues relating to the design and implementation of PCMA. The first implementation issue is some of the limitations of power control protocols, including determining the initial power level to reach the destination and collision avoidance of ACKs in the RPTS-APTS-DATA-ACK handshake. The second issue deals with a set of design choices for enabling PCMA to operate robustly in the presence of diverse channel conditions. Next a generic air interface is shown that would support the needs of PCMA to demonstrate the complexity and feasibility of implementing a mobile node with PCMA. Finally, the ability of PCMA to coexist with 802.11 is investigated.

8.1 Limitations of Power-Controlled Protocols

In this section, two issues pertaining to the control sequence in power-controlled MAC protocols for shared access mobile networks are investigated. The first issue is that before doing an initial handshake with the destination, the source does not know the amount of power needed to reach the destination and, therefore, does not know how long it should backoff. The second issue is protecting the ACK from collision at the source.

8.1.1 Initial transmission power level

As mentioned in Section 4.3, power-controlled protocols provide some initial biasing toward short range source-destination pairs in the contention process under high network loads. The reason specified was that the upper power bound (calculated from the busy tone pulses sent by neighboring receivers) becomes smaller as the load is increased. As load increases there are more active transmitters that will expose the receivers to more background noise such that they can tolerate less power from new transmitters, reducing the power bound. This reduces that probability that a source requiring a significant amount of power to reach its destination will be able avoid collisions with other receivers, and still send with enough power to reach its destination. Therefore, these hosts will be forced to backoff with a greater probability.

An addition problem associated with the current PCMA backoff mechanism that also has an impact on the fairness is that after sending an RPTS at most seven times the MAC layer gives up sending that packet. It is then up to the transport layer to decide what to do with the packet, in which case the transport layer may decide to make another send request to the MAC or go onto the next packet, depending on the type of application. Backing off and retransmitting at the transport layer adds delay to the transmission. The problem here is that the source does not know the amount of power needed to reach its destination before the successful completion of a control handshake (RPTS/APTS exchange). PCMA's approach is to send the packet just below that allowed by the current transmission power upper bound (see Section 3.2). As a result, when the source times out after sending a RPTS because it did not receiver a corresponding APTS, it does not know which of the following occurred:

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- The destination is out of maximum transmission range and a new route should be computed.
- The destination does not respond in order to avoid colliding with another transmission, so the source should try back after the completion of the transmission.
- The current power the RPTS is sent with is not enough to reach the destination, and the source should wait until a larger floor size can be acquired (a greater transmission power is allowed).

The first two problems are also present in non-power-controlled collision avoidance networks protocols, but the last is particular to power-controlled collision avoidance protocols. One method to overcome this may be to place the initial control packets involved in the handshake (RPTS, APTS) on a separate control channel such that the maximum power can be used to send the RPTS so that we can then disregard the last point. However, to make this approach reasonable, the control channel would have to take up significantly less spectrum than the data channel, but this means the control packets would take considerably longer to send, significantly delaying the transmission of the data packet. To overcome this the RPTS packet could be sent before the end of the current data transmission such that the data is not delayed. However, if the there are collisions (as often happens when the network is heavily loaded), the RPTS/APTS transmission could still cause considerable delays to the start of the the data packet transmission.

Another approach would be to incorporate a more sophisticated backoff mechanism into power-controlled MAC protocols, one that not only uses a multiplicative increase in time for the backoff but also waits for some change in available floor size. PCMA currently used a backoff mechanism similar to 802.11. While this simple backoff mechanism does not prevent PCMA from demonstrating considerable improvements, its limitations can be improved with a more sophisticated backoff method that utilizes both an increasing time window and changes in power constraints as mechanisms for dictating the duration of the MAC backoff.

8.1.2 Collision suppression of acknowledgment

The lack of protection of acknowledgments in PCMA leads to some interesting issues. The lack of protection of acknowledgments is due to two key issues listed below that are part of the PCMA approach and a problem in power-controlled protocols in general:

- Recall that busy tones are the mechanism for achieving power-control-based collision avoidance, and that only receivers advertise busy tones. There is no mechanism at the transmitter to notify other transmitters of the amount of power required to avoid collision with the returning ACK from the receiver. The PCMA methods utilizes busy tone pulses to notify transmitters of the noise tolerance at the destination receiving the data packet, but no such mechanism is provided at source for the ACK.
- When a sender initiates an RPTS, it can send the receiver its noise level so that the receiver knows the minimum power with which it must transmit the APTS to reach the sender (see Section 3.2). However, after the transmitter has finished transmitting the data packet, at what power must the receiver send back an acknowledgment? The old noise level at the sender may be outdated. On the other hand, in PCMA the source does not monitor its channel noise and reconvey it to the destination at the end of the data packet because it is very difficult to do carrier sensing when transmitting in wireless channels. In PCMA, the receiver sends the

ACK packet at the same power level as the APTS packet (subject to its current power bound), but this does not guarantee collision-free reception of the ACK.

It turns out that protection of the ACK is a fundamental problem in a power controlled MAC and is not merely an artifact of the PCMA design. Our engineering solution is to piggyback ACKs in subsequent APTS/RPTS packets when possible and also to execute a RPTS/ACK handshake in response to a retransmit request by the sender because of a lost ACK. This will allow the destination to respond with an ACK instead of an APTS if the corresponding data backet was already received.

8.2 Channel Design Issues

This section continues to investigate some of the design issues presented in Section 2.2 and outlines additional problems associated with sending on the busy tone channel while receiving a data signal. Our approach to these engineering issues is then presented.

The coherence bandwidth determines how far apart two channels can be and still experience similar gains. Therefore, to ensure that the gain on the data and busy tone channels are similar, or at least somehow proportional, the busy tone frequency components must be within the coherence bandwidth of the data channel. The coherence bandwidth is inversely proportional to the multipath delay spread, which may vary greatly depending on the environment. In many outdoor environments the delay spread can be greater than 1 μ s resulting in a coherence bandwidth of less than 1 MHz [12, 15]. This effect dictates the maximum channel spacing. However, there is also an additional problem that imposes minimal channel spacing constraints on channels used for simultaneously transmitting and receiving from the same device. This occurs because of the

finite transmit and receive isolation provided by the practical duplexer [35, 36]. The problem is that a reasonably priced duplexer, which is used to separate the transmitted and received signals, cannot prevent all of the transmitted energy from entering the receiver. This scenario is depicted in Figure 8.1, where a node is receiving a data packet on the data channel and simultaneously sending busy tone pulses on the busy tone channel. This would not be a problem if the transmitter and receiver filters were designed with ideal filters that sharply cutoff any energy outside the desired bands. However, such components would drive the price of mobile devices to unreasonable levels, so the filters found in most mobile devices have a much slower cutoff (allowing several MHz to fully attenuate the signals outside the desired frequency range) [37]. Also the power amplifier that boost the signal power before it is sent on the channel can introduce some nonlinear effects that cause additional energy to leak outside of the desired spectrum [38]. Mobile phone designers overcome this problem by placing a large gap in frequency between the up and down link channels. The typical rule of thumb is to separate the transmit and receive frequencies by about 5% of the nominal RF frequency, so that the duplexer can provide sufficient isolation while being inexpensive to manufacture [12]. However, spacing the busy tone and data channel by this much frequency spectrum is not acceptable for PCMA because it would place the busy tone channel far outside of the coherence bandwidth of the data channel. A final problem is that for efficient bandwidth usage it would be desirable to use a narrowband channel for the busy tone channel and a wideband for the data channel. However, frequency dependent fading will cause the gain function of such channel designs to differ more significantly.

One approach that would overcome these problems is placing both channels over the same frequency spectrum, but implement different codes for each channel (such as is done



Figure 8.1 Problems associated with simultaneously sending and receiving

in code-division multiple access (CDMA)) [39]. The data channel can be set up to use several codes while the busy tone channel uses just one. This will result in the busy tone pulse corrupting the data (due to the energy reflection and slight correlation between channel codes), but assuming the data has a sufficient amount of redundancy it can correct the errors. This is further simplified by the fact that the receiver knows the bit positions that may be corrupted by the busy tone transmission since it knows during what periods of data reception the packet was corrupted. Errors whose bit location are known are called *erasures*. For the most efficient codes (i.e., maximum-distance (MDS) codes like the Reed-Solomon code [40] used most cellular networks) only one bit of redundancy is required for each erasure to be corrected.



Figure 8.2 Air interface that supports PCMA

8.3 Air Interface Design

At this point we discuss the air interface design. Here the method discussed above that overcomes erasures with redundancy coding is used to implement busy tone. This, however, does not assume the use of any particular air interface. There are in fact many possible implementations of air interface that will satisfy these assumptions. Though to demonstrate the validity of the protocol and its assumptions a sample air interface is outlined.

Figure 8.2 shows a high-level schematic of an air interface that meets the requirements of PCMA. The outgoing data sent by PCMA is first sent into a Reed-Solomon encoder and then through a convolutional encoder. The data transmission power is set by PCMA, and the data is encoded and modulated by the direct sequence CDMA (DS-CDMA) encoder/modulator and then transmitted on the wireless medium. When a busy tone needs to be sent, the busy tone the Send_BT flag is set to 1 and the busy tone power level is set by PCMA to the appropriate level causing a busy tone pulse to be generated. The pulse is then sent through the modulator and broadcast on the wireless channel. When the busy tone is sent, the Send_BT flag indicates to the Reed-Solomon decoder in the receiver that the bit should be classified as an erasure. When data is received, it passes through the DS-CDMA demodulator/decoder, followed by the Viterbi decoder, and finally the Reed-Solomon decoder before being passed to PCMA. The data signal is taken from the combination of the correlated rake taps and the noise from an uncorrelated tap. These signals are then passed to a component (usually an integrator) that measures their power level and passes the corresponding values to PCMA. The busy tone input is demodulated and measured over the duration of a busy tone pulse. The maximum value observed over a time window W is then output to PCMA.

The protocol makes no requirement on the implementation of the lower layer only that it takes the information passed from PCMA to set the appropriate power levels and send busy tone signals, and send to PCMA the power levels of the received data, noise, and busy tone signals.

8.4 Interoperability With Existing Standards

In this section, the issue involving interoperability of power-controlled MAC protocols (namely, PCMA) with existing MAC protocols (namely, the current standard IEEE 802.11) are presented.

It is not difficult to make the power controlled MAC respect the existence (avoid collisions) of the non-power-controlled MAC. Although, 802.11 will not be as considerate to the the PCMA transmissions. We first show how PCMA can be designed to avoid most collisions with 802.11, and then show the problems associated with 802.11

avoiding collisions with PCMA. The node with the PCMA protocol can easily backoff for the duration of the transmission when it hears a RTS or CTS packet, or try again later when it hears a data transmission. Though the implementation must be able to decode the packet, it is not enough to be able to just detect the presence of a carrier for collision avoidance since the implementation must be able to understand the packet to know that it is an 802.11 transmission and not a PCMA transmission that would not preclude it from continuing to send a packet. This will slightly increase the number of collisions, but still allow 802.11 to operate reasonably well. The fundamental complexities of PCMA coexisting with 802.11 is that the existing 802.11 protocol dose not use the same collision avoidance mechanism. Further, it was shown in Section 1.2 that the current MAC protocol's collision avoidance mechanisms cannot be used to avoid collisions in a transmission power-controlled environment. The fundamental reason is because the current MAC protocols are unable to guaranteed the detection of (power-controlled) source-destination pairs that restrict their transmission range (as demonstrated in the example illustrated in Figure 1.6). Therefore, 802.11 would cause collisions with many PCMA transmissions that are not sent with enough power for 802.11 to hear it.

As a result of 802.11 not avoiding collisions with PCMA packets, it is unfortunately required that PCMA operate in a separate frequency spectrum from 802.11 and other non-power-controlled MAC protocols. As demonstrated in Section 1.2, this is a fundamental problem associated with all non-power-controlled MAC protocols preventing coexistence with power-controlled MAC protocols that fit within the collision avoidance framework (shared channel model).

8.5 Overview

The implementation issues addressed in this chapter present some of the major considerations that must be taken into account in order to make PCMA a complete working and implementable protocol. It is our belief that this discussion addressed these key implementation issues, and provides insight into various implementation approaches.

CHAPTER 9

RELATED WORK

In this chapter we we first present related work on transmission power control in wireless packet data networks networks and utilizing power control multihop ad hoc networks, followed by related work on transport layer design for ad hoc networks.

9.1 Transmission Power Control Protocols

This section outlines the previous work on controlling the transmission power control for improving for various performance improvements, primarily capacity and energy efficiency.

Past work on power control has primarily dealt with cellular networks, where separate frequency bands are typically allocated for uplink and downlink channels and base stations provide centralized control [1, 2]. This work has showed that power control can provide improvements in capacity [1] and fairness [41]. Distributed power control algorithms have also been presented [42, 43] in the sense that individual base stations control the power. However, these techniques still require the fundamental cellular configuration (mobile users communicate through base stations – centralized access).

Wu et al. [11] presented a power-controlled MAC protocol for ad hoc networks, where the dual busy tone multiple access (DBTMA) protocol framework introduced by Deng and Hass [13] was used as a basis for collision avoidance. The DBTMA algorithm uses a separate channel to send a fixed signal tone called a *busy tone*¹ that provided and additional collision avoidance mechanism eliminate certain cases where the 802.11 protocol would not prevent collisions. However, there are several fundamental design issues that are not addressed by DBTMA or the new power controlled version of it. Namely, the simultaneous sending of a busy tone and receiving of a data packet is not addressed, and based on the channel layout shown in [11] the busy tone would in fact corrupt the incoming data. Also the busy tones are solid tones instead of pulses, so there would be significant interference among busy tones observed from multiple transmitters or receivers. Further, since the busy tone pulses are a continuous signal sent from both transmitter and receiver for the duration of the data packet transmission, they will consume additional power from the system, reducing the battery lifetime of mobile devices. Other work has focused on the energy consumption associated with various MAC protocols [44]. In addition, [45] presented a joint power management and power control technique to extend battery life in portable devices.

The research presented here differs from related work in two significant ways:

- 1. Our focus is on wireless multiple access networks, where all nodes share a single channel and there is no centralized control or access.
- 2. We concentrate on transmission power control as a mechanism for jointly increasing channel efficiency and extending battery life.

¹Note that this busy tone is a continuous signal as opposed to a busy tone pulse used by PCMA. Also the busy tone used here was originally implemented as an additional "on-off" mechanism, and not "variably bounded" mechanism as PCMA uses its busy tone pulses.

9.2 Power Control in Multihop Wireless Ad Hoc Networks

In this section, related work is presented that provides energy savings in mobile devices and particularly those those that use transmission power control in multihop wireless ad hoc networks.

There are several power saving approaches for published in the past literature. Most of them deal with system level techniques for reducing the power consumption of particular devices. Examples of these system device optimizations include: disk drives [46, 47], CPUs [48, 49], and network interface cards [50, 51]

More recent work investigated the savings that can be exploited by scheduling at the MAC layer such that some of the communications components such as the receiver can be turned off for extended periods of time [51, 52, 53, 54]. Other techniques optimize the MAC contention method for particular operating conditions such as hidden terminal scenarios [55] and very low bit error rates [56]. Additional approaches adapt the channel coding and modulation according to the radio channel characteristics [57]. There are also techniques that control the length of the MAC packet based on the current channel conditions (bit error rate (BER)) [58]. Yet other techniques perform higher level approach by looking at the way nodes send packets. These approaches perform energy efficient tuning of TCP [59] and energy-aware routing in wireless packet networks [60].

However, researchers have only very recently started to investigate RF output power control as a method of reducing energy consumption in ad hoc networks. Some of this work has focused on topology control as a method of minimizing the transmit power of mobile such that connectivity is still guaranteed. In recent work by Ramanathan and Rosales-Hain [61], an algorithm is proposed that calculates the minimum power settings needed to for biconnectivity. Biconnectivity is where two paths exist between every source-destination pair, and it was shown that this method provides significant reliability over a connected graph (monoconnectivity). However, one issue to note is that this algorithm requires complete knowledge of all link gains. Other research by Wattenhofer et al. [62] proposes a distributed algorithm that makes local decisions to adjust the transmission power of nodes and to collectively guarantee global connectivity. However, this work assumes the presence of a power-controlled MAC that performs power control with collision avoidance.

Another area of RF output power control for energy savings is controlling the transmission power level and network topology for maximum lifetime of nodes [63, 64, 65].

All the above techniques describe methods that can provide energy savings for mobile devices in a wireless packet data network. However, the past work does not look at the impact of these techniques on the capacity of the wireless network as is done in this thesis. Furthermore, past work on reducing energy consumption of mobiles operating in an ad hoc wireless network have disregarded MAC issues such as collision avoidance which will further impact the performance of these techniques. This thesis defines and implements a power-controlled MAC (PCMA) and investigates the trade-offs in energy and capacity for various types of topologies and different transmission ranges.

9.3 Transport Layers for Wireless Networks

In this section, we present related work to our congestion control mechanism for ad hoc networks.

Some wireless TCP approaches try to use the existing features of TCP to take care of mobility and high error rates. Caceres and Iftode [66] proposed a mechanism based on fast retransmits. After the mobile registers with a new base station, it enters into the fast retransmit mode and also sends a signal to the other end to do the same. One of the ways this signaling can be done is by sending three duplicate ACKs. Similarly, the mobile TCP (M-TCP) [67] approach, which is based on the split connection approach, makes use of the persist mode of TCP. At the split point of the TCP connection (or proxy), ACK for all but the last byte is forwarded to the fixed host. On detection of a link failure, the TCP layer at the mobile is frozen. The proxy on receiving no ACKs from the mobile, advertises zero window along with the ACK for the last byte, thus putting the fixed host in persist mode. When the link is up, the proxy receives an ACK from the mobile, resulting in the proxy informing the true window and thus restarting TCP.

There are several similarities between the space communication environment and the mobile and wireless environments, such as link outage, high latency, varying RTT, data corruption etc. As a result, research on transport layers for satellite networks, is also relevant for our work. Durst et al. [68], propose space communications protocol standards transport protocol (SCPS-TP), a protocol for space communications, which has several mechanisms for enhancing TCP to counter the problems of data corruption, link asymmetry and limited bandwidth. The mechanisms include using Internet control message protocol (ICMP) messages to distinguish various losses, header compression, use of an efficient selective negative acknowledgment (SNACK) scheme, etc. Henderson and Katz [69] have proposed satellite transport protocol (STP) as a transport layer protocol for use over a satellite link to a mobile or over a link connecting two satellites. STP has a very low a reverse traffic because it is not clocked by ACKs from the receiver. Instead, the sender polls periodically to enquire about the status of the receiver's buffer. The sender can also send an unsolicited status update message to the sender. Our work on congestion control on ad hoc networks also borrows ideas from several related literature. TCP in multihop wireless networks have been studied by various researchers [26, 27, 28, 29, 30]. The approach proposed in [26, 30] is based on explicit link failure notifications. Gerla et al. [28] looked at the impact of the MAC protocol on the performance of ad hoc TCP. Chandran et al. [29] proposed a mechanism based on explicit route failure feedback and re-establishment messages called TCP-feedback.

Rate control using mechanisms such as back-pressure has been proposed by Pazos et al. in wired networks [70].

CHAPTER 10

CONCLUSIONS AND FUTURE WORK

This thesis demonstrates that implementing a transmission-power-controlled MAC in ad hoc wireless packet data networks will provide considerable benefits in capacity and energy savings. In addition, a power-controlled MAC (PCMA) was presented that fits within the collision-avoidance multiple access framework. The PCMA mechanisms for discovering the power needed to reach the intended destination and avoid collisions with other receivers were defined, and their effectiveness was tested with various network configurations. It was also demonstrated that PCMA overcomes the problem of both discovering the power level for a source to reach its destination and allowing the receiver to provide collision avoidance information to future transmitters in a nonintrusive manner (without causing a collision with other ongoing packets transmissions). It was shown that this is not possible with a simple extension to the current wireless MAC protocols. We have demonstrated that PCMA allows for a greater number of simultaneous senders than 802.11 by adapting the transmission power to be the minimum value required for a successful reception at the intended destination. This also reduces the average transmission power such that the power-controlled system also results in an improvement in energy savings.

Our performance results in Chapter 4 show that PCMA can achieve more than a two times improvement in aggregate throughput compared to 802.11 for dense mobile

networks and a 50% average reduction in transmission power. As the connectivity range is reduced, the aggregate throughput gain over 802.11 continues to increase, and the energy savings increases considerably. That is, PCMA continues to exploit spectral reuse when the source and destination pairs reside in various isolated regions (clusters) of the network. Several extensions were also proposed to PCMA, the first of which (those that are referred to as PCMA Methods 2 and 3) are designed to more fully exploit the spectral reuse by utilizing a range of available overcompensation levels. This would allow sources to contend who would not other wise be able to with a fixed overcompensation level, and provides the greatest signal quality level at the receiver that would prevent interference with other transmissions. It was shown that there is a trade-off in fairness for the increase in throughput provided by allowing the PCMA protocol to favor sources contending with less power (whose destinations are closer). To overcome some of these issues, an alternate method was introduced (PCMA Method 4) that improves the fairness by restricting the conditions under which a source can contend for the channel. However, this method also limits the protocols ability to fully exploit the network resources. This is a trade-off that must be evaluated based on the constraints of the applications employed in the mobile network. With overcompensation in transmission power, PCMA can be designed to degrade approximately the same as 802.11 under channel distortion. These results lead us to believe that if engineered correctly, PCMA can achieve significant performance gains without significant compromises in robustness, and hence provides a powerful motivation to migrate towards power-controlled MAC protocol standards.

It was further shown in Chapter 5.4 that utilizing additional intermediate hops between source and destination can provide more than an order of magnitude reduction in power consumption at the cost of giving up some throughput. For devices that are greatly limited in power reserves such as hand-held mobile devices, giving up some throughput for a significant gain in battery lifetime may be be an attractive trade-off, while for other devices, such as vehicles (where power is less of an issue), it may be desirable to reduce the number of hops. This work further evaluated the throughput and power consumption with different network topologies using differing number of hops between source and destination.

The results in Chapter 6.3 motivated shaping the network traffic by employing rate control at the individual hops to improve the speed of adapting to changes in the local environments, namely contention, congestion, and routing overhead (route recomputation and flooding). These changes in network conditions may take place more frequently in some areas of the network than in others. Therefore, a rate control algorithm was integrated into the intermediate hops (nodes) of each flow such that they can adapt to the changes as they occur in their area of the network. This method allows nodes upstream to quickly slow their rate with back-pressure information provided by the downstream nodes whose link rates change. These techniques avoid both buffer overflow and additional routing traffic from further congesting the link.

The power control MAC (PCMA) framework was extended to the the multihop wireless ad hoc scenario, but the routing was performed off-line to demonstrate the performance of PCMA, independent of the overhead of a particular routing protocols. Thus, we did not want to bias the performance results based on a particular type of routing protocol. However, past work has shown that the routing overhead in multihop wireless ad hoc networks can account for more than half of total packets sent in the network. Further, these routing packets must be sent over the entire transmission range such that the improvements in spectral reuse and energy savings of implementing power control would be less substantial. Therefore, it would be of interest in future work to investigate combining the routing protocol with a power-controlled MAC (such as PCMA) to evaluate under what conditions significant benefits can still be observed. This may also make PCMA Method 4 more attractive since a significant number of the packets are still sent over the maximum range. That is, we do not want to favor a few short-range transmissions over many longer-range transmissions. Another method that can be integrated into the routing layer to overcome some of these issues is topology control. This entails controlling the maximum transmission range that the MAC layer is allowed to transmit over based on the density of the network and location of neighboring nodes.

The work presented in this thesis provided considerable benefits in throughput and energy savings. However, as we discussed above, there are still many areas where future research can provide additional benefits of power control in a multihop wireless ad hoc network.

APPENDIX A

CHANNEL MODELS

In this section, the channel effects are outlined for different operating environments. The relationship between the channel characteristics and the resulting gain demonstrate the degradations that a MAC protocol may encounter.

Let G_{ij} be the gain between a source *i* and a destination *j*. In the Fresnel zone [12] the gain is proportional to $1/d^2$ (and we refer to it as the $1/d^2$ field) and is expressed as

$$G_{ij} = \left(\frac{A\lambda}{d_{ij}}\right)^2,\tag{A.1}$$

where A is a constant that accounts for the signal strength gains from the transmitter and receiver antennas, λ is the wavelength, and d_{ij} is the distance between nodes *i* and *j*. Outside the Fresnel zone the gain is proportional to $1/d^4$ (it is then referred to as the $1/d^4$ field) and is expressed as

$$G_{ij} = \frac{A}{d_{ij}^4}.\tag{A.2}$$

This is the two-ray ground reflection model (see [12, 14]) and is also the model used for the Carnegie Mellon University mobile extensions to the ns2 simulator [22]. At this point, we focus on the $1/d^4$ field since this is the area with the greatest amount of spectral reuse, and we generalize the path loss by a factor of 4 (the value typically used in most channel models) because α since this component can take on a range of 2-6 [12], depending on the environment. While this model is appropriate for flat and open areas, objects in the path between a transmitter and receiver may introduce additional interference such as shadowing [12, 14], which results in a log normal contribution to the gain to produce a slow fading model:

$$G_{ij} = \frac{A}{d_{ij}^{\alpha}} 10^{\zeta/10}, \tag{A.3}$$

which is referred to as log normal shadowing.

In addition to shadowing, the signals may follow multiple paths from source to destination, each with independent shadowing, from the transmitter to receiver. Each path will have an amplitude component that is typically modeled by a Rayleigh distributed (also called the *fast fading component*) and a uniformally distributed complex phase (i.e. $r \exp(j\Theta)$, where r is Rayleigh distributed and is uniformally distributed) [12, 14]. If we look at an M-ray (M paths) Rayleigh fading model, the resulting gain is then

$$G_{ij} = \left| \sum_{\rho=1}^{M} \frac{A}{d_{ij}^{(\rho)\alpha}} 10^{\zeta_{\rho}/10} r_{\rho} e^{j\Theta_{\rho}} \delta(t - \tau_{\rho}) \right|,$$
(A.4)

where $d_{ij}^{(\rho)}$ is the distances between nodes *i* and *j* following path ρ , and ζ_{ρ} , r_{ρ} , and Θ_{ρ} are random variables representing the shadowing, Rayleigh amplitude, and phase angles, respectively, for each path paths.

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