

**Energy-Efficient Routing and Control
Mechanisms for Wireless Ad Hoc Networks**

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ABSTRACT

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This thesis contributes toward the design of new network layer protocols for emerging wireless ad hoc networks based on a foundation of variable-range transmission control. Wireless ad hoc networks represent autonomous distributed systems that are infrastructureless, fully distributed and multihop in nature. The thesis begins by investigating some fundamental tradeoffs and performance limits of wireless ad hoc networks based on common-range transmission control. We show how an alternative approach that uses variable-range transmission control can improve the overall performance of the wireless network. The advantage of using variable-range transmission control is twofold. First, it can reduce the overall transmission power in the network, therefore, increasing the energy savings of wireless devices that are typically energy limited. Second, it can increase the traffic carrying capacity of these wireless networks in comparison to existing systems that are based on common-range transmission control.

More specifically, we study the impact of transmission power on the physical and network connectivity, network capacity, and power savings from a mathematical perspective. We make a number of fundamental contributions. First, we show that the use of variable-range transmission approaches achieve lower transmission power levels compared with the minimum transmission power levels that can be obtained by common-range transmission based routing protocols. Second, we show that a variable-range transmission policy can maintain constant per-node capacity

even when more nodes are added in a fixed area network. Third, we derive a model that approximates the signaling overhead of a routing protocol as a function of the transmission range and node mobility for both route discovery and route maintenance.

Based on the results and insights from the first part of the thesis we propose a network level routing scheme called *PARO*. We present the design, analysis and implementation of PARO, which represents a new approach to dynamic power controlled routing that helps to minimize the transmission power needed to forward packets between devices in wireless ad hoc networks. Using PARO, one or more intermediate nodes called “redirectors” elects to forward packets on behalf of source-destination pairs thus reducing the aggregate transmission power consumed by wireless devices. We use a combination of analysis, simulation and results from an experimental wireless testbed implementation of PARO to show the performance of our approach. We discuss the limitations of existing radio and MAC technology in realizing the initial goals of the protocol using off-the-shelf technology.

In the final part of the thesis we investigate the feasibility of supporting traditional QoS performance (e.g., bandwidth or delay assurances) in a network that is based on variable-range transmission control and PARO style routing protocols. Specifically, we study the impact of PARO on throughput and end-to-end delay and study its implementation for wireless ad hoc networks using IEEE 802.11 and an alternative power controlled multiple access scheme. We show the limitations of these MAC protocols under single and multihop operations. We then propose QoS enhancements to the original PARO protocol called QoS-PARO that builds new mechanisms into the original PARO system for a class of applications that wish to tradeoff better QoS performance for sub optimal power savings.

The thesis makes a number of important contributions towards the design of

large-scale energy conserving wireless ad hoc networks. While the thesis presents guidelines that govern the design of new protocols based on variable-range transmission control, the practical deployment of such systems is limited today. Significant advancements are needed before these systems can be realized particularly in the area of new radio and MAC layer protocols that can exploit this variable-range transmission design principle, and hence, provide better support for the new network layer mechanisms that are proposed in this study.

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Chapter 1

Introduction

1.1. Overview

While circuit based cellular networks are still the dominant player in the wireless arena as a revenue generator for vendors and carriers, emerging packet-based wireless systems are witnessing considerable attention in industry and academia. These emerging wireless technologies represent a significant departure from the design and operation of cellular systems and include wireless local area networks (WLANs) [80], personal area networks (PANs) [3] [4], wireless ad hoc networks [53] [28] [18], and wireless sensor networks [8].

The use of wireless LAN access is becoming a commodity in most corporations and educational institutions, extending Internet services to mobile users. In the public domain, new wireless Internet service providers (ISPs) sell WLAN connectivity to mobile subscribers equipped with WLAN radios for a monthly fee. Personal area networks are also seeing some action in the market after a number of years of standardization and development, allowing personal devices such as laptops, printers, cellular phones, and other devices in close proximity to communicate with each other, enhancing the capabilities of each device. Using PAN technology a cellular phone may communicate via wireless with a laptop to search a phone number

database. New radio modem technologies such as Bluetooth and HomeRF [4] enable short-range radio connectivity required in PAN networks. Solutions based on these radios are already available in the market. Wireless ad hoc networks allow mobile users to interact with each other in places where no infrastructure is available [40] [42]. These networks have seen considerable interest in academia recently with rising interest in commercial exploitation of the technology from the industry. Until recently their application has mainly been associated with military and emergency service sectors. Disaster recovery networks are also considering the use of rapid deployable wireless ad hoc networks in places where the installed infrastructure suddenly breaks down. Emerging peer-to-peer (P2P) data and media sharing applications are expected to move to wireless, creating wireless ad hoc networks on-the-fly [62]. Sensor networks are an active topic of research where small network-based sensor devices with limited radio capabilities allow humans to monitor their surrounding environment and, in some cases, modify it.

Effective transmission power control is a critical issue in the design and performance of these emerging wireless networks, including system design metrics such as physical connectivity, network connectivity and reachability, power-savings, and quality of service (QoS) (e.g., throughput, packet loss and delay). The manner in which each performance metric is affected by power control and the resulting interaction and interdependencies between these different system metrics is complex to model and understand. For example, transmitting with high power may improve the performance of the network layer by reducing the number of forwarding nodes, and therefore, the signaling overhead to maintain routes. However, such an approach is likely to negatively impact the performance of the medium access control (MAC) layer as wireless nodes experience more interference every time they attempt to transmit.

The use of power control has been used in cellular networks for a long time as a way to increase the number of simultaneous voice-calls that can be accommodated in the network. Systems based on CDMA technology, for example, use power control as the foundation in design and operation. Dynamic power control, however, has yet to be introduced in packet-oriented wireless networks such as wireless LANs, PANs, wireless ad hoc and sensor networks because its utility is still the object of research. A common approach taken in the design and operation of existing packet-based wireless networks [53] [14] [45] [51] is the use of a common-range (usually the maximum) transmission power in radio modems. This design choice has a tremendous impact on the design of network algorithms shaping the design and operation of the link, MAC, network and transport protocols.

Network solutions based on a common, maximum transmission range approach improve the physical connectivity of wireless networks. However, this goal is achieved at the expense of sacrificing network capacity and wasting precious transmission power in the network. We conjecture in this thesis that the existing design philosophy of favoring connectivity at the detriment of capacity, power conservation and QoS is limited and not a good foundation to build emerging wireless ad hoc networks. Rather, we argue in this thesis that a system designed on variable-range transmission power control is more suited to the needs of these emerging wireless ad hoc networks, and their devices and applications.

1.1.1 Variable-Range Transmission Control Issues

Switching from a common-range transmission design to a variable-range transmission design is not a straight forward transition, and in many cases requires a significant re-design of the operation of the system in order to gain better power-conserving performance over existing systems that are based on legacy common-range, maxi-

imum power control. In what follows, we discuss the impact of adopting variable-range transmission power control in wireless ad hoc networks from the perspectives of energy savings, physical connectivity, network connectivity, and QoS.

1.1.1.1 Energy Savings Issues

A critical design issue for future wireless ad hoc networks is the development of suitable communication architectures, protocols, and services that efficiently reduce power consumption thereby increasing the operational lifetime of network enabled wireless devices. If the transmission between the source and destination could be broken into a number of smaller hops, it would reduce the total transmitted power since wireless power increases with distance. Transmission power control used for communications impacts the operational lifetime of devices in different ways. For devices where the transmission power only accounts for a small percentage of the overall power consumed, (e.g., a wireless LAN radio attached to a notebook computer), reducing the transmission power may not significantly impact the device's operational lifetime. In contrast, for small computing/communication devices with built-in or attached radios (e.g., ad hoc nodes, sensors) reducing the transmission power may significantly extend the operational lifetime of a device, thus, enhancing the overall user experience.

1.1.1.2 Physical Layer Issues

Power control mainly affects the performance of the physical layer in two ways. First, power control impacts the traffic carrying capacity of the network. On the one hand, choosing too high a transmission power reduces the number of forwarding nodes needed to reach the intended destination, but creates excessive interference in a medium that is commonly shared. In contrast, choosing a lower transmission

power reduces the interference seen by potential transmitters but packets require more forwarding nodes to reach their intended destination. In [37] the authors show that, considering the physical layer only, reducing the transmission power is a better approach because this increases the traffic carrying capacity of the network (for more details refer to Chapter 2). Second, power control affects how connected the resulting network is. By a connected network we mean a network in which any node has a potential route of physical links (or forwarding nodes) to reach any intended receiver node in the network. A high transmission power increases the connectivity of the network by increasing the number of direct links seen by each node but this is at the expense of reducing network capacity.

1.1.1.3 Network Layer Issues

The design of routing protocols for wireless ad hoc networks is challenging [76]. Bandwidth and power resources available in wireless networks represent scarce resources. Similar to the physical layer, power control impacts the connectivity performance of the network layer. Choosing a high transmission power increases the connectivity of the network. Routing protocols can take advantage of highly connected networks to provide multiple routes for a given source-destination pair in cases where some nodes or links fail. However, this goal is achieved at the expense of reducing network capacity and energy-savings in the network. In addition, power control impacts the signaling overhead of routing protocols for mobile wireless ad hoc networks. Higher transmission power levels decrease the number of forwarding hops between source-destination pairs, therefore reducing the signaling load necessary to maintain routes when nodes are mobile. The signaling overhead of routing protocols may consume a significant percentage of the available resources at the network layer reducing the end user's bandwidth and power availability. This is compounded by

the fact that topology changes in wireless and mobile networks occur at a much faster time scale in comparison to wired networks. Thus, routing protocols should be capable of rapidly responding to these changes using minimum signaling and taking into account the power reserves distributed in wireless networks.

1.1.1.4 Quality of Service Issues

The main QoS tradeoff involved in wireless ad hoc networks based on variable-range transmission control is related to the average number of times a packet is forwarded versus the average number of interfering nodes per attempted transmission. This is the same tradeoff at the physical layer. In [37] it is shown that reducing the transmission range is a better solution in terms of increasing the traffic carrying capacity of a wireless ad hoc network. The analysis presented in [37] considers the physical capacity of the network only, and not, the inefficiencies of the MAC protocol being used to transport data on top of the physical network. Unfortunately, MAC protocols designed for shared medium wireless access are not appropriate for multihop wireless ad hoc operation [82]. In addition, in [37] the authors show that the end-to-end throughput available to each node is $O(\frac{1}{\sqrt{n}})$ for random traffic patterns using common-range transmission where n is the number of nodes. This result suggests that adding nodes to a fixed area network decreases the end-to-end throughput available to each node. This result puts severe limitations on the throughput available to mobile nodes in dense nodal areas.

1.1.2 Problem Statement

This thesis investigates the tradeoffs and performance limits of using common-range transmission and proposes new approaches in which variable-range transmission control can be used to improve the overall performance of wireless ad hoc networks.

The advantages of using variable-range transmission control are twofold:

- to reduce the total power transmitted in the network, therefore, increasing the energy savings of wireless devices that are typically energy limited; and,
- to increase the traffic carrying capacity of the network in comparison to existing systems that rely on a common-range transmission.

We argue in this thesis that the enhanced traffic carrying capacity and power-savings that can be achieved when using routing protocols based on variable-range transmission power control provides a suitable foundation for future wireless ad hoc networks where the connectivity of the network is not the only design concern. However, the design of routing protocols based on variable-range transmission power control requires significant advances to resolve the existing technical barriers.

1.1.3 Technical Barriers

Improving the energy-savings of energy limited wireless nodes by means of power control is dependent on the availability of new radios. New hardware needs to be designed for a model where the power consumption during the transmission mode is dominant and far outweighs the collective power consumption during the other radio operations such as reception, idle and sleep mode operations. Such radios do not exist today and are an open area of research [78]. Existing radio technology is limited in meeting the needs of variable-range transmission based systems. For example, a typical IEEE 802.11 radio has a power consumption of 1400mW in the transmission mode, 1000mW in the reception mode, 830mW in the idle mode, and 130mW during the sleep mode [77] [79]. Such a radio consumes as much power during reception and transmission modes, therefore is limited as a basis for building variable-range transmission based wireless systems, calling for advances in radio modem technology.

In terms of the physical and network connectivity of the network, reducing the transmission power in order to increase the capacity of the network presents several challenges. It is not possible to arbitrarily reduce the transmission power to any value to promote a higher capacity and energy savings in the network. Rather, there is a minimum bound for the transmission power necessary to avoid having network partitions [36]. This is a severe limitation because this minimum bound increases its value as the distribution of nodes in the network becomes less homogeneous. An ideal variable-range transmission based routing protocol should be able to transmit without any transmission power bounds. In addition, power control impacts the connectivity and signaling overhead of the routing protocol being used. Existing routing protocols discussed in the mobile ad hoc networks (MANET) working group of the IETF [53] are designed to use flooding techniques at maximum transmission power to discover routes. These protocols are optimized to minimize the number of hops between source-destination pairs so as to promote minimum end-to-end delay. Modifying existing MANET routing protocols to promote and support lower transmission power levels in order to increase network capacity, energy savings and throughput seen by applications, is a non-trivial problem. This is because the signaling overhead of the routing protocol increases when transmission power level decreases. Even the assumption that reducing the number of forwarding nodes minimizes end-to-end delays may not be true. This is specially the case in densely populated networks due to the excessive interference generated while transmitting at maximum transmission power. Because of these characteristics MANET routing protocols do not provide a suitable foundation for capacity-aware and power-aware routing in emerging wireless ad-hoc networks. As a result, there is a need to develop new routing approaches that take capacity and power savings into account as key design goals.

At the MAC layer, media access protocols designed with a common-range transmission requirement can not be migrated easily to a variable-range transmission environment without major modifications [23]. The fact that ad hoc networks have simply borrowed MAC protocols designed for wireless LAN operations propagates this limitation to wireless ad hoc networks. In fact, the IEEE 802.11 WLAN standard has become a de-facto standard for MAC operation in wireless ad hoc networks. The addition of power control is particularly challenging at the MAC level because of the presence of hidden terminals [55]. In general, nodes transmitting with lower transmission power levels may not be noticed by other nodes transmitting at higher transmission power levels, and as a result, collisions may be difficult to avoid. Recently, we have witnessed the emergence of new proposals in MAC design that address this limitation and attempt to take full advantage of the spectral reuse potential acquired when using dynamic power control [55] in this manner.

Commercial off-the-shelf packet radios usually have a discrete operational granularity (i.e., the number of transmission power levels available). This limitation may affect the performance every time the desired transmission power level is approximated to the best available power level at the radio modem. In addition, it is desirable that radio modems are capable of switching the transmission power level of the radio modem rapidly (i.e., in very short time). This is currently not the case [32]. This fast switchover speed is necessary because back-to-back packets in a queue may be destined to nodes requiring different transmission power values. Long switching delays would limit the throughput significantly.

1.2. Thesis Outline

In order to overcome the technical barriers discussed above, we propose the use of a combination of analytical modeling, simulation, and experimentation to best

understand the problem and solution space. The outline of our study is as follows.

1.2.1 Foundations

Chapter 2 sets out the mathematical foundations that govern the performance of variable-range transmission for wireless ad hoc systems. The results from this chapter guide the design of variable-range transmission based algorithms for wireless ad hoc networks. Specifically, results from Chapter 2 guide the design of the network layer routing solution presented in Chapter 3. In particular, we study the impact of transmission power control on the physical and network connectivity, network capacity and power savings in these networks from a mathematical perspective. We make a number of fundamental contributions. First, we show that use of variable-range transmission approaches achieve lower transmission power levels compared with the minimum transmission power levels that can be obtained using common-range transmission based routing protocols. This is an important result because it suggests that future routing protocols based on variable-range transmission power control can increase the traffic carrying capacity of wireless networks, and, at the same time, reduce the overall transmission power consumption by the network. Second, we derive a model that approximates the signaling overhead of a routing protocol as a function of the transmission range and node mobility for both route discovery and route maintenance. We show how routing protocols based on common-range transmission limit the capacity available to mobile nodes. The results presented in Chapter 2 highlight the need to design future network protocols (e.g., routing protocols) for wireless ad hoc networks based, not on common-range transmission which is prevalent today, but on variable-range transmission control.

1.2.2 New Routing Model

In Chapter 3, we present the design of *PARO*, a dynamic power controlled routing scheme that helps to minimize the transmission power needed to forward packets between wireless devices in ad hoc networks. Using *PARO*, one or more intermediate nodes called “redirectors” elects to forward packets on behalf of source-destination pairs thus reducing the aggregate transmission power consumed by wireless devices. *PARO* is applicable to a number of networking environments including wireless sensor networks, personal area networks and mobile ad hoc networks. *PARO* can also perform power optimization as a layer 2.5 routing technology operating below wide-area MANET routing protocols. We present the detailed design of *PARO* and evaluate the protocol using simulation and experimentation. We show through simulation that *PARO* is capable of outperforming traditional common-range transmission based routing protocols (e.g., MANET routing protocols) due to its energy conserving point-to-point on-demand design. We discuss our experiences from an implementation of the protocol in an experimental wireless testbed using off-the-shelf radio technology. The experimental results show that *PARO* can be partially implemented using off-the-shelf radio technology providing transmission power savings. However, the true potential of the approach is limited by the existing radio modem and MAC layer technologies that are available today.

The main goal of *PARO* is to reduce the overall transmission power in the network in a simple and scalable manner. Adding and removing redirectors to accomplish this goal, however, impacts traditional application-level QoS metrics such as throughput and end-to-end delay. Clearly, the introduction of one or more redirectors may have a negative impact on some of these metrics in CSMA/CA MACs (e.g., end-to-end delays). We first study this impact for IEEE 802.11 and the power controlled media access protocol (PCMAP) [55] and show the limitations of these MAC

protocols for single and multihop wireless operations. We then propose enhancements to the baseline PARO protocol introduced in Chapter 3, called *QoS-PARO*, which builds QoS mechanisms into the original PARO system for specific applications that wish to tradeoff better QoS performance for sub-optimal power-savings. QoS-PARO allows selected flows to add and remove redirectors from their paths in order to coarsely modify their observed application QoS performance or energy-savings. We present simulation results and show that QoS-PARO can be used to provide a coarse control over traditional QoS metrics (e.g., delay and throughput) and energy savings.

1.2.3 Thesis Contribution

The contribution of this thesis can be summarized as follows:

Our extension to Steele’s work [75] on the length of minimum spanning trees to compute the average range of links in variable-range transmission based wireless ad hoc networks is a fundamental contribution to the analysis and performance of wireless ad hoc networks.

Our model to compute the expected signaling overhead of routing protocols in mobile and wireless ad hoc networks as a function of the transmit power contributes to the design and analysis of routing protocols, respectively.

The PARO protocol presented in Chapter 3 is to the best of our knowledge the first practical implementation of a routing protocol based on variable-range transmission power control in wireless ad hoc networks that can operate efficiently at any transmission range. This model represents a significant departure from conventional approaches found in the literature.

The implementation of PARO in an experimental wireless testbed using off-the-shelf radios also represents the first realization of a wireless ad hoc network testbed

based on variable-range transmission power control.

The QoS-PARO formulation is the first proposal that uses variable-range transmission control as a means to obtain QoS differentiation in a multiclass system for wireless ad hoc networks.

Chapter 2

A Case for Variable-Range Transmission Power Control

2.1. Introduction

Effective transmission power control is a critical issue in the design and performance of wireless ad hoc networks. Today, the design of packet radios and protocols for wireless ad hoc networks are primarily based on common-range transmission control. For example, the design of routing and MAC protocols for wireless ad hoc networks use common-range maximum transmission power. In this chapter, we take an alternative approach and make a case for variable-range transmission control. We argue that variable-range transmission control should underpin the design of future wireless ad hoc networks, and not, common-range transmission control.

In this chapter, we investigate the tradeoffs and limits of using a common-range transmission approach and show how variable-range transmission control can improve the overall network performance [31]. We analyze the impact of power control on the connectivity at both the physical and network layers. We compare how routing protocols based on common-range and variable-range transmission control techniques impact a number of system performance metrics such as the connectiv-

ity, traffic carrying capacity, and power conserving properties of wireless ad hoc networks. The manner in which each of these performance metrics is affected by power control and the resulting interaction and interdependencies between these different system metrics is complex to model and understand. For example, transmitting with higher power may improve the performance of the network layer by reducing the number of forwarding nodes, and therefore, the signaling overhead to maintain routes. However, such an approach is likely to negatively impact the performance of the medium access control (MAC) layer as wireless nodes experience increased interference when they attempt to transmit.

Power control affects the performance of the physical layer in two ways. First, power control impacts the traffic carrying capacity of the network. On the one hand, choosing too high a transmission power reduces the number of forwarding nodes needed to reach the intended destination, but as mentioned above this creates excessive interference in a medium that is commonly shared. In contrast, choosing a lower transmission power reduces the interference seen by potential transmitters but packets require more forwarding nodes to reach their intended destination. In [37] the authors show that, when considering the physical layer only, reducing the transmission power is a better approach because this increases the traffic carrying capacity of the network. Second, power control affects how connected the resulting network is. By a connected network we mean a network in which any node has a potential route of physical links (or forwarding nodes) to reach any intended receiver node. A high transmission power increases the connectivity of the network by increasing the number of direct links seen by each node but this is at the expense of reducing network capacity. However, it is not possible to arbitrarily reduce the transmission power to any value to promote a higher capacity and energy savings. Rather, there is a minimum bound for the transmission power necessary to avoid

network partitions [36]. In [36], the authors assume that all nodes use the same common transmission power. This power is varied until a connected tree is constructed. In this chapter, we consider the use of variable-range transmission control to allow nodes to construct a minimum spanning tree (MST) [27]. We show that the use of a minimum spanning tree can lead toward lower total weight than a tree based on common-range transmission links that minimally avoid network partitions.

The type of power control used can also impact the connectivity and performance of the network layer. Choosing a higher transmission power increases the connectivity of the network. Routing protocols can take advantage of highly connected networks to provide multiple routes for a given source-destination pair in cases where some nodes or links fail [70]. However, this goal is achieved at the expense of reducing network capacity and energy-savings. In addition, power control impacts the signaling overhead of routing protocols used in mobile wireless ad hoc networks. Higher transmission power decreases the number of forwarding hops between source-destination pairs, therefore reducing the signaling load necessary to maintain routes when nodes are mobile. The signaling overhead of routing protocols can consume a significant percentage of the available resources at the network layer reducing the end user's bandwidth and power availability. This is compounded by the fact that topology changes in wireless and mobile networks occur at a much faster time scales in comparison to wired networks. Thus, routing protocols should be capable of rapidly responding to these changes using minimal signaling and taking into account the power reserves distributed in wireless networks.

Existing routing protocols discussed in the mobile ad hoc networks (MANET) working group of the IETF [53] are designed to discover routes using flooding techniques at common-range maximum transmission power. These protocols are optimized to minimize the number of hops between source-destination pairs, promoting

minimum end-to-end delay. Delivering data packets using a “minimum-hop route”, however, requires more transmission power to reach the destination, and reduces the network capacity compared to an alternative approach that uses lower transmission power levels. MANET routing protocols [17] discover unknown routes using high power to reduce both the signaling overhead and to make sure routing information is entirely flooded in the network. This increases the physical connectivity of nodes in MANET-based wireless ad hoc networks. Such a design philosophy favors connectivity to the potential detriment of potential power-savings and available capacity. Even the assumption that reducing the number of forwarding nodes minimizes end-to-end delays may not hold true in reality. This is certainly the case in densely populated wireless ad hoc networks due to the excessive interference generated while always transmitting at maximum transmission power.

Systems based on common-range transmission control [53] usually assume homogeneously distributed nodes. Such a regime, however, raises a number of concerns and is an impractical assumption in real networks. For some nodes the topology will be too sparse with the risk of having network partitions. For other nodes the topology will be too dense resulting in many nodes competing for transmission in a shared medium. This problem is discussed in [67] where the authors propose a method to control the transmission power levels in order to control the network topology, (e.g., to avoid a topology that is either too sparse or too dense). The work in [67] is concerned with controlling the connectivity of the network, and ignores the routing and traffic-carrying capacity aspects of the problem.

Modifying existing MANET routing protocols to promote lower transmission power levels in order to increase network capacity and potentially higher throughput seen by applications, is not a trivial nor viable solution. For example, lowering the common transmission power forces MANET routing protocols to generate a

prohibitive amount of signaling overhead to maintain routes in the presence of node mobility. Similarly, it is not possible to reduce the common transmission power to any value. There is a minimum transmission power beyond which nodes may become disconnected from other nodes in the network. Because of these characteristics MANET routing protocols do not provide a suitable foundation for capacity-aware and power-aware routing in emerging wireless ad-hoc networks.

In this chapter we set out the mathematical foundations that govern the performance of new routing protocols based on variable-range transmission control. The specific contributions of this chapter are as follows. We show that use of variable-range transmission approaches achieve lower transmission power levels compared with the power levels obtained using common-range transmission approaches. This is an important result because it suggests that variable-range transmission based routing protocols can increase the traffic carrying capacity of wireless ad hoc network, and at the same time, reduce the overall transmission power consumption in the network. We show that for the specific case of random node distributions in the wireless ad hoc networks, the power level transmissions in common-range transmission based routing protocols is approximately twice the average power level transmissions found in variable-range transmission based routing protocols for similar routes.

Another important result is related to the network layer. We derive expressions to compute the signaling generated by the route-discovery and maintenance phases of an ideal common-range transmission on-demand routing protocol akin to MANET routing protocols, which have been widely researched over the last several years. We show that in contrast to static networks where the minimum transmission power achieves the best performance, for mobile networks there is an optimum transmission range, not necessarily the minimum, which maximizes the capacity available to

nodes in the presence of node mobility. Finally we show how routing protocols based on common-range transmission limit the available capacity to mobile nodes.

The main contribution of this chapter is that it confirms the need to study, design, implement and analyze new routing protocols based on variable-range transmission approaches that can exploit the theoretical power savings and improved capacity indicated by the results presented in this chapter. In the next chapter we take up this challenge and propose a new routing protocol based on dynamic power control called PARO.

The structure of this chapter is as follows. Section 2.2. studies the impact of power control on the physical layer. In Section 2.3., we extend our analysis to the network layer and consider mobility. In particular, we investigate and model the signaling overhead of a common-range transmission based routing protocol considering both route discovery and route maintenance. In Section 2.4., we present numerical examples to further analyze the models derived in Sections 2.2. and 2.3.. Section 2.5. discusses our results and their implication on the design of future protocols for wireless ad hoc networks. Finally, we present related work in Section 2.6. and some concluding remarks in Section 2.7.

2.2. Physical Connectivity

We represent a wireless ad hoc network as a graph as a means to discuss several results of interest. Consider a graph M with a vertex (e.g., node) set $V = \{x_1, x_2, \dots, x_n\}$ and edge (e.g., link) set $E = \{(x_i, x_j)\} : 1 \leq j \leq n \text{ for } x_i \in \mathbb{R}^d, 1 \leq i \leq n^1$. Here the length of an edge $e = (x_i, x_j) \in E$ is denoted by $|e|$, where $|e| = |x_i - x_j|$ equals the Euclidean distance from x_i to x_j .

¹In this chapter we will indistinctly use edge or link, as well as vertex or node

Vertices or nodes in M are allowed to use different transmission power levels P to communicate with other nodes in their neighborhood, $P_{min} \leq P \leq P_{max}$. Connectivity from node x_i transmitting at power P_i to node x_j exists, if and only if $S_j > S_0$, (e.g., the received power at node x_j is above a minimum threshold value S_0). An edge or link connecting node x_i with node x_j can be uni-directional or bi-directional depending on whether or not connectivity exists in only one or in both directions. In this chapter we model the received signal using a traditional decay function of the transmitted power, e.g., $S_j \sim \frac{P_i}{|x_i - x_j|^\alpha}$ [59], where $2 \leq \alpha \leq 4$. It is important to note that more elaborate propagation models [59] can also be incorporated without modifying the applicability and accuracy of the analysis and results that follow. In the rest of the chapter we will use transmission range rather than transmission power for convenience.

Definition: A *route or walk* from node u to node v is an alternating sequence of nodes and links, representing a continuous traversal from node u to node v .

Definition: A graph M is connected if for every pair of nodes u and v there is a walk from u to v .

Definition: The transmission range of node i transmitting with power P_i , denoted R_i , is the maximum distance from node i where connectivity with another node exists.

Definition: The common transmission range of nodes transmitting with a common transmission power P_{com} , denoted R_{com} , is the maximum distance where two nodes can communicate with each other.

2.2.1 Common-range Transmission Control

We analyze the case where all nodes use a *common* transmission range (R_{com}) to communicate with peer nodes in the network. This case is of particular importance

because a common transmission range approach is the foundation of most routing protocols in ad hoc networks [64] [65] [43]. Figure 2-1 (a)(b)(c) illustrates an example of the resulting graph for different common transmission power values. The dotted circles in Figure 2-1(a)(b)(c) correspond to the transmission range of the transmission by each node.

Definition: A graph M is k - *edge* connected if M is connected and every node has at least k links (i.e., $k_v(M) > k$).

The connectivity measure $k_v(M)$ indicates the ability of the network to retain connections among its nodes after some links or nodes are removed. The larger the common transmission range is, the larger the parameter $k_v(M)$, and therefore the more connected the resulting graph.

A high $k_v(M)$ value may be desired from a certain point of view because it provides the graph with several alternative routes in case some edges come down due to nodes powering down, node's movement or links facing severe fading conditions. However, a high level of connectivity may create too much interference for simultaneous transmissions with the resulting channel contention and delays associated with it. Thus, it seems reasonable to reduce the common transmission range to allow for space/frequency-reuse in the network, hence reducing the number of contending/interfering nodes per attempted transmission.

Reducing the common transmission range, however, needs careful examination. It is not possible to arbitrarily reduce R_{com} to any value in order to maintain a connected graph. Rather, there is a lower bound of R_{com} , R_{com}^{min} , that is needed to maintain the connected graph.

Definition: The minimum common transmissions range, denoted R_{com}^{min} is the minimum value of R_{com} that maintains a connected graph.

This bound depends on the density and distribution of nodes in the network.

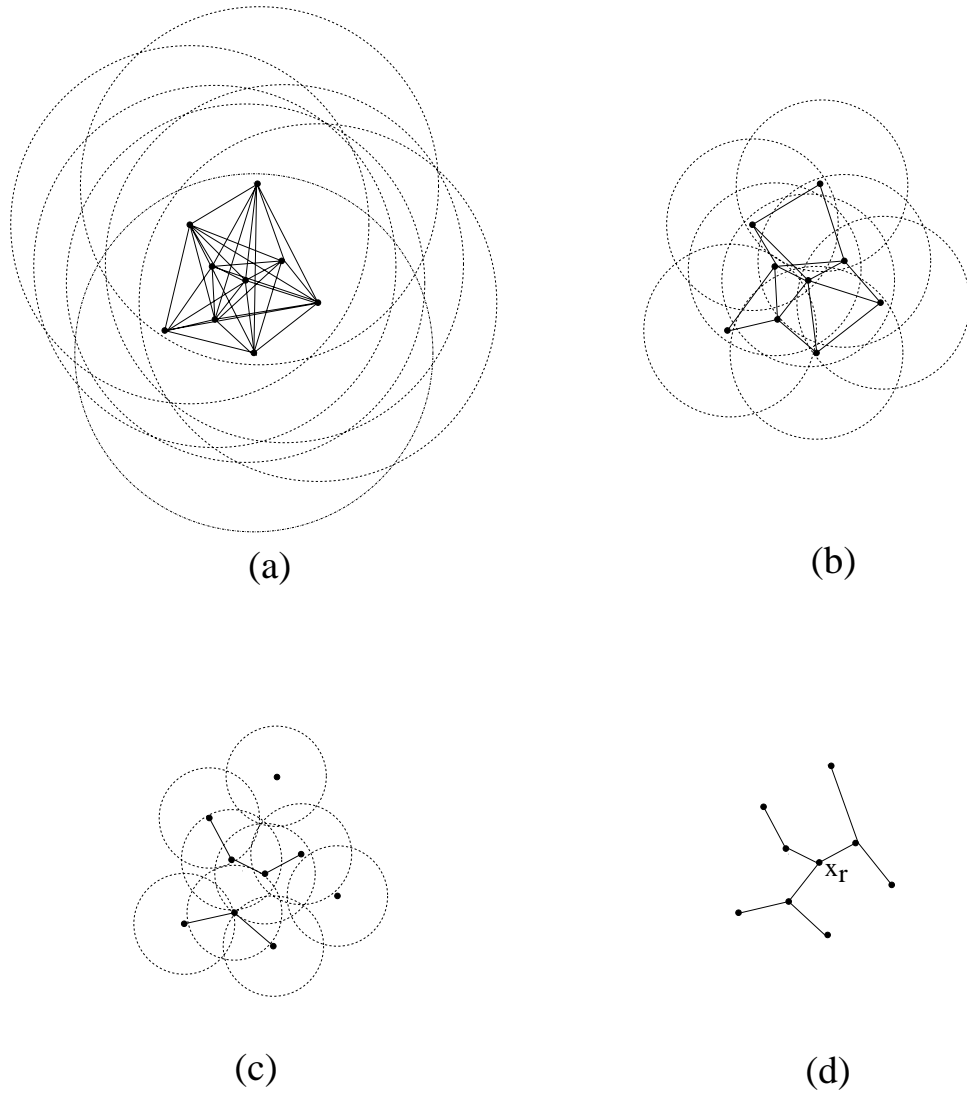


Figure 2-1: Transmission Range and Graph Connectivity: (a) illustrates a highly connected network where all nodes are reachable in one hop (e.g., $k_v \gg 1$); (b) illustrates a connected network; (c) illustrates the case where at least one node is disconnected forming network partitions; and (d) illustrates a minimum spanning tree that uses variable-range transmission with node x_r as root of the tree.

Packets transmitted using less power than required to maintain R_{com}^{min} are likely to get lost rather than reaching the final destination node. This may lead to network partitions.

In [36], Gupta and Kumar (1998) found an asymptotic expression to characterize the dependence of the common transmission range for asymptotic connectivity (R_{com}) in wireless networks. They found that when the range of R_{com} is such that it covers a disk of area $\frac{\log n + k_n}{n}$ [36], then the probability that the resulting network is connected converges to one as the number of nodes n goes to infinity if and only if $k_n \rightarrow +\infty$. Then the critical transmission range for connectivity of n randomly placed nodes in A square meters is shown to be [36],

$$R_{com}^{min} > (1 + \epsilon) \sqrt{\frac{A \ln n}{\pi n}}; \epsilon > 0 \quad (2.1)$$

One way to interpret the meaning of this bound is to randomly select a node in V , say x_r , and then build a spanning tree to all the other $n - 1$ nodes in V using node x_r as the root of the tree.

Definition: A tree T with node set V is called a *spanning tree* of V if each node of V is incident to at least one edge of T .

Definition: A minimum spanning tree for V , denoted MST, is a tree such that the sum of the edge lengths is minimal among all the spanning trees.

In this case the *minimum common transmission range* is the minimum value of the transmission range that permits the construction of a spanning tree.

In [37] Gupta and Kumar found the average traffic carrying capacity λ that can be supported by the network to be given by,

$$\lambda(R) \leq \frac{16AW}{\pi \Delta^2 nLR} \quad (2.2)$$

where A is the total area of the network, L is the average distance between source-destination pairs, each transmission can be up to a maximum of W bits/second. There can be no other transmission within a distance $(1 + \Delta)R$ from a transmitting node. The quantity $\Delta > 0$ models the notion of allowing only weak interference. Due to the inverse dependence of the right hand side on R , one wishes to decrease R . As discussed earlier, too low a value of R results in network partitions. This justifies our goal of reducing the common power level to the lowest value at which the network is connected. Combining Equations 2.1 and 2.2 it is clear that the average maximum traffic carrying capacity of the network that uses a common transmission power is limited by,

$$\lambda(R_{com}^{min}) \leq \frac{16\sqrt{A}}{\sqrt{\pi}\Delta^2 L} \frac{W}{\sqrt{n \ln n}} \quad (2.3)$$

If the maximum traffic carrying capacity of the network is bounded by the lowest value of R that keeps the network connected, then one can easily ask the question if the use of variable-range transmission can reduce the value of R beyond the bound given by Equation 2.1, thus increasing the average traffic carrying capacity and power savings of the network. This intuition motivates the study of variable-range transmission policies that follows.

2.2.2 Variable-Range Transmission

Now let us assume that each node can dynamically control the transmission power it uses independently of other nodes.

Definition: The weight (or cost) of each individual link e in graph M , denoted $\psi(|e|)$, is the minimum transmission range between two nodes connected by link e .

Definition: The end-to-end weight of a route from node u to node v , is the summation of the weight of the individual links representing a continuous traversal from node u to node v .

Let us also assume there is a unique route between any source-destination pair in the network that minimizes the end-to-end weight and that the average range of each transmission using these unique routes is \bar{R} . It is interesting to compare the ratio between R_{com}^{min} and \bar{R} because such a ratio accounts for how much lower a capacity is obtained and extra power is used in the network for holding to a common transmission power approach. As we will show later, even for homogeneous conditions this *extra* power is a very significant waste of transmission power that affects both network capacity and transmission power savings.

Now let us again randomly pick a node in M , say x_r , where $1 \leq r \leq n$, and compute a minimum spanning tree (MST) to all the other $n - 1$ nodes in V using node x_r as the root of the MST. Figure 2-1(d) illustrates an example of a MST with node x_r as the root of the tree². If E is such that the distances $|x_i - x_j|$ are all different then there is a unique MST for V . Dividing the length of the MST by the number of edges in the tree we get the average range of each transmission for a MST (\bar{R}_{MST}). Therefore,

$$\bar{R}_{MST} = \frac{M(x_1, x_2, \dots, x_n)}{n - 1} \quad (2.4)$$

To generalize, let $M(x_1, x_2, \dots, x_n)$ be the weight of the MST, denoted as

$$M(x_1, x_2, \dots, x_n) = \lim_T \min \sum_{e \in E} \psi(|e|) \quad (2.5)$$

where the minimum is over all connected graphs T with node set V . The weighting function which is of the most interest is $\psi(|e|) \sim x^\alpha$, where $2 \leq \alpha \leq 4$. In [75], Steele (1988) showed that if x_i , $1 \leq i < \infty$ are uniformly distributed nodes in and M is

²It is outside the scope of this chapter to describe how to build a MST. Interested readers may refer to the Prim [66] and Kruskal [47] algorithms for details.

the length of the MST of (x_1, x_2, \dots, x_n) using the edge weight function $\psi(|e|) = x^\alpha$, where $0 < \alpha < d$, then there is a constant $c(\alpha, d)$ such that with probability 1,

$$M(x_1, x_2, \dots, x_n) \sim c(\alpha, d)n^{(d-\alpha)/d} \quad \text{as } n \rightarrow \infty \quad (2.6)$$

where $c(\alpha, d)$ is a strictly positive constant that depends only on the power attenuation factor α and the dimension d of the Euclidean space being analyzed. Thus the average length of the edges of a *MST* using Equation 2.4 is,

$$\overline{R}_{MST} \sim c(\alpha, d) \frac{n^{(d-\alpha)/d}}{n-1}; \quad 0 < \alpha < d \quad (2.7)$$

2.2.2.1 The Special Case of \mathfrak{R}^2

In order to compare \overline{R}_{MST} with R_{com}^{min} we need to derive an expression for \overline{R}_{MST} for \mathfrak{R}^2 and $\psi(|e|) = x^\alpha$, for the particular case where $2 \leq \alpha \leq 4$. Because of the condition $0 < \alpha < d$ in Equation 2.7, setting $d = 2$ limits the value of α to $\alpha < 2$. Since $\lim_{\alpha \rightarrow 2} n^{(d-\alpha)/d} = 1$ for $d = 2$, the following simplification still holds

$$\lim_{\alpha \rightarrow 2} \overline{R}_{MST} \sim c(\alpha \rightarrow 2, d = 2) \frac{1}{n-1}; \quad n \rightarrow \infty \quad (2.8)$$

Equation 2.8 assumes the area of the network to be a normalized 1 m^2 . For a network of area A m^2 we must scale the previous result by \sqrt{A} . Thus the average minimum transmission range of n randomly placed nodes in A m^2 is,

$$\lim_{\alpha \rightarrow 2} \overline{R}_{MST} \sim c(\alpha \rightarrow 2, d = 2) \frac{\sqrt{A}}{n-1} \quad (2.9)$$

Despite its simplicity this expression for \overline{R}_{MST} and $\alpha \rightarrow 2$ holds fairly well for large n as we will show later in Section 2.4. when we present numerical examples.

However, we can not extend the validity of this expression for the case where $\alpha > 2$ because of the $0 < \alpha < d$ limitation of the model [75].

Comparing the common-range and variable-range transmission expressions we end up comparing expressions $\sqrt{\frac{\log n}{\pi n}}$ for common range with expression $\frac{1}{n-1}$ for variable-range transmissions. These expressions decrease their values asymptotically as n increases. Therefore, the absolute difference between common-range and variable-range transmission values is determined by the respective proportionality constants (e.g., $(1 + \epsilon)$ for common and $c(\alpha = 2, d = 2)$ for variable-range transmission). In future work we plan to investigate the traffic carrying capacity of the network when variable-range transmissions are used.

In Section 2.4., we show results of numerical examples to compute the proportionality constants for both R_{com}^{min} and \bar{R}_{MST} . As we show later, a variable-range transmission policy can significantly reduce the average transmission range used compared with the minimum common-range transmission bound. This result has a significant impact on the performance of wireless ad hoc networks since it suggests that a variable-range transmission policy may increase the capacity and power savings of the network.

The previous analysis for both common-range and variable-range transmissions does not consider node mobility, however. For the case where nodes move in random directions at random speeds the results derived in this section still hold. The reason is that even in the presence of mobility, the distribution of nodes in the network remains homogeneous at any particular time, which is a necessary condition for the analysis shown in this section to be valid. Node mobility, however, does impact the signaling overhead of the routing protocol, and therefore, it affects the available capacity left to mobile nodes (e.g., effective capacity). We quantify the impact of node mobility on the signaling overhead of the routing protocol and its impact on the

effective capacity available to mobile nodes given a certain transmission range. The analysis presented in the next section generalizes and extends the results presented in this section for mobile ad hoc networks.

2.3. Network Connectivity

In the previous section we discussed physical connectivity issues, and how they relate to network capacity and power savings in wireless ad hoc networks. Physical connectivity alone, however, does not provide nodes with end-to-end connectivity. A routing protocol is necessary to provide nodes with the means to communicate with each other in a multi hop environment. Routing protocols use signaling messages over the underlying physically connected network as a means to build end-to-end connectivity among nodes.

The transmission range used has a significant impact on the rate of signaling packets required to discover and maintain these “pipes” of connectivity over time in the presence of a node’s mobility. The derivations that we present in this section are focused on the behavior of an ideal on-demand common-range transmission based routing protocol. Most of the results and insights obtained from this section, however, apply to variable-range transmission based routing protocols as well. We will discuss the specifics of variable-range transmission based routing protocols in Section 2.5..

In general, the lower the common transmission power the higher the number of signaling packets required by the routing protocol to discover and maintain routes. Those signaling packets consume capacity and power resources in the network. Choosing a low common transmission power hoping to increase network capacity, as suggested by the analysis in the previous section, may generate too many signaling packets in the presence of node mobility, and therefore, a higher transmission power

may be desirable. In what follows, we study this tradeoff.

2.3.1 Mobility Model

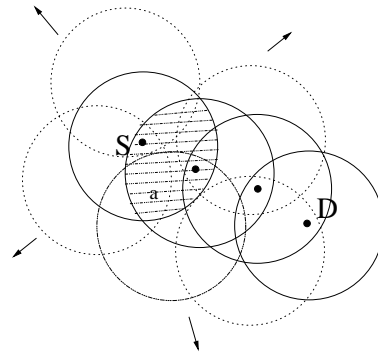
In a wireless ad hoc network environment some nodes may want to communicate with other nodes outside their maximum transmission range, thus requiring other nodes to forward packets on behalf of source nodes. In general, there will be none, one, or several intermediate forwarding nodes between source-destination pairs. Figure 2-2(b) illustrates an example of a route from a source node S to a destination node D involving several forwarding nodes. Each circle in Figure 2-2(b) represents the transmission range of each forwarding node in this route. The shaded regions illustrated in Figure 2-2(b) represents the overlapping regions between forwarding nodes.

Using the same notation as in Section 2.2., consider a graph M with a node set $V = \{x_1, x_2, \dots, x_n\}$ and link set $E = \{(x_i, x_j) : 1 \leq j \leq n \text{ for } x_i \in \mathfrak{R}^2, 1 \leq i \leq n\}$. Nodes move at a speed of v meters per second in random directions. Figure 2-2(c) highlights one of these overlapping regions. The length of the arc of the circle subtended by an angle θ , shown as S in Figure 2-2(c), is $R\theta$. The overlapping region b is then given by

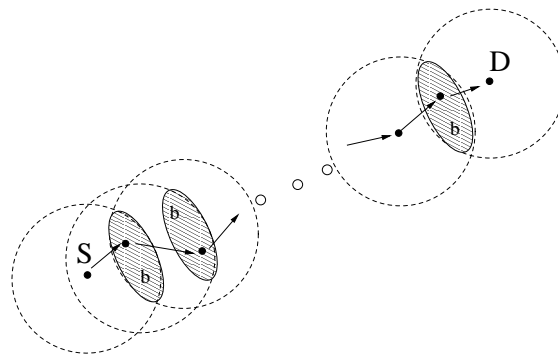
$$\begin{aligned} b &= R^2(\theta - \sin \theta) = (RS - cd) = 2R^2 \arccos\left(\frac{d}{R}\right) - 2d\sqrt{R^2 - d^2} \\ &= 2R^2 \arccos\left(\frac{R-h}{R}\right) - 2(R-h)\sqrt{2Rh - h^2} \end{aligned} \quad (2.10)$$

This expression is an approximation only. Forwarding nodes do not always space themselves equally along a path and they may move in random directions with respect to each other. As a result the actual overlapping area for each forwarding node may be smaller or larger in size than b .

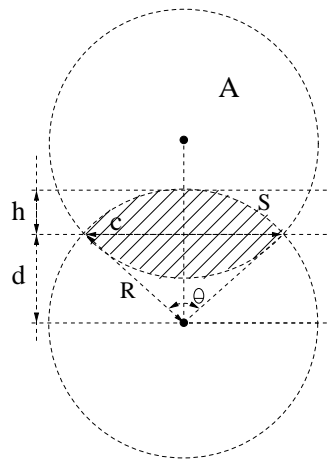
The factor h plays a crucial role in the operation and performance of routing



(a) Route Discovery



(b) Route Maintenance



(c) Overlapping Region

Figure 2-2: Routing in MANET-type Ad hoc Networks

protocols for wireless ad hoc networks. As illustrated in Figure 2-2(c), h accounts for how much area between adjacent forwarding nodes overlaps. Setting the value of h in a real network is rather difficult and, in general, the value of h is constantly changing as forwarding nodes may move in different directions at different speeds. Clearly the value of h ranges from a minimum of 0 meters to a maximum of R meters. When a forwarding node moves outside its forwarding region a new node in that region needs to take its place. We call this process a *route-repair* event. Having $h = 0$ indicates that forwarding nodes are located on a straight line connecting source-destination nodes and there is a minimum number of hops involved. Having $h = 0$, similarly, means that any node's movement results in a route-repair event. As a result having small h is only feasible in static networks (e.g., sensor networks) [48]. On the other hand having $h \rightarrow R$ minimizes the number of route-repair events seen by the routing protocol at the expense of significantly increasing the number of forwarding nodes per route.

In most on-demand routing protocols [17] for ad hoc networks there are route-discovery and maintenance phases. Route-discovery is responsible for finding new routes between active source-destination pairs whereas route-maintenance is responsible for updating existing routes in the presence of node mobility. In what follows, we derive a model to compute the signaling overhead of each component in an on-demand routing protocol as a function of the common transmission range being used.

2.3.2 Route Discovery

A source node intending to transmit a packet to a destination node outside its transmission range needs a chain of one or more forwarding nodes in order to successfully reach the intended destination node. We call this process of finding such a chain

of nodes *route-discovery*. Figure 2-2(a) illustrates a route-discovery process where node S searches for a route toward node D . The solid circles in Figure 2-2(a) illustrate the transmission range of the nodes associated with the final route, whereas the dotted circles illustrate the transmission range of nodes in all other directions that did not become part of the final route. Route-discovery can become very demanding in terms of both the number of signaling packets generated as well as the delay involved in finding the intended receiver. This is especially true in medium and large size networks³. An important part of the complexity found in most routing protocols for on-demand ad hoc networks is how to reduce this overhead. Some of the preferred choices to achieve this goal include limiting the geographic scope of the flooding as well as taking advantage of route-caching at intermediate nodes. In this analysis, however, we will consider that the process of route-discovery consist of flooding the entire network with a route-discovery request.

A node searching for a route broadcasts a route-discovery message which is heard within a circular region $A = \pi R^2$. Assuming that the intended receiver is not located within this region, then another node in region A will re-broadcast the original message, thus extending the region unreached by the original broadcast message, and so on [61]. A percentage of the second broadcast is wasted because it overlaps with the area covered by the first broadcast message (see Figure 2-2(a)), however. This problem is also addressed in [57]. As a result there is an inherited space-waste while flooding the network with broadcast messages. The node transmitting the second broadcast message can be located anywhere between 0 and R meters from the node transmitting the first broadcast message. This is equivalent to varying the parameter h between $\frac{R}{2}$ and R (see Figure 2-2(c)). The average overlapping area of

³In the case of large networks flooding techniques do not scale well and hierarchical routing appears more efficient.

a re-broadcast message is,

$$\bar{a} = \frac{2}{R} \int_{\frac{R}{2}}^R \left[2R^2 \arccos \left(\frac{R-h}{R} \right) - 2(R-h)\sqrt{2Rh-h^2} \right] dh \quad (2.11)$$

for the first part in Equation 2.11, integrating by parts with $s = \frac{R-h}{R}$

$$\int 2R^2 \arccos \left(\frac{R-h}{R} \right) = - \int 2R^3 \frac{s}{1-s^2} ds - 2R^3 s \arccos(s) \quad (2.12)$$

substitute $t = 1 - s^2$

$$= \int R^3 \frac{1}{\sqrt{t}} dt - 2R^3 s \arccos(s) = 2R^3 \sqrt{\frac{2hR-h^2}{R^2}} - 2R^2(R-h) \arccos\left(\frac{R-h}{R}\right) \quad (2.13)$$

for the second part in Equation 2.11, substituting $s = 2hR - h^2$ we obtain ,

$$\int -2(R-h)\sqrt{2Rh-h^2} dh = -\frac{2}{3}(2hR-h^2)^{\frac{3}{2}} \quad (2.14)$$

putting the two parts together ,

$$\int \left[2R^2 \arccos \left(\frac{R-h}{R} \right) - 2(R-h)\sqrt{2Rh-h^2} \right] dh = 2R^3 \sqrt{\frac{2hR-h^2}{R^2}} - 2R^2(R-h) \arccos \left(\frac{R-h}{R} \right) - \frac{2}{3}(2hR-h^2)^{\frac{3}{2}} \quad (2.15)$$

finally the average overlapping region between first and second broadcast messages is,

$$\bar{a} = \frac{2}{R} \int_{\frac{R}{2}}^R \left[2R^2 \arccos \left(\frac{R-h}{R} \right) - 2(R-h)\sqrt{2Rh-h^2} \right] dh \sim 0.68A \quad (2.16)$$

Clearly a re-broadcast message may overlap not only with the originating node, but potentially with regions covered by re-broadcast messages by other nodes. Therefore

the number in Equation 2.16 may be even lower than ~ 0.68 . If the total area of the network is A_T , then the total number $Q(R)$ of broadcast messages at range R necessary to successfully flood the network entirely is ,

$$Q(R) \sim \frac{A_T}{(1 - 0.68)A} = \frac{A_T}{(1 - 0.68)\pi R^2} \quad (2.17)$$

Due to the reciprocal square dependence of the right hand side on R^2 in Equation 2.17 reducing the transmission power may generate a prohibitive number of broadcast messages necessary to completely flood the network for low values of R . As a result, the use of a higher transmission range may provide better performance (e.g., higher per node average capacity).

2.3.3 Route Maintenance

A property of most MANET-style routing protocols is that they attempt to minimize the number of forwarding nodes per route in the network. The resulting effect of applying this routing policy is that routes seem to fall on a region connecting source and destination nodes (see Figure 2-2(b)). From the point of view of the routing protocol being used there is a region b where a potential forwarding node may be located as the next hop in the route toward the destination (assuming a high density of nodes allows for several nodes to be located in that region). Figure 2-2(b) illustrates an example of this region for each forwarding node in the route toward the destination. In what follows, we analyze how much node mobility and transmission range impact the number of route-repair events per second generated by the routing protocol.

The number of nodes per second crossing region b , denoted by M , is given by $\frac{\rho v F}{\pi}$. Here ρ is the density of nodes in the network, v is the velocity of nodes and F is the area boundary length or perimeter of region b . The perimeter F of region b

is given by ,

$$F = 2S = 2R\theta = 4R \arccos\left(\frac{R-h}{R}\right) \quad (2.18)$$

therefore,

$$M = \frac{4\rho v R \arccos\left(\frac{R-h}{R}\right)}{\pi} \quad (2.19)$$

Equation 2.19 assumes that nodes move in a random direction at a constant velocity and there is always conservation of flow in the shaded region. Let $N = \rho b$ be the average number of nodes in region b . A node entering region b at speed v remains an average of $T = N/M$ seconds inside the region before leaving. Using equations 2.18 and 2.19 we can compute $T(R)$ as,

$$T(R) = \frac{\pi R^2 \arccos\left(\frac{R-h}{R}\right) - \pi(R-h)\sqrt{2Rh-h^2}}{2vR \arccos\left(\frac{R-h}{R}\right)} \quad (2.20)$$

The parameter T directly relates to network connectivity because it accounts for how long a node in a route remains in a forwarding position before it needs to be replaced by a new forwarding node. We can assume, therefore, that the number of route-repair events in the network per second is proportional to $\frac{1}{T}$.

If L is the average length in meters separating source-destination pairs in the network over time, then there are L/d forwarding nodes per route on the average. Therefore, the average number of route-repair events per second per route, $J(R)$, is proportional to ,

$$J(R) \propto \frac{L}{R-h} \frac{1}{T} = \frac{L}{R-h} \frac{2vR \arccos\left(\frac{R-h}{R}\right)}{\left(\pi R^2 \arccos\left(\frac{R-h}{R}\right) - \pi(R-h)\sqrt{2Rh-h^2}\right)} \quad (2.21)$$

The factor R^2 in the denominator of Equation 2.21 dominates the behavior of $J(R)$, and thus a higher value of transmission range R keeps a forwarding node in the

route for a longer interval before there is a need to replace it, thus requiring less signaling messages to maintain existing routes. The actual number of signaling messages necessary to maintain a route after a route-repair event occurs depends on the actual routing protocol being deployed. A property of a well-designed MANET-type routing protocol is its ability to locally repair a route using nodes located within the affected area only. In some situations, however, local repairs may not work and end-to-end route-repair/discovery becomes necessary.

2.3.4 Capacity and Signaling Overhead

Clearly the rate of signaling packets generated by the routing protocol has an impact on the capacity available to nodes for data transmission. In Equation 2.2 we showed an expression for $\bar{\lambda}(R)$, the average traffic carrying capacity per node that can be supported by the network. Now let C be the number of bits exchanged by the routing protocol triggered by a route-repair event. The value of C depends on the number of signaling messages exchanged during a route-repair operation and the average size of each signaling message. Then the total capacity available to nodes using a transmission range R removing the portion of the capacity used by the routing protocol is

$$\bar{\lambda}(R, t) = \lambda(R, t) - CJ(R, t) \quad (2.22)$$

The route-discovery process occurs once per each route, and thus the corresponding amount $Q(R, t_0)$ is subtracted from the available capacity of the network once, and therefore not taken into account in Equation 2.22. This is in contrast with the signaling overhead of the route-maintenance process, which continuously uses a portion of the available capacity. We mentioned previously that R must be made as small as possible to maximize the traffic carrying capacity of the network. In the previous section we showed that R is limited by Equation 2.1 if a common

transmission range is used, and by Equation 2.7 if a variable-range transmission is used. Reducing the transmission range, however, has the effect of increasing the number of signaling packets transmitted to discover and maintain routes in the presence of node mobility. Clearly there is an optimum setting of R for a given node mobility v that maximizes the network capacity available to nodes. Because route-discovery occurs once we do not include $Q(R, t_0)$ in the derivation of R_{opt} ,

$$\frac{d}{dR}\bar{\lambda}(R) = \frac{d}{dR} \frac{16AW}{\pi\Delta^2 nLR} - \frac{d}{dR} \frac{4CLv \arccos\left(\frac{R-h}{R}\right)}{3(\pi R^2 \arccos\left(\frac{R-h}{R}\right) - \pi(R-h)\sqrt{2Rh-h^2})} \quad (2.23)$$

In order to remove the dependency on h in Equation 2.23, we first compute the average overlapping region b between two forwarding nodes in a route. Because h can vary between 0 and $\frac{R}{2}$ in this case, the average overlapping region is,

$$\bar{b} = \frac{2}{R} \int_0^{\frac{R}{2}} \left[2R^2 \arccos\left(\frac{R-h}{R}\right) - 2(R-h)\sqrt{2Rh-h^2} \right] dh \approx 0.16A \quad (2.24)$$

which corresponds to a value of $\bar{h} = 0.265R$ or $\bar{h} \sim \frac{1}{4}R$. Substituting this value in Equation 2.23 and using the chain rule $\frac{du^n}{dR} = nu^{n-1} \frac{du}{dR}$, where $u = \pi R^2 \arccos\left(\frac{3}{4}\right) - \frac{3}{16}\sqrt{7}\pi R^2$ and $n = -1$, we obtain ,

$$\begin{aligned} \frac{d}{dR}\lambda(R) &= -\frac{16AW}{\pi\Delta^2 nLR^2} - \frac{4CLv \arccos\left(\frac{3}{4}\right)}{3(\pi R^2 \arccos\left(\frac{3}{4}\right) - \frac{3}{16}\sqrt{7}\pi R^2)^2} \frac{d}{dR} \left(\pi R^2 \arccos\left(\frac{3}{4}\right) - \frac{3}{16}\sqrt{7}\pi R^2 \right) \\ &= -\frac{16AW}{\pi\Delta^2 nLR^2} - \frac{4CLv \arccos\left(\frac{3}{4}\right) \left[\pi \arccos\left(\frac{3}{4}\right) \frac{d}{dR}(R^2) - \frac{3\sqrt{7}\pi}{16} \frac{d}{dR}(R^2) \right]}{3(\pi R^2 \arccos\left(\frac{3}{4}\right) - \frac{3}{16}\sqrt{7}\pi R^2)^2} \\ &= -\frac{16AW}{\pi\Delta^2 nLR^2} - \frac{4CLv \arccos\left(\frac{3}{4}\right) \left(2\pi R \arccos\left(\frac{3}{4}\right) - \frac{3}{8}\sqrt{7}\pi R \right)}{3(\pi R^2 \arccos\left(\frac{3}{4}\right) - \frac{3}{16}\sqrt{7}\pi R^2)^2} \end{aligned}$$

Simplify,

$$= -\frac{16AW}{\pi\Delta^2 nLR^2} - \frac{128LCv \arccos\left(\frac{3}{4}\right)}{9\sqrt{7}\pi R^3 - 48\pi R^3 \arccos\left(\frac{3}{4}\right)} \quad (2.25)$$

making Equation 2.25 equal to zero we find the value of R that maximizes $\bar{\lambda}(R, t)$ as,

$$R_{opt} = \frac{8C\Delta^2 L^2 nv \arccos\left(\frac{3}{4}\right)}{AW(48 \arccos\left(\frac{3}{4}\right) - 9\sqrt{7})} \quad (2.26)$$

In this section we derived expressions for both the route-discovery and maintenance parts of an ideal on-demand routing protocol for wireless ad hoc networks. Results from this section show that there is an optimum setting for the transmission range, not necessarily the minimum value we found in Section 2.2.2 based on connectivity issues only, which maximizes the capacity available to nodes in the presence of node mobility. This result contrasts the main result of the previous section that pointed toward minimizing the transmission range as a mean to increase the capacity of static networks.

2.4. Numerical Examples

In what follows, we present numerical examples about physical and network connectivity. We analyze the fundamental relationship (i.e., the ratio) between the R_{com}^{min} and \bar{R}_{MST} . In addition, we quantify the signaling overhead of the network layer in the presence of node mobility.

2.4.1 Physical Connectivity

The main limitation with the previous derivations of both R_{com}^{min} and \bar{R}_{MST} is that the analytical results presented only hold for large values of n and, similarly, the proportionality constants of both bounds remain unknown. In order to quantitatively compare the two bounds we performed extensive computations to find these constants. Figure 2-3 shows the transmission range in a 200x200 square network for different numbers of nodes randomly distributed in the network. For each point in Figure 2-3 we performed 50 experiments, each of them using a different *seed* number to vary the location of nodes in the network. Figure 2-3 contrasts \bar{R}_{MST} with R_{com}^{min} (the numerical values corresponds to the 99% confidence interval).

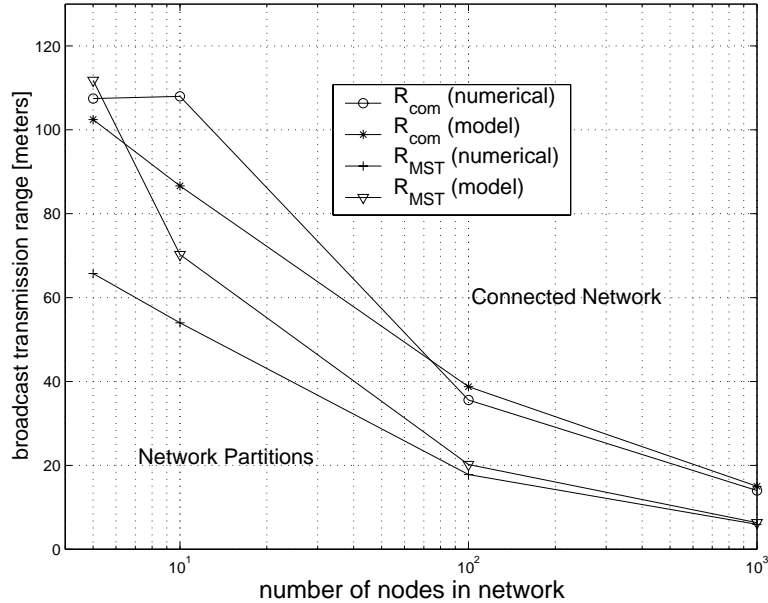


Figure 2-3: Transmission Range in Wireless Ad hoc Networks

There are several interesting observations we can make from Figure 2-3. As expected from equations 2.1 and 2.7, the values of R_{com}^{min} and \bar{R}_{MST} decrease as the density of nodes per unit area increases. This behavior is quite intuitive. The minimum transmission range that keeps the network connected is sensitive to the

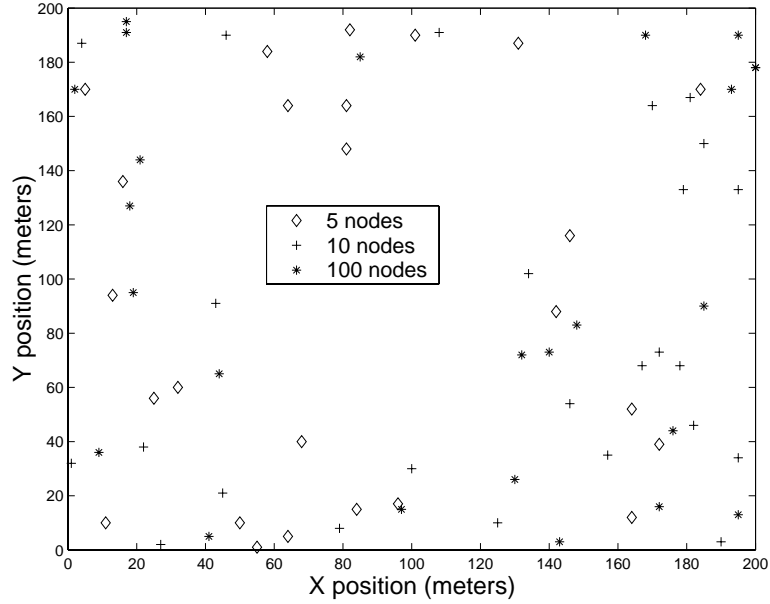


Figure 2-4: Edge Effects in Wireless Ad hoc Networks

average number of nodes seen by any node within its current transmission range. The more nodes in the network the more stable the average number of neighbors per coverage area seen by a node, and thus, the lower the transmission range required to keep them connected. A key observation from Figure 2-3 relates to the ratio $R_{com}^{min}/\bar{R}_{MST}$ which remains roughly constant and is ~ 2 . This results indicates,

that the value of the minimum common-range transmission is approximately twice the average value of the minimum variable-range transmission for similar routes.

As a caveat, these are numerical results and therefore the results apply to the network settings only, and cannot be extended to other network topologies without further experimentation.

This result has its power consumption counterpart. Using a common transmission power approach to routing results in routes that consume $\sim (1 - \frac{2}{2^\alpha}) \%$ ($2 < \alpha < 4$) more transmission power than routes that use a variable-range transmission. Figure 2-3 also shows the theoretical bound for both \bar{R}_{MST} and R_{com}^{min} using

the respective equations introduced earlier. We found that the proportionality constant for \bar{R}_{MST} , $C(\alpha, d) \sim 1$ whereas the proportionality constant for R_{com}^{min} , $\epsilon \sim 2$. Figure 2-3 clearly shows that the model breaks down for a density below 0.0025 *nodes/meter*² (e.g., $n < 100$).

Homogeneous distribution of nodes refers to the fact that the number of neighbors seen by each node within its transmission range remains more or less constant at least for a large n . Because of edge effects this property, unfortunately, does not hold even when nodes are uniformly distributed in the network. A node located right at the edge of the network has 1/2 as many neighbors while a node located in one of the corners (e.g., for a square network) has 1/4 as many neighbors on the average compared with a node located in a more central position of the network. In Figure 2-4 we recorded the position of the node triggering the first partition of the network while finding R_{com}^{min} in each of the 50 experiments of Figure 2-3. We found that approximately 50-60% of the time the node triggering the partition is located in a position within 10% from the edge of the network. This confirms the fact that edge effects can play a critical role in determining the value of R_{com}^{min} .

2.4.2 Network Connectivity

In Figure 2-5 we plot the signaling overhead generated by the route-discovery process $Q(R)$ as a function of the transmission range R . As expected the number of broadcast messages required to flood the network increases exponentially as the transmission range decreases. Similarly Figure 2-5 shows $Q(R)$ for different sizes of network. Because $Q(R)$ increases linearly with respect to A_t , for large networks flooding generates far too many signaling messages and hierarchical routing approaches becomes more efficient.

In Figure 2-6 we plot the average capacity per node, the signaling overhead of

route-maintenance and the average capacity left per node after removing the capacity used by the signaling packets. The value of the parameters used for this plot is as follows: $L=50$ meters; $A=10000$ square meters; $v=10$ meter/second; $W=2000000$ bits/second; $C=150$ bits; $\Delta=10$ meters; and $n=1000$ nodes. As Figure 2-6 shows the average available capacity per node increases as the common transmission range decreases up to a certain point P_{opt} . After that point the signaling overhead component dominates the performance and the available average capacity per node decreases sharply.

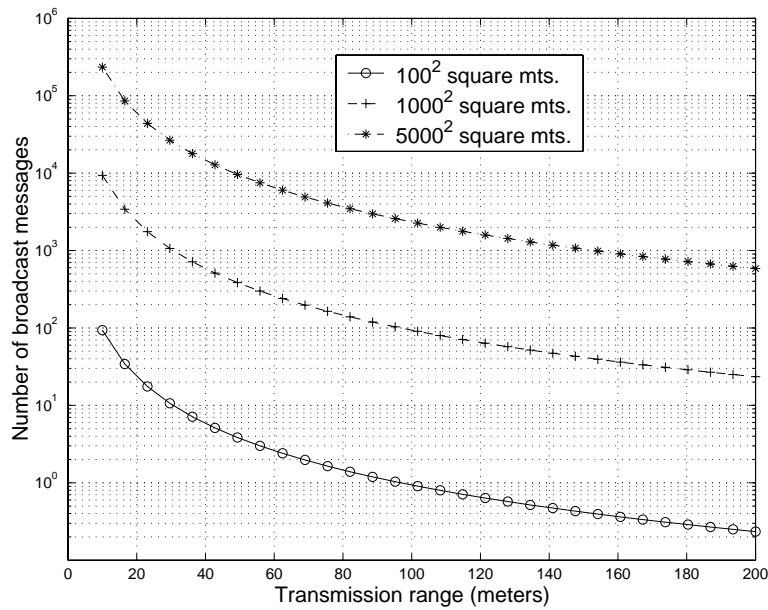


Figure 2-5: Route Discovery in Wireless Ad hoc Networks

2.4.3 MANET Routing Protocols

In order to complement the previous analysis we performed a series of simulations to observe the behavior of a MANET-type on-demand routing protocol stressing the impact that varying transmission range has on the rate of signaling messages generated. We use the ns2 simulator [58] and the CMU wireless extensions. Our

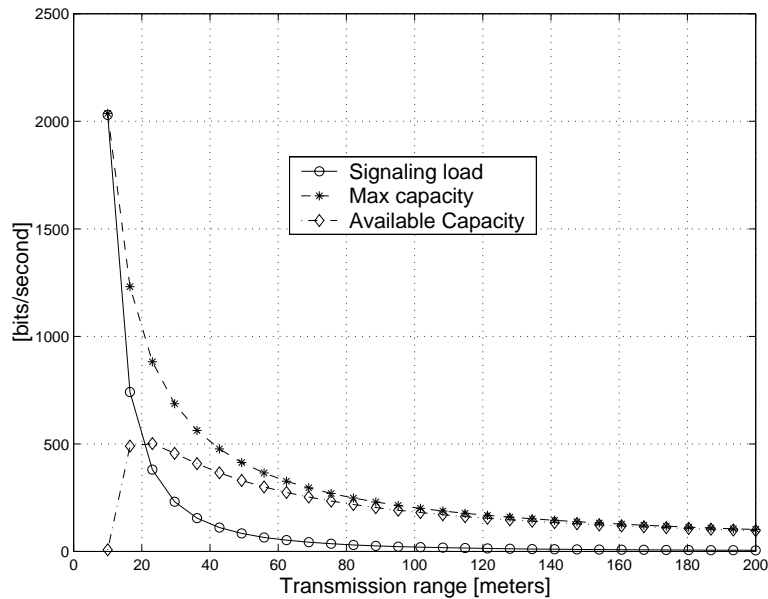


Figure 2-6: Route Maintenance and Available Capacity in Wireless Ad hoc Networks

simulation settings are as follows: there are 50 nodes in a 1500x300 meters network, nodes move at a maximum speed of v meters/second and there are 20 CBR connections among the 50 nodes. Each CBR connection transmits 4 packets (512 bytes long) per second. We use the Dynamic Source Routing (DSR) protocol [43]. The mobility model in the simulator works in the following way. A node randomly selects a destination point within the network limits and then moves toward that point at a speed selected uniformly between 0 and a maximum speed. After reaching the destination point a node pauses for a period of time before moving to a new randomly selected destination at a new speed. Figure 2-7 shows the signaling overhead of the routing protocol versus the transmission power and node speed. As shown in Figure 2-7, the number of signaling packets is low for high transmission power values, and grows in an exponential manner when transmission range approaches the minimum common transmission range. A similar behavior is observed in Figure 2-8 which shows the number of times a received packet found no routing information to continue its journey toward the destination (e.g., because of the number of network

partitions). These results highlight the fact that MANET-style routing protocols do not provide a suitable foundation for the development of routing protocols that are capacity-aware and power-aware. The choice of DSR in these experiments does not limit us from generalizing these results to other MANET routing protocols. This is because all MANET routing protocols to our knowledge use a common broadcast transmission range to discover and maintain routes. It is this particular feature what shapes the results shown in figures 2-7 and 2-8.

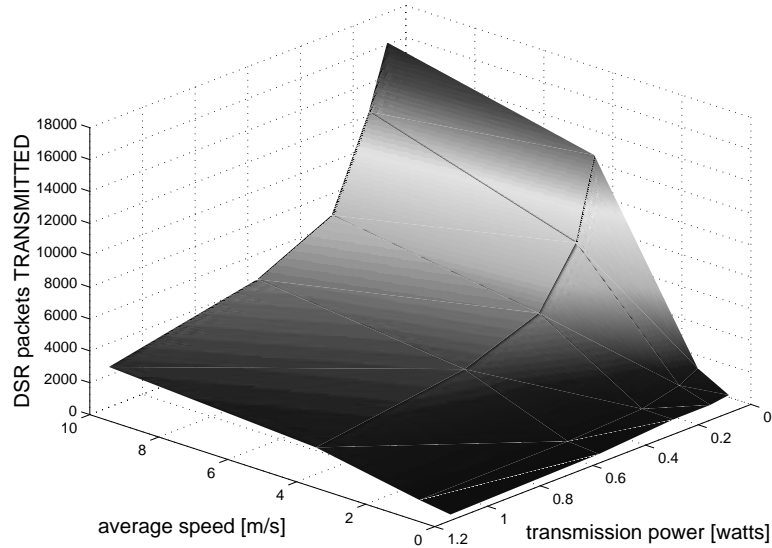


Figure 2-7: Signaling Load in MANET Protocols

2.5. Discussion

In this chapter we model and discuss some of the advantages of using a variable-range transmission rather than a common-range transmission based routing protocols in ad hoc networks. We believe the enhanced traffic capacity and power savings achieved by variable-range transmission based routing protocols provides a suitable foundation for networks where connectivity is not the main requirement. Now we discuss some deployment issues that motivates even further study of variable-range

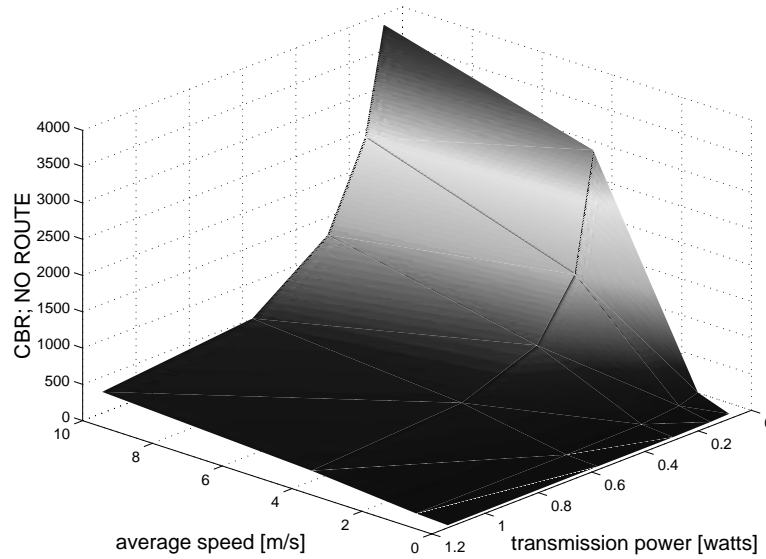


Figure 2-8: Network Partitions in MANET Protocols

transmission support in the design of protocols for wireless ad hoc networks.

At the physical layer we show that using a common-range transmission based routing protocol results in routes that, at best, involve transmission range levels that approximately double the average range in variable-range transmission based routing protocols for similar routes. In practice, however, it is relatively difficult to discover R_{com}^{min} from a practical implementation point of view. Similarly, nodes in a real network are not uniformly distributed in the network, but follow terrain and building layouts in complex ways. These facts will increase even more the gap between R_{com}^{min} and \bar{R}_{MST} on real network deployments. A common and safe approach used in most MANET-type routing protocols for ad hoc networks is to set $R_{com} \gg R_{com}^{min}$, or simply, $R_{com} = R_{max}$. These solutions, while improving the physical connectivity of the network, achieve that goal at the expense of sacrificing network capacity and wasting transmission power in the network significantly.

Figure 2-9 illustrates the main drawback of a common transmission range approach to routing. In this example the smaller circle in Figure 2-9 corresponds the

minimum common transmission range where node x_i is not part of the graph. Once node x_i is part of the graph then the new minimum common transmission range becomes the larger circle. Now we can see why the minimum common transmission power is a worst case approach to routing and why it is so dependent on the distribution of nodes in the network. In this simple example the addition of a single node to the graph results in a minimum common transmission range that is more than double its previous value. For real networks where nodes follow building and street layouts this type of scenarios is the common case and not an exception of the rule.

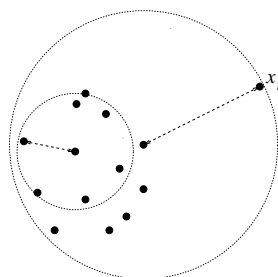


Figure 2-9: Disadvantages of Common-range Transmission Based Routing Design

At the network layer we also show that in the presence of node's mobility, reducing the transmission range as a mean to increase network capacity could be harmful to the available capacity remaining for nodes. The tradeoff between network connectivity and network capacity presents a very interesting paradigm: is it possible to maintain low overhead for the routing protocol while at the same time provide higher capacity to the nodes in the network? Following the design and performance of common-range transmission MANET-type routing protocols the answer is "no", unless a different method for discovering and maintain routes that departs from common transmission range broadcast technique is used. Recently, there has been

some initial work in this area [69] [29] [67] that provides variable-range transmission support for routing protocol operation.

If variable-range transmission control is going to be fully introduced in wireless packet networks it needs support at all layers in the protocol stack, especially at the MAC layer. Most ad hoc networks designs simply borrowed MAC protocols designed for wireless LAN operation. In fact, the 802.11 WLAN standard has become a de-facto standard for MAC operation in ad hoc networks. 802.11 as well as most CSMA MAC protocols use a common-range transmission and are not flexible enough to exploit the spectral reuse potential of the network. The addition of power control is particularly challenging at the MAC level because of the presence of hidden terminals [55]. In general, nodes transmitting with lower transmission power levels may not be noticed by nodes transmitting with higher transmission power levels and as a result collisions may be difficult to avoid. Fortunately there are some new proposals in MAC design that overtake this limitation and take full advantage of the spectral reuse potential acquired when using dynamic power control [55].

2.6. Related Work

In what follows, we discuss how our contribution discussed in this chapter contrasts to the related work in the area. The work by Gupta and Kumar [36] [37] on the mathematical foundations of common-range transmission in wireless ad hoc networks represents the seminal related research in his area. In this chapter, we take a similar approach to Gupta and Kumar but consider variable-range transmission in contrast to common-range transmission.

Gupta and Kumar [37] show that when considering the physical layer, reducing the transmission power is a better approach because this increases the traffic carrying capacity of the network. This is a fundamental result because previous to this work,

it had not been shown mathematically whether reducing the power (e.g., reduce the observed interference per attempted transmission) or increasing the power (with the result of decreasing the number of forwarding nodes per route) was the better solution to increase the overall capacity of wireless ad hoc networks. Gupta and Kumar also show that it is not possible to arbitrarily reduce the transmission power to any value in order to promote higher capacity and energy savings. Rather, there is a minimum bound for the transmission power necessary to avoid network partitions [36]. The authors in [36] use principles of percolation theory [74] to find a bound for the minimum common-range transmission that keeps wireless ad hoc networks connected. Percolation theory addresses the fundamental problem of finding out which link probability (e.g., the probability of having a link or not between two adjacent nodes) can connect a node in one extreme of a graph to a node in the opposite extreme of the graph. Percolation theory assumes that the weight (e.g., range) of all links is similar, and therefore, can not be used in our analysis where nodes transmit with different power levels.

The work presented in this chapter on the bounds of variable-range transmissions in wireless ad hoc networks uses traditional graph theory [35]. In particular, we used the theory explaining the behavior of minimum spanning trees (MST) to compute the weight of a minimum spanning tree [75]. As a reference, the two main algorithms to construct MSTs are the Prim [66] and Kruskal [47] algorithms. A similar problem to computing the weight of a minimum spanning tree is the *traveling-salesman problem*, or the problem of finding the shortest path through many points [12]. In the work described in [7], the authors discuss the impact on TCP throughput on the number forwarding nodes in static wireless ad hoc networks for unreliable links. Results from [7] show that there is an optimum transmission range that maximizes TCP throughput.

At the network layer, existing routing protocols discussed in the mobile ad hoc networks (MANET) working group of the IETF [53] are the best example of protocols designed based on common-range transmissions. As discussed earlier, these protocols discover routes using flooding techniques at common-range maximum transmission power. These protocols are optimized to minimize the number of hops between source-destination pairs, promoting minimum end-to-end delay. The work in [69] [29] intuitively suggest that a variable-range transmission approach can outperform a common-range transmission approach in terms of power savings, however, no definite analytical results are provided. In [69], wireless-enabled nodes discover energy-efficient routes to neighboring nodes and then use the shortest path Bellman-Ford algorithm to discover routes to other node in the network. The PARO protocol [29] discussed in detail in Chapter 3, uses redirectors to break longer-range transmissions into a set of smaller-range transmissions.

Power control can also impact the connectivity and performance of the network layer. Choosing a higher transmission power increases the connectivity of the network. Routing protocols can take advantage of highly connected networks to provide multiple routes for a given source-destination pair in cases where some nodes or links fail. Systems based on common-range transmission control like MANET protocols [53] usually assume homogeneously distributed nodes. As discussed earlier, such a regime raises a number of concerns and is an impractical assumption in real networks. The authors in [67] discuss this problem and propose a method to control the transmission power levels in order to control the network topology. The work in [67] is concerned with controlling the connectivity of non-homogeneous networks, but it does not provide a mathematical description of the problem space, and ignores the power savings and traffic-carrying capacity aspects of the problem. We address these issues in this chapter.

Mobility management principles in both cellular networks [68] [38] and IP based cellular networks [63] [19] [21] guide our work on the mobility aspects of wireless ad hoc networks. Mobility management in cellular and mobile networks is concerned with the rate of cellular/mobile nodes crossing cell boundaries. This parameter is very important in cell planning [16] and the provision of resources in the network in both wired and wireless segments for handoff from one cell to another [20] [5]. In wireless ad hoc networks there are no cells and the concept of handoff is very different. In general, the lower the transmission power used in wireless ad hoc networks, the higher the number of signaling packets required by the routing protocol to discover and maintain routes. In most MANET routing protocols, mobility analysis relies on simulations [17] due to the lack of a mobility model for this environment. For the specific case of route discovery, the work by [57] shows that the inherited space-waste involved while flooding the network with broadcast messages. However, no comprehensive mobility management analysis is presented. To our knowledge, our analysis of mobility management is a first attempt at modeling the various aspects of mobility in multihop wireless ad hoc networks.

2.7. Conclusion

There has been little analysis in the literature that quantifies the pros and cons of common-range and variable-range transmission control on the physical and network layer connectivity. In this chapter, we provide new insights beyond the literature that strongly support the development of new variable-range transmission based routing protocols. Our results indicate that a variable-range transmission approach can outperform a common-range transmission approach in terms of power savings and increased capacity. We derive an asymptotic expression for the computation of the average variable-range transmission in wireless ad hoc networks. We show

that the use of a variable-range transmission based routing protocol uses lower transmission power compared with common-range transmission approaches. We also derive expressions for the route-discovery and maintenance phases of an ideal on-demand routing protocol. We show that there is an optimum setting for the transmission range, not necessarily the minimum, which maximizes the capacity available to nodes in the presence of node mobility.

The main contribution of this chapter is that it provides a formal proof about the advantages of variable-range over common-range transmission approaches in wireless ad hoc networks. These results motivate the need to study, design, implement and analysis new routing protocols based on variable-range transmission approaches can exploit the theoretical power savings and improved capacity indicated by the results presented in this chapter. In the next chapter we take up this challenge and propose a new routing protocol based on dynamic power control called PARO.

Chapter 3

PARO: A Dynamic Power Controlled Routing Protocol

3.1. Introduction

A critical design issue for future wireless ad hoc networks is the development of suitable communication architectures, protocols, and services that efficiently reduce power consumption thereby increasing the operational lifetime of network enabled wireless devices. Transmission power control used for communications impacts the operational lifetime of devices in different ways. For devices where the transmission power accounts only for a small percentage of the overall power consumed, (e.g., a wireless LAN radio attached to a notebook computer), reducing the transmission power may not significantly impact the device's operational lifetime. In contrast, for small computing/communication devices with built-in or attached radios (e.g., sensors) reducing the transmission power may significantly extend the operational lifetime of a device, thus, enhancing the overall user experience.

The design of routing protocols for wireless ad hoc networks is challenging. Bandwidth and power resources available in wireless networks represent scarce resources. The signaling overhead of routing protocols may consume a significant percentage

of the available resources reducing the end user’s bandwidth and power availability [46]. This is compounded by the fact that topology changes in wireless and mobile networks occur at a much faster time scale in comparison to wired networks. Thus, routing protocols should be capable of rapidly responding to these changes using minimum signaling and taking into account the power reserves distributed in wireless networks.

In this chapter, we propose, design, implement and evaluate PARO [30] [29] [32], a new variable-range transmission power-aware routing protocol for wireless, mobile ad hoc networks where all nodes are located within the maximum transmission range of each other. PARO uses a packet forwarding technique where immediate nodes can elect to be *redirectors* on behalf of source-destination pairs with the goal of reducing the overall transmission power needed to deliver packets in the network, thus, increasing the operational lifetime of networked devices.

Optimization of transmission power as a means to improve the lifetime of wireless-enabled devices and reduce interference in wireless networks is beginning to gain attention in the literature [68] [73] [34] [49] [81] [55]. Typically, more power is consumed during the transmission of packets than the reception or during “listening” periods. Transmission to a distant device at higher power may consume a disproportionate amount of power in comparison to transmission to a node in closer proximity. PARO is based on the principle that adding additional forwarding (i.e., redirectors) nodes between source-destination pairs significantly reduces the transmission power necessary to deliver packets in wireless ad hoc networks. We propose that intermediate redirector nodes forward packets between source-destination pairs even if the source and destination are located within direct transmission range of each other. Therefore, PARO assumes that radios are capable of dynamically adjusting their transmission power on a per-packet basis to achieve variable-range transmissions.

PARO uses redirector nodes to shorten the length of individual hops, thereby reducing the overall power consumption. This approach is in direct contrast to MANET routing protocols (e.g., AODV, DSR and TORA) [53], which attempt to minimize the number of hops between source-destination pairs. One common property of these routing protocols [53] is that they discover routes using a variety of broadcast flooding protocols by transmitting at common-range maximum power in order to minimize the number of forwarding nodes between any source-destination pair. Wide-area routing protocols discover unknown routes using high power to both reduce the signaling overhead and to make sure routing information is entirely flooded in the network. Delivering data packets in wireless ad hoc networks using minimum-hop routes, however, requires more transmission power to reach destinations in comparison to alternative approaches such as PARO that uses more intermediate nodes. In this chapter, we show that common-range transmission based broadcast flooding techniques are either inefficient, because they generate too many signaling packets at lower transmission power, or are incapable of discovering routes that “maximize” the number of intermediate forwarding nodes between source-destination nodes. Because of these characteristics, MANET routing protocols do not provide a suitable foundation for discovering optimal power-aware routes in wireless ad hoc networks. As a result, there is a need to develop new variable-range transmission based power-aware routing approaches.

The design of a power-efficient routing protocol should consider both data transmission and route discovery. In terms of power transmission, these protocols should be capable of efficiently discovering routes involving multiple hops, thus minimizing the transmission power in comparison to standard flooding based ad hoc routing designs. PARO departs from common-range transmissions based designs and supports a node-to-node variable-range transmission based routing that is more suited to the

efficient discovery of power-aware routes. PARO is not only applicable as a local area routing technology where all nodes are within direct transmission range of each other (e.g., personal area networks, home networks, sensor networks, WLANs) but it can also perform power optimization as a layer 2.5 routing technology operating below wide-area MANET routing protocols. In this case, PARO provides wide-area routing protocols with local energy-conserving routes and wide-area routing is used to forward packets when the source and destination nodes are outside the maximum transmission range of each other.

The main contribution of the chapter is the design, implementation, analysis and evaluation of PARO in an experimental wireless ad hoc testbed. To our best knowledge PARO represents the first deployed routing protocol in wireless ad hoc networks that is based on the foundation of variable-range transmission control.

The structure of this chapter is as follows. Section 3.2. presents the PARO model and Section 3.3. discusses the detail design of the core algorithms that include the overhearing, redirecting, route convergence and route maintenance mechanisms. Following this, enhancements to the core algorithms to support mobility are presented in Section 3.4.. A performance evaluation of PARO, and comparison to a broadcast-based link state routing protocol that uses transmission power as the link cost unit are presented in Section 3.5. and Section 3.6., respectively. Section 3.7. discusses our experiences from an implementation of the protocol in an experimental wireless testbed using IEEE 802.11 technology [60]. Finally, we present related work in Section 3.8. and some concluding remarks in Section 3.9.

3.2. PARO Model

3.2.1 Link Assumptions

PARO requires that radios are capable of dynamically adjusting the transmission power used to communicate with other nodes. Commercial radios that support IEEE 802.11 and Bluetooth include a provision for power control. PARO assumes that the transmission power required to transmit a packet between nodes A and B is somewhat similar to the transmission power between nodes B and A. This assumption may be reasonable only if the interference/fading conditions in both directions are similar in space and time, which is not always the case. Because of this constraint PARO requires an interference-free Media Access Control (MAC) found in frequency band radios such as Channel Sense Multiple Access (CSMA). Note that even in CSMA access protocols, packets are subject to interference (collisions) during the sensing period, as a result of hidden terminals. In addition, PARO requires that every data packet successfully received is acknowledged at the link layer and that nodes in the network are capable of overhearing any transmissions by other nodes as long as the received signal to noise ratio (SIR) is above a certain minimum value. Any node should be capable of measuring the received SIR of overheard packets. This includes listening to any broadcast, unicast and control (e.g., acknowledgment) packets.

3.2.2 Cost Function

The goal of PARO is to minimize the transmission power consumed in the network. A node keeps its transmitter “on” to transmit one data packet to another node for L/C seconds, where L is the size of the transmitted frame in bits (e.g., data plus layer 2 headers), and C is the raw speed of the wireless channel in bits/second. Similarly, the receiver node keeps its transmitter on to acknowledge a successful

data transmission for a combined period of l/C seconds, where l is the size of the acknowledgment frame including layer 2 headers.

Now consider a network composed of several static nodes. Lets assume there are several alternative routes between a given source-destination pair in the network and that each route involves a different set and number of forwarding nodes. Then the aggregate transmission power to forward one packet along an alternative route k , P_k , is defined as,

$$P_k = \sum_{i=0}^{N_k} (T_{i,i+1}L + T_{i+1,i}l)/C \quad (3.1)$$

The factor $T_{i,j}$ in Equation 3.1 is the *minimum transmission power* at node i such that the receiver node j along route k is still able to receive the packet correctly ($T_{i,j}$ will be defined formally in Section 3.3.1), while N_k is the number of times a data packet is forwarded along route k including the source node. Equation 3.1 considers transmission power only, thus, it neglects the cost of processing overheard packets and the cost of keeping the radio in a listening mode. PARO is suitable for devices for which adjusting the transmission power benefits the overall power consumption. The power consumption during the transmission mode of such devices is higher than the power consumption during reception and listening modes, as is the case with a number of commercial radios. In this case, Equation 3.1 represents an “idealized” communication device.

PARO mainly uses data packets for route discovery. However, in some cases the protocol uses explicit signaling to discover routes in the network, as discussed in Section 3.3. and Section 3.4. The goal of any power-efficient routing protocol should be to reduce the signaling overhead to a minimum in order to save power. PARO tries to find the route k for which the transmission power, P_k , is minimized, and furthermore, it tries to discover this route using as little transmission power as possible. Let R_k be the transmission power consumed by the routing protocol to

discover the route for which P_k is a minimum, then the cost function for transmitting Q packets between a given source-destination pair along the best route, k , is:

$$C_k = R_k + Q \sum_{i=0}^{N_k} (T_{i,i+1}L + T_{i+1,i}l)/C \quad (3.2)$$

PARO accommodates both static (e.g., sensor networks) and mobile (e.g., MANETs) environments. In the case of static networks, once a route has been found there is no need for route maintenance unless some nodes are turned on or off. In a static network, transmitting a large amount of data traffic (e.g., a large Q) clearly outweighs the cost of finding the best power-efficient route (R_k). In this case, PARO may not need to be as efficient while discovering such a route. In mobile environments, however, there is a need for route maintenance.

3.2.3 Protocol Operations

Prior to transmitting a packet, a node updates its packet header to indicate the power required to transmit the packet. A node overhearing another node's transmission can then use this information plus, a localized measure of the received power, to compute (using a propagation model) the minimum transmission power necessary to reach the overheard node. In this simple manner, nodes can learn the minimum transmission power toward neighboring nodes. PARO does not, however, maintain routes to other nodes in the network in advance but discovers them on a per-node on-demand basis. This approach has the benefit that signaling packets, if any, are transmitted only when an unknown route to another node is required prior to data transmission, thus reducing the overall power consumption in the network.

At first the operation of PARO may seem counter-intuitive because in the first iteration of PARO the source node communicates with the destination node directly without involving any packet forwarding by intermediate nodes (i.e., redirectors).

Any node capable of overhearing both source and destination nodes can compute whether packet forwarding can reduce the transmission power in comparison to the original direct exchange between source and destination nodes. When this is the case an intermediate node may elect to become a redirector and send a *route-redirect* message to the source and destination nodes to inform them about the existence of a more power efficient route to communicate with each other. This optimization can also be applied to any pair of communicating nodes; thus, more redirectors can be added to a route after each iteration of PARO with the result of further reducing the end-to-end transmission power. PARO requires several iterations to converge toward a final route that achieves the minimum transmission power, as defined in Equation 3.1. This convergence delay restricts PARO to operate in networks where nodes are either static or move slowly.

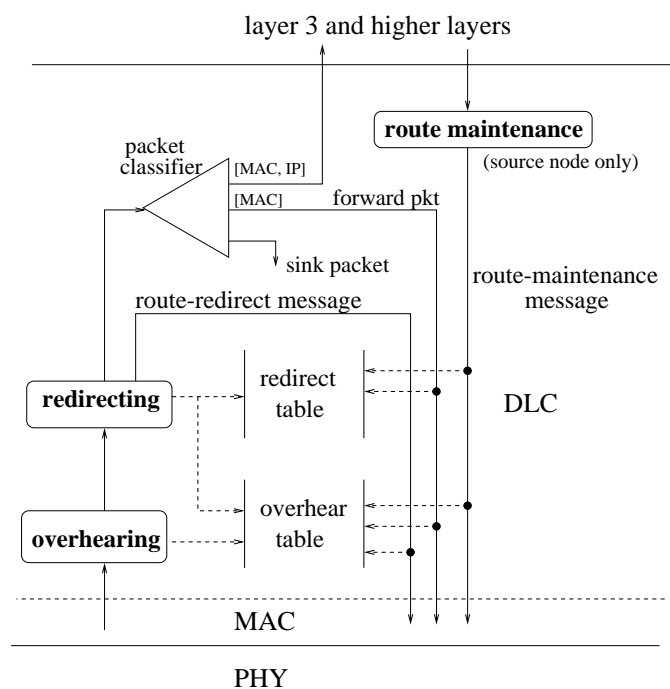


Figure 3-1: PARO Model

The PARO model comprises three core algorithms that support *overhearing*, *redirecting* and *route-maintenance*, as shown in Figure 3-1. The overhearing algorithm receives packets overheard by the MAC and creates information about the current range of neighboring nodes. Overheard packets are then passed to the redirecting algorithm, which computes whether route optimization through the intermediate node would result in power savings. If this is the case, the node elects to become a potential redirector, transmits *route-redirect* messages to the communicating nodes involved and creates appropriate entries in its redirect table. The overheard packet is then processed by the packet classifier module with the result that one of the following actions is taken: (i) the packet is passed to the higher layers if both MAC and IP addresses match; (ii) the packet is dropped if neither MAC nor IP addresses match; or (iii) the packet is forwarded to another node when only the MAC addresses match. In the latter case, PARO searches the redirect table to find the next node en route and then searches the overhear table to adjust the transmission power to reach that node.

When PARO receives a data packet from the higher layers it searches the redirect table to determine if a route toward the destination node exists. If this is not the case, PARO searches the overhear table to determine if there is any transmission power information related to the destination node available. If this is not the case, PARO transmits the packet using the maximum transmission power anticipating that the receiving node is located somewhere in the neighborhood. Once the destination node replies with a packet of its own then PARO's route optimization follows as described previously. PARO relies on data packets as the main source of routing information in the network. When nodes are mobile and no data packets are available for transmission, a source node may be required to transmit explicit signaling packets to maintain a route. The role of the route maintenance algorithm

is to make sure that a minimum flow of packets is transmitted in order to maintain a route when there are no data packets available to send at the transmitter.

3.3. Protocol Design

In what follows, we first describe the necessary core algorithms for overhearing, redirecting and route-maintenance. These core algorithms provide support for static environments (e.g., sensor networks) and serve as a set of foundation algorithms for mobile environments. In Section 3.4., we discuss the detailed enhancements to the core algorithms to support mobility.

3.3.1 Overhearing

The overhearing algorithm processes packets that are successfully received by the MAC, and creates a cache entry in the overhear table or refreshes an entry in the case that information about the overheard node already exists. This cache entry contains the triple $[ID, time, T^{min}]$, where the ID is a unique identifier of the overheard node (e.g., MAC or IP address), $time$ is the time at which the overheard event occurred, and T^{min} is the *minimum transmission power* necessary to communicate with the overheard node. Definition: Let R_i^{min} be the minimum signal sensitivity level at node i at which a packet can still be received properly. If $R_{j,i}$ is the measured received signal power at node i from a packet transmitted by node j at power T_j , then the minimum transmission power for node i to communicate with node j , $T_{i,j}^{min}$, is such that $R_{j,i} = R_i^{min}$.

The computation of $T_{j,i}^{min}$ is difficult because of the time-varying characteristics of wireless channels. In our analysis and simulation results discussed later we use a traditional propagation model that considers the strength of the received signal to be $\sim \frac{T}{d^\gamma}$. It is important to note, however, that other propagation models that best

match a particular operating environment should replace the simple model presented here. We first compute the distance separating the source and destination nodes by:

$$d^\gamma = \omega \frac{T_{i,j}}{R_{j,i}} \quad (3.3)$$

where d is the distance separating the transmitter and the overhearing node, γ is the attenuation factor of the environment typically in the range 2-4 (e.g., for indoor and outdoor environments) and ω is a proportionality constant that typically depends on factors such as antenna gain and antenna height of the transmitter and overhearing nodes. Initially a transmitter use $T_{j,i} = P_{max}$ if no previous information about the intended receiver is known. After this $T_{j,i}^{min}$ can be approximate by:

$$T_{i,j}^{min} = \frac{R_i^{min} d^\gamma}{\omega} \quad (3.4)$$

Because of fading and other channel impairments it is not recommended to compute $T_{i,j}^{min}$ using only a single overheard packet. Rather, a better approximation for $T_{i,j}^{min}$ is to take a moving worst-case approach, $\overline{T}_{i,j}^{min}$, where the overhearing node buffers up to M previous measurements of $T_{i,j}^{min}$ and then chooses the one with the highest value. If $T_{i,j}^{min}[k]$ is the value of $T_{i,j}^{min}$ computed for the last overheard packet then we can compute the value of $\overline{T}_{i,j}^{min}$ as:

$$\overline{T}_{i,j}^{min} = \max[T_{i,j}^{min}[k], T_{i,j}^{min}[k-1], \dots, T_{i,j}^{min}[k-M]] \quad (3.5)$$

where M is the number of previous measurements of $T_{i,j}^{min}$. The actual value of M can be tuned for each particular environment depending on the observed variations of the measured path attenuation. Depending on the statistical nature of these variations in time of $T_{i,j}^{min}$ a more complex computation of $\overline{T}_{i,j}^{min}$ can be provided. Similarly, we can define the minimum transmission range between nodes i and j ,

$\overline{D}_{i,j}^{min}$, as:

$$\overline{D}_{i,j}^\gamma = \frac{\omega \overline{T}_{i,j}^{min}}{R_{j,i}} \quad (3.6)$$

3.3.2 Redirecting

The redirecting algorithm is responsible for performing the route optimization operation that may lead to the discovery of new routes that require less transmission power. The redirecting algorithm performs two basic operations: *compute-redirect*, which computes whether a route optimization between two nodes is feasible; and *transmit-redirect*, which determines when to transmit route-redirect messages.

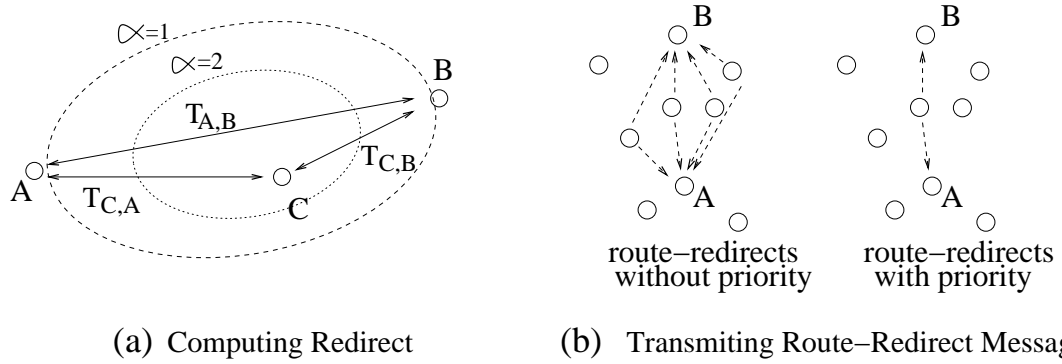


Figure 3-2: Redirect Operation

Compute Redirect. Figure 3-2(a) illustrates how compute-redirect operates. In this example, nodes A , B and C are located within maximum transmission range of each other and, initially, node A communicates directly with node B . Because node C is capable of overhearing packets from both A and B nodes, it can compute whether the new route $A \leftrightarrow C \leftrightarrow B$ has a lower transmission power than the original route $A \leftrightarrow B$. More precisely, node C computes that a route optimization between

nodes A and B is feasible if:

$$\overline{T}_{A,B}^{min} > \alpha(\overline{T}_{C,A}^{min} + \overline{T}_{C,B}^{min}) \quad (3.7)$$

Similarly, we define the optimization percentage of adding a redirector between two other communicating nodes in a route, Opt , as:

$$Opt = \frac{(\overline{T}_{C,A}^{min} + \overline{T}_{C,B}^{min})}{\overline{T}_{A,B}^{min}} \quad (3.8)$$

The factor α in Equation 3.7 restricts the area between two communicating nodes where a potential redirector node can be selected from. In Figure 3-2(a), we show the equivalent region where a potential redirector can be located for $\alpha = 1$ and $\alpha = 2$. The size and shape of these regions for finding potential redirectors depend mainly on the propagation loss parameter. For networks where nodes are static and saving battery power is important (e.g., a sensor network) α can be set to approximately 1.1-1.2, meaning that even a small improvement in transmission power savings is worth the effort of adding an extra redirector to the route. Once a node computes that route optimization is feasible, it creates an entry in its redirect table that contains the IDs of the source and destination nodes, the time when the table entry is created, the IDs of the previous hop and next node en route, and the total transmission power for single packet to traverse the route. The items contained in a route-redirect message include the IDs of the source and destination nodes, optimization percentage, ID of the target node that sent the route-redirect message, ID of node transmitting route-redirect message, and the transmission power to reach the node transmitting the route-redirect message.

Transmit Redirect. Using PARO several intermediate nodes may simultaneously contend to become redirectors on behalf of a transmitting node with the result

that multiple route-redirect messages are sent to a single transmitting node. Because only one intermediate node between two communicating nodes can be added as a redirector node at a time the transmission of multiple route-redirect messages (with the exception of the one transmitted by the node computing the lowest Opt percentage) represents wasted bandwidth and power resources. For sparsely populated networks, this may not be a problem. However, this is clearly an issue in the case of densely populated networks where several candidate redirector nodes would be anticipated. The transmit-redirect algorithm addresses this issue by giving priority for the transmission of a route-redirect message to the candidate redirector that computes lowest route optimization values first. In this manner, a potential redirector that overhears a route-redirect request from another potential redirector with a lower Opt value refrains from transmitting its own route-redirect request (see Figure 3-2(b)).

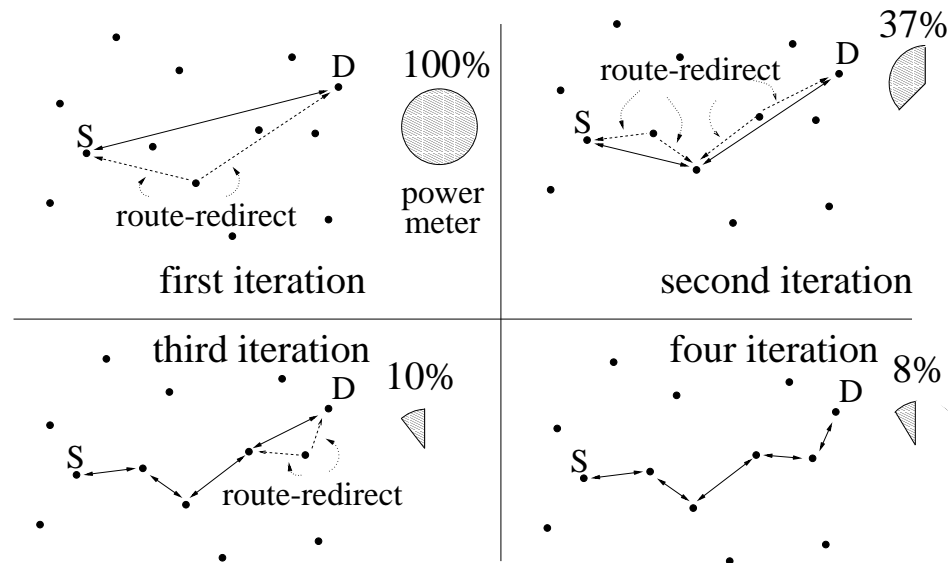


Figure 3-3: PARO Convergence

There are several ways to give preferential access to certain messages in a distributed manner. We used a simple approach that consists of applying a different

time-window before transmitting a route-redirect message after the triggering event takes place (e.g., the lower the Opt value computed, the shorter the intermediate node waits to transmit its route-redirect request). The lower and upper bound of the waiting interval are set such that they do not interfere with predefined timers used by the MAC protocol, making these bounds MAC dependent. In this chapter, we use the IEEE 802.11 MAC protocol and compute the waiting interval as:

$$interval = Opt * 100msec \quad (3.9)$$

In the unlikely scenario that more than one route-redirect request is transmitted, the target node will choose the one providing the lowest Opt value. After receiving a route-redirect message, a node modifies its redirect-table putting the source of the redirect message as the next hop node (i.e., redirector) for a specific source-destination route.

3.3.3 Route Convergence

Previously we discussed the case where only one intermediate redirector node is added to a route between a source-destination pair. The same procedure can be applied repeatedly to further optimize a route into smaller steps with the result of adding more redirectors between source-destination nodes. Figure 3-3 illustrates an example of a source-destination route comprised of five segments with four redirectors requiring four iterations for route convergence. Figure 3-3 shows the route taken by data packets after each iteration and the intermediate nodes selected as redirectors after transmitting successful route-redirect requests.

PARO optimizes routes one step at a time, thus it requires several iterations to converge to an “optimum” route. The word “iteration” refers to the event in which a data packet triggers a node to transmit a route-redirect request for the first time.

As a result PARO will converge as fast as the transmission rate of data (e.g., a flow measured in packets per second) transmitted by a source. Applications based on TCP (e.g., FTP, HTTP, etc.) transmit packets in bursts, potentially providing faster convergence. Applications based on UDP, on the other hand, are suitable for transmission of real-time media where the periodicity of packets transmitted depends on each specific application, thus the convergence of a route is application specific.

Figure 3-3 illustrates the transmission power (see “power meter”) used to transmit one packet between the source and destination nodes after each iteration of PARO. During the first iteration, the source node communicates directly with the destination node. Lets consider that the transmission power $\overline{T}_{S,D}^{min}$ corresponds to 100% when no redirector is presented. During the second iteration, adding one redirector in the route reduces the transmission power by 63% compared to the original $\overline{T}_{S,D}^{min}$ value. Note that the third and four iterations represent less impressive reductions in transmission power, especially the last iteration which only provides a 2% improvement. A nice property of PARO is that even after the first iteration of the protocol, considerable savings in transmission power is achieved. This means that nodes do not have to wait for the protocol to converge to the best/final route before obtaining significant power saving benefits. It can be observed from Figure 3-3 that each iteration simply adds one more redirector between adjacent forwarding nodes found in the previous iteration. In this respect, the new redirectors added to a route during an iteration are very much dependent on the redirectors found in the previous iteration. It is possible that the first iteration, which seemed optimal (e.g., it optimized the route better than any other intermediate node), can lead to a final route which is not the route achieving the minimum transmission power. In fact, PARO cannot avoid this from a practical point of view unless an exhaustive

search is applied which works against saving power in the network. Therefore, the use of terms such as “optimum” and “minimum” assume this caveat when used in the context of PARO.

3.4. Mobility Support

In static networks (e.g., sensor networks) there is no need for route maintenance once the initial route between source-destination pairs has been found, other than when nodes are turned off or on. However, in many cases nodes are mobile (e.g., MANETs). Adding support for mobile nodes to the core algorithms is challenging because of the uncertainty concerning the current range of neighboring nodes as they move in the network [44]. In what follows, we discuss the necessary enhancements to the core algorithms to support mobility.

3.4.1 Route Maintenance

PARO relies on data packets as the main source of routing information. In the case of mobile nodes, data traffic alone may not be sufficient to maintain routes. Consider the extreme case of a source node transmitting packets once every second to a destination where every node moves at 10 meters/second on average. In this example, information about the range of the next redirector en route would be outdated as a basis for the transmission of the next packet. Depending on node density and mobility there is a need to maintain a minimum rate of packets between source and destination pairs in order to discover and maintain routes as redirectors move in and out of existing routes.

A natural solution to this problem is to let the source node transmit explicit signaling packets when there are no data packets available to send. Transmitting signaling packets, however, consumes bandwidth and power resources even if those

signaling packets are only a few bytes in length. Under fast mobility conditions signaling packets could potentially consume more power resources than the case where a source communicates directly with a destination node assuming certain traffic patterns. In what follows, we discuss a number of enhancements to the overhearing and redirecting algorithms to resolve these issues in support of mobile nodes.

3.4.2 Overhearing

Any node transmitting a packet to the next hop redirector in the route has to determine the next hop's current range, which may be different from its last recorded position. Clearly, the preferable transmission estimate is the one that transmits a packet using the minimum transmission range. If a node transmits a packet assuming that the next hop's current range is the same as the last recorded range, then three scenarios may occur: *(i)* The current position of the next redirector is within the current transmission range. In this case, the transmitting node finds the next redirector but some power is wasted because more power is used than necessary for this operation. *(ii)* The current position of the next redirector is at the same transmission range thus the transmission is optimum. *(iii)* The current position of the next redirector is outside the current transmission range. In this case, the transmitting node fails to find the next redirector and has to attempt a new transmission using more power than the current level.

Scenario 3 is more inefficient than Scenario 1 because not only is more power used, but also longer delays are experienced in reaching the next hop. An intuitive solution to this problem is to transmit a packet with a higher transmission range than previously recorded, increasing the probability of reaching the next hop node

on the first attempt. We define a new minimum transmission range, $\overline{D}_{i,j}^{new}$, as:

$$\overline{D}_{i,j}^{new} = \overline{D}_{i,j}^{old} + \Delta, \quad (3.10)$$

where Δ represents how much the transmitting node over estimates the transmission range of the next node en route. The value of Δ depends on the average speed of nodes and the time interval between the last time the next redirector en route was overheard and the current time; we refer to this interval as the *silence-interval*. The longer the silence-interval the greater the uncertainty about the current range of the next node, and therefore, the larger the value of Δ . We resolve this problem by requiring that the source nodes transmit *route-maintenance* packets toward destination nodes whenever no data packets are available for transmission for a specific interval called *route-timeout*. Transmission of route-maintenance messages only occurs whenever a node (which is actively communicating with another node) stops transmitting data messages for a route-timeout period. The transmission of route-maintenance messages puts an upper bound on the silence-interval, thus, an upper bound on Δ .

3.4.3 Redirecting

Because of mobility, a redirector node may move to a new location where it no longer helps to optimize the transmission power between two communicating nodes. In this case, it is necessary to remove such a node from the path using a route-redirect message. Figure 3-4 illustrates this scenario. Node *A* communicates with node *D* using nodes *B* and *C* as redirector nodes, as shown in Figure 3-4(a). Figure 3-4(b), shows the position of nodes after some time has elapsed. In Figure 3-4(b) node *B* moves to a position where both nodes *B* and *C* are within the same transmission range of node *A*. When node *A* sends a packet to node *B*, it is also overheard by node

C . Because node B is the previous hop to node C along the route between nodes A and D , then node C can determine that node B has moved out of the optimum route. In this case, node C transmits a route-redirect message toward node A requesting node A to re-route its data packets directly to node C . Figure 3-4 (c) shows the new route after node A re-routes new packets to node C .

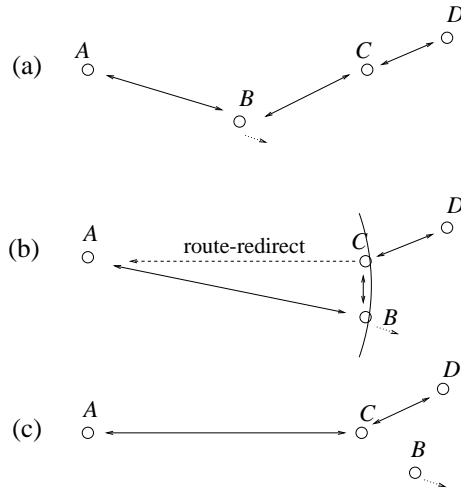


Figure 3-4: An Example of Removing a Suboptimal Redirector from an Existing Route

3.5. Performance Evaluation

In this section, we present an evaluation of PARO and discuss a number of performance issues associated with route convergence, power optimization and route maintenance.

3.5.1 Simulation Environment

We used the *ns* network simulator with the CMU wireless extension [1] to evaluate PARO. The simulator supports physical, link and routing layers for single/multi hop

ad-hoc networks. The propagation model is based on a two-ray model, which is appropriate for outdoor environments where a strong line of sight signal exists between the transmitter and receiver nodes and where the antennas are omnidirectional. The two-ray propagation model assumes there are two main signal components. The first component is the signal traveling on the line of sight and the second component is a reflection wave from a flat ground surface. This model computes the strength of the received signal source and destination nodes by:

$$R_{j,i} = \frac{T_{i,j}G_tG_r h_t^2 h_r^2}{d^4} \quad (3.11)$$

where d is the distance separating transmitter from the overhearing node, and $G_t h_t^2$ and $G_r h_r^2$ are the antenna gain and antenna height of the transmitter and overhearing node, respectively. After receiving a packet each node invokes the propagation model to determine the power at which the packet was received. If the node determines that the packet was successfully received (e.g., the received power was above a certain threshold) it passes the packet to the MAC layer. If the MAC layer receives an error-free packet it passes the packet to the link layer and so on [83]. The simulation uses the standard ns/CMU mobility model.

We use the IEEE 802.11 MAC protocol which uses Channel Sense Multiple Access with Collision Avoidance (CSMA/CA) also referred to in IEEE 802.11 as the Distributed Coordination Function (DCF). In IEEE 802.11 a packet is successfully captured by a node's network interface if the sensed power of the received packet is above a certain minimum value¹ otherwise the packet cannot be distinguished from background noise/interference. Communication between two nodes in IEEE 802.11

¹For Wavelan, this values corresponds to 0.2818 watts for normal power transmission; 1.559e-11 watts for carrier sense threshold to detect a collision; and 3.652e-10 watts for the sensitivity of receiver.

uses RTS-CTS signaling before the actual data transmission takes place. Due to the potential problem of nodes not being able to listen to RTS-CTS packets in the case of a system with dynamic transmission power control, we always transmit RTS-CTS packets at maximum transmission power. Figure 3-5 illustrates this problem. In the figure node A communicates with node B while at the same time node C communicates with node D. In this scenario nodes C and D transmit RTS-CTS packets using minimum transmission power. Under such conditions nodes A and B may not be able to overhear (dashed circle) or sense (dotted circle) the RTS-CTS packet exchange between nodes C and D and may attempt to transmit their own RTS-CTS thereby interfering and disrupting the on-going communication between nodes C and D.

Clearly transmitting RTS-CTS packets at maximum transmission power does not exploit the spectral reuse potential in the network. A node transmitting a packet to another node in close proximity at the minimum transmission range uses RTS/CTS at full transmission range. This inhibits other nodes in the entire RTS/CTS region from transmitting even if deferring transmission for the nodes is unnecessary. There are a number of new MAC proposals that address such limitations. In [55] the authors present the Power Controlled Media Access Protocol (PCMAP) that operates within the framework of collision avoidance protocols such as CSMA/CS that use RTS/CTS. In PCMAP, active receivers advertise a periodic busy tone on a separate frequency band to other potential transmitters including their maximum tolerance to admit extra noise (e.g., interference). A node intending to transmit a packet first senses the busy tone signal. If a busy tone exists, then the node adjusts its transmission power such that it does not disrupt ongoing transmissions prior to communication with its intended receiver. We believe MAC protocols such as PCMAP can efficiently support the necessary power-controlled operations required

by PARO in comparison to off-the-shelf radios such as IEEE 802.11. We discuss these limitations further in Section 3.7.

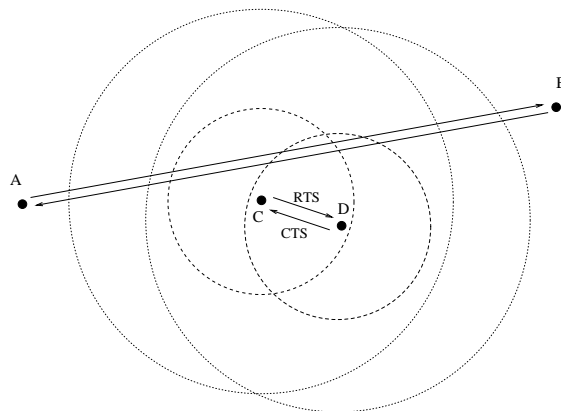


Figure 3-5: An Example of the Problem of Transmitting RTS-CTS Packets using Dynamic Transmission Power Control

As a general methodology comment each point in the graphs shown in the following sections on route convergence, power optimization and route maintenance represents an average of five different simulation runs. Each simulation run uses a different seed number affecting both the traffic and mobility behavior

3.5.2 Route Convergence

Figure 3-6 shows simulation results concerning the convergence of PARO versus different packet inter-arrival rates. Twenty static nodes are randomly positioned in a 100x100 network. We conducted two separate experiments for UDP/CBR and TCP/FTP applications. In each experiment each node is the source and recipient of a flow. In the case of UDP/CBR applications, each source node transmits a 512-byte packet with different inter-packet intervals times ranging from 30 msec to 1.5 seconds. In the case of the TCP/FTP applications, each source node transmits

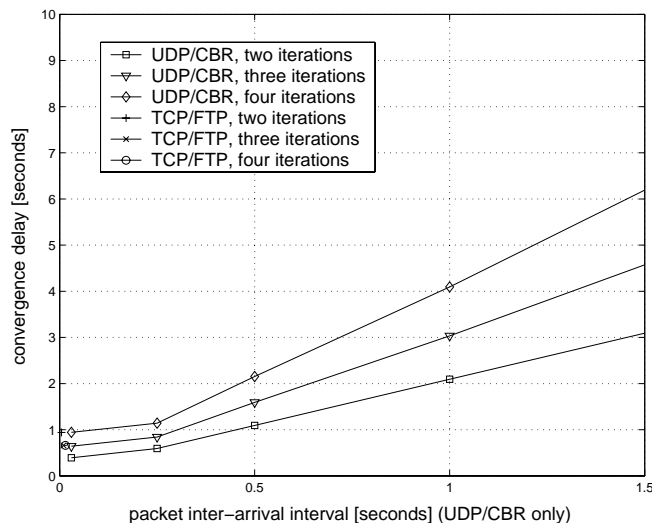


Figure 3-6: Route Convergence Time

512-byte packets as fast as the link layer permits. As anticipated the results show that PARO converges in the same proportion as the inter-packet interval times. Thus, the faster nodes transmit packets the faster routes converge. In the case of TCP/FTP applications, this time represents a few dozens milliseconds (the corresponding points in Figure 3-6 are so close to each other that they appear to be overlapping). As discussed in Section 3.3.3, PARO requires several iterations to converge to an optimum route with minimum power. The number of iterations per session is dependent on the node density and the specific position of nodes with respect to each other. Because different sessions may require a different number of iterations to converge, the session needing more iterations will take the longest time to converge assuming all sessions have similar traffic patterns and start at the same time. Figure 3-6 also contrasts the convergence of PARO for different number of iterations for the same network size and number of nodes. As expected PARO converges linearly with respect to the number of iterations required.

3.5.3 Power Optimization

As discussed in Section 3.3.3, the more densely populated the network the higher the average number of potential redirector nodes, and the lower the average transmission power between source-destination pairs. The simulation topology consists of a 100x100 network with 10, 30 and 100 randomly positioned static nodes for each experiment. The simulation trace lasts for a duration of 100 seconds with ten UDP/CBR flows transmitting 512 bytes packet every three seconds. The simulation uses a value for $\alpha = 1$ which configures PARO to find the best power-efficient route. Figure 3-7 shows the aggregate energy necessary to transmit a packet versus the number of nodes in the network. Figure 3-7 also indicates (between parenthesis) the average number of times a packet is forwarded before reaching its destination node (i.e., average number of redirectors en route). This number is dependent on the node density, as mentioned previously. The higher the number of nodes in the network the higher the probability of having more redirectors between communicating nodes. At first the aggregate transmission power decreases rapidly when there are between an average of 0.5 and 2.9 redirectors present. The aggregate transmission power then decreases slowly up to an average of 5.4 intermediate redirector nodes, as shown in the simulation plot. We observe the aggregate transmission power decreases as the number of nodes increases from 10 to 30. This is a consequence of the availability of additional appropriately located redirectors.

Figure 3-7 shows that in terms of transmission power alone, it does not pay to have more than three redirectors per source-destination pair in networks where nodes are distributed homogeneously². Having more than three redirectors may increase end-to-end delay and likelihood of network partitions. Figure 3-7 also indicates the

²When nodes are not distributed homogeneously in the network it may occur that having 4 or even 5 redirectors per route on the average provides a noticeably power savings improvement.

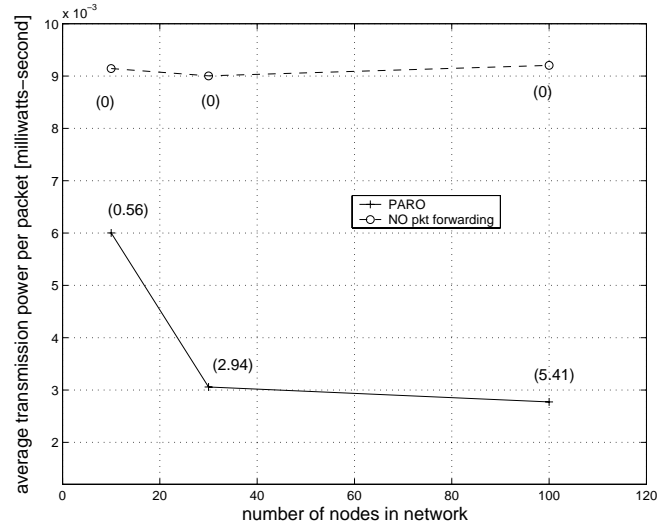


Figure 3-7: Transmission Power versus Number of Nodes

transmission power needed if no redirectors were added between source-destination pairs. Comparing the two scenarios (i.e., with and without redirectors) in Figure 3-7, we clearly observe the benefit (i.e., power savings) of adding intermediate redirector nodes. However, even if no intermediate nodes are found between source-destination pairs, by default PARO will use the minimum transmission power information (if available) to communicate with a destination node. This operation is in contrast with traditional wireless LAN systems, which always use the maximum transmission power to communicate with a destination node even if the destination node is in very close proximity to the transmitter.

3.5.4 Route Maintenance

In this section, we analyze the performance of PARO in support of mobile nodes. Figure 3-8 shows the transmission success ratio versus the speed of nodes and the packet inter-arrival interval. We define the “transmission success ratio” as the num-

ber of packets that are correctly received by the corresponding destination nodes divided by the total number of packets transmitted. The simulation includes 30 nodes in a 100x100 network. Ten randomly chosen nodes transmit a UDP/CBR flow to 10 randomly chosen destination nodes. Each flow consists of 100 byte packets transmitted using different time intervals. In Figure 3-8, we highlight three separate regions on the graph which are of interest because of the different network dynamics operating in those regions; these are as follows. Region (I): Nodes operating in this region move slowly. As a result, redirectors remain in the path of a route for longer intervals which translates into fewer route/updates per second. This condition results in a high transmission success ratio, even in the case of a slow flow of packets traversing between source-destination pairs. Region (II): Nodes operating in this region transmit packets with small inter-arrival intervals compared with those packets transmitted in region (III). The faster data packets are transmitted the faster PARO can discover, for example, that a redirector has moved to a different location and to take appropriate measures. As a result, the transmission success ratio is high even for the case where nodes move fast. Region (III): Nodes operating in this region move fast and transmit packets slowly. Because of high mobility several route changes per second occur. However, packets are not transmitted at a fast enough rate to maintain routes in the network due to the long silence-intervals between packets. Data packets transmitted by nodes operating in this region are likely to be lost. This is because transmitting nodes may not have accurate range information concerning the next hop redirectors en route. As a result, the transmission success ratio is low. Figure 3-8 also shows the importance of transmitting route-maintenance packets to maintain a route in the case where a source node transmits packets too slowly.

Determining the optimum value of the silence-interval (introduced in Section

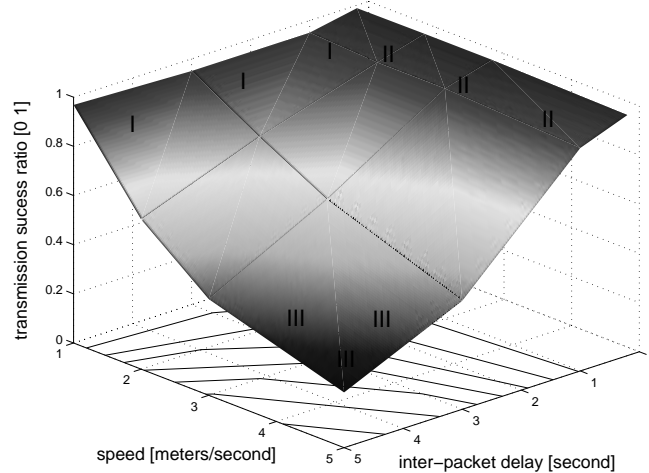


Figure 3-8: Transmission Success Performance

3.4.2) to overcome node mobility (in order to guarantee a certain success ratio) is a complex issue. This value is dependent on the size of the network and the node density as well as mobility and data packet inter-arrival rate. Larger areas with high nodal density will likely support routes with several redirectors. Maintaining a route with fewer redirectors requires less signaling packets both in terms of route-redirect and route-maintenance messaging. A route reduces the transmission power by a significant amount simply by limiting the number of redirectors to 2-3 forwarding nodes, as discussed in Section 3.5.3. The benefit of adding additional redirectors beyond this point may be undermined by the signaling overhead required to maintain longer multi-hop routes. Two complementary methods can be used to reduce the number of redirectors along a route. Choosing a higher value for α (see Section 3.3.2) restricts the area where a redirector can be located between two communicating nodes. Such an approach would reduce the number of redirectors compared to the case where a parameter value of $\alpha = 1$ is adopted. Second, packets could carry a counter similar to the IP packet TTL field that would be decremented by each

redirector visited en route toward the destination. After reaching zero, no other redirectors would be added to further optimize the route. This enhancement is currently being studied.

3.6. Comparison

PARO discovers routes on-demand on a node-to-node basis. An alternative approach would generate full routing tables in advance where, for example, all nodes would be aware of power-efficient routes to all other nodes in the network. Such protocol behavior is similar to a common-range transmission based Link State Routing (LSR) using transmission power as the link cost unit. We refer to this modification to LSR as MLSR (where the “M” in MLSR stands for Modified LSR) in the remainder of this section. The basic LSR operation requires each node in the network to broadcast a routing packet with a common range (or PROP message using link state terminology). The PROP packet contents contains information about the transmission cost of all known destinations. After collecting PROP messages from all parts of the network, any node should be capable of computing optimum routes to any other node in the network.

Because of the fundamental difference in these two approaches, we compare PARO and MLSR to best understand the various tradeoffs and limitations of our design. In what follows, we describe an MLSR implementation that supports transmission power as in the case of PARO. We then compare the performance of MLSR to PARO. Consider a network composed of N nodes located within transmission range of each other. MLSR nodes can compute the minimum transmission power T^{min} to a transmitting node by listening to a PROP signaling packet transmitted by the node. The PROP message includes the transmission power T^{PROP} used to transmit the packet. Depending on the value of T^{PROP} , the content of a PROP

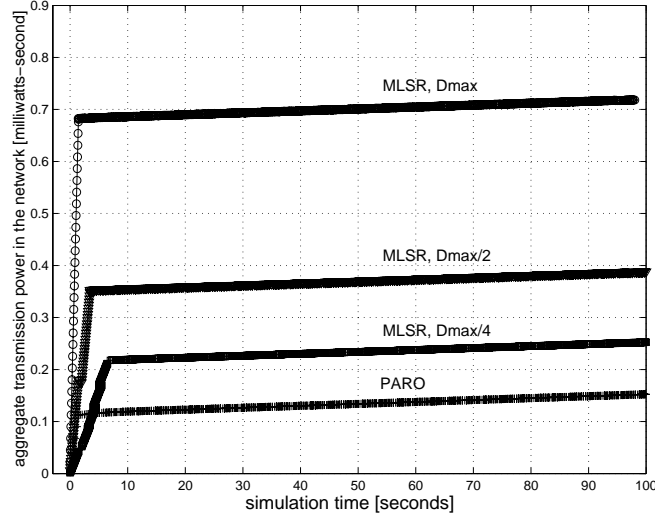


Figure 3-9: Aggregated Transmission Power Consumed by Data and Signaling for PARO and MLSR

message may require to be forwarded by other nodes to flood the entire network. Each node computes routes to any other node in the network using a standard link-state Dijkstra algorithm. In a network of N nodes, it takes K iterations (i.e., K PROP packets transmitted by each node) for the content of a PROP message to be entirely flooded in the network. The value K mainly depends on the parameter T^{PROP} and the density of nodes and size of the network.

Figure 3-9 shows a simulation trace of the aggregate transmission power consumed by both signaling and data packets for both PARO and MLSR. The network simulation consists of 30 static nodes 100x100 in size with ten UDP/CBR flows transmitting a 100-byte packet every 3 seconds. In the case of MLSR, signaling packets are first transmitted at different transmission ranges to generate full routing tables. Once routing information is available MLSR data packets are transmitted using power-efficient routes. In the case of PARO, data packets are first transmitted at high power because the range of destination nodes is unknown to source nodes.

Figure 3-9 shows the transmission “power offset” (shown in the figure as the initial fast increase in power consumption) while the routing protocol converge to optimum routes for both PARO and MLSR. In the case of MLSR, this offset is independent of the number of active sessions and dependent on the number of nodes in the network and the number of iterations required for the content of a PROP message to flood the network. This means that if there is double the number of nodes in the network then the value of the offset would roughly double. In contrast, the routing offset for PARO depends on the number of active sessions. Therefore, PARO is less sensitive to the number of nodes in the network. We observe from Figure 3-9 that relative to the power consumed by the first data and signaling packets, the contribution of data transmission to the overall power consumption is less significant. This result suggests an important design principle for future power-aware routing protocols is the avoidance of “blind” (e.g., broadcast) transmissions at high power.

In the case of the MLSR simulations, a transmission range of $D_{max}/4$ represented the lowest transmission range observed before route partitions appeared in the network. As discussed previously, route partitions appear because broadcast messages do not completely flood the network. When we consider a transmission range of $D_{max}/5$ for PROP messages (not shown in Figure 3-9), we observe that network partitions consistently appear leaving nodes with routes to only a subset of destination nodes. This result emphasize the fact that even if the performance of MLSR at $D_{max}/4$ is somewhat similar to PARO (i.e., being able to reduce its transmission range), this operation results in non-stable performance. In addition, it is unlikely that MLSR could find such a transmission range in a practical setting.

3.7. Implementation

In what follows, we discuss our experiences implementing PARO in an experimental wireless ad hoc testbed. We implemented PARO using the Linux Redhat 6.2 software platform on 700 MHz Pentium III notebooks equipped with Aironet PC4800 series radios. The Aironet PC4800 supports the IEEE 802.11 standard and provides five different transmission power levels (viz. 1, 5, 20, 50 and 100 milliwatts). The overhearing, redirecting, and route-maintenance algorithms are implemented in user space using the Berkeley Packet Filter's Packet Capture Library (PCAP) [54] for processing and forwarding of IP packets. We conducted experiments with PARO operating in both indoor and outdoor settings.

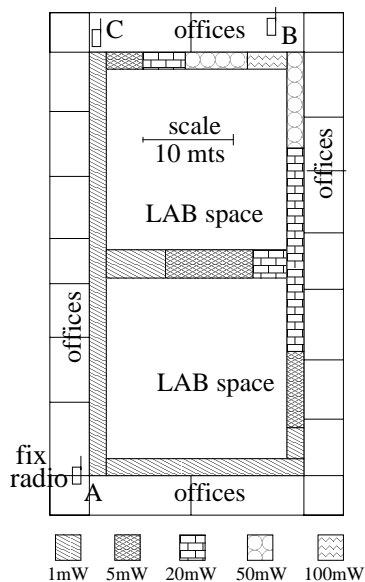


Figure 3-10: Signal Coverage at Different Transmission Powers for an Indoor Experiment

3.7.1 Propagation Model

Figure 3-10 shows the area covered by a transmitter used for our indoor experimentation. This represents an indoor laboratory environment for 1, 5, 20, 50 and 100 milliwatts transmission levels. There has been considerable work on propagation models for indoor environments [71] [59]. The main purpose of this experiment is to illustrate what can be expected for this particular IEEE 802.11 radio in an indoor laboratory setting as a basis for understanding PARO's approach to dynamic power control. In this experiment, we kept one radio in a fixed position while we moved a second radio around the corridors of the floor. Both radios use the same transmission power level and transmit five small UDP packets to each other every second.

We define the coverage area for a given transmission power level as the area for which both radios did not observe packet loss. As we can observe from Figure 3-10, the path attenuation factor for this setting is quite strong, especially around the corridor corners. The strong attenuation is mostly due to radio signals going through walls, floor, ceilings and metal obstacles. Strong attenuation factors emphasize the advantages of performing PARO-style route optimization. In the extreme case, where node A communicates with node B through node C, an aggregate transmission power of two milliwatts is required compared with the original 100 milliwatts when node A communicates directly with node B. In those environments where direct communications between two nodes is not possible due to signal obstacles, PARO can improve connectivity by adding redirectors in other locations where signals can travel more freely.

In the implementation of PARO we used two different path attenuation models in place of Equation 3.3 depending of the type of environment. For the outdoor environment we used a typical path attenuation of $n = 2$ [59]. In contrast, for

the indoor environment we used a propagation model presented in [71] with a path attenuation of $n = 3.25$ with a standard deviation $\sigma = 16.3[\text{dB}]$. The model in [71] was obtained from an office building with a large layout area divided into several smaller cubicles-style offices. The path attenuation for a transmitter and receiver separated by d meters is defined by[71]:

$$PL(d)[\text{dB}] = \overline{PL}(d)[\text{dB}] + X_\sigma[\text{dB}] \quad (3.12)$$

With $\overline{PL}(d)[\text{dB}]$ the mean path attenuation between transmitter and receiver separated by d meters and $X_\sigma[\text{dB}]$ is a zero mean log-normally distributed random variable with standard deviation σ in decibels. The parameter $\overline{PL}(d)[\text{dB}]$ is computed as follows:

$$\overline{PL}(d)[\text{dB}] = PL(d_0[\text{dB}]) + 10n \log_{10}\left(\frac{d}{d_0}\right), \quad (3.13)$$

where $PL(d_0[\text{dB}])$ is the free-space propagation from the transmitter to a 1 meter reference distance and n is the path attenuation factor. For complete details see [71].

3.7.2 Power Optimization

One initial drawback of using the Aironet PC4800 radio as a basis to implement PARO is that it could only approximate the minimum transmission power much of the time. This is a product of only offering a small set of transmission power levels. PARO software is designed to always round up to the next available power level. For example, if PARO computed the minimum transmission power to be 10 milliwatts then the packet would be transmitted at 20 milliwatts using the Aironet radio. This has the impact of using more power than necessary but the extra margin

is useful in the case of mobility and stability of routes. Figure 3-11 shows the aggregate transmission power necessary to transmit one packet between a source-destination pair using a single redirector; that is, a single packet between nodes A and B using packet forwarding by redirector node C . Node C is positioned at different locations along a line between nodes A and B . Figure 3-11 shows the power optimization results for an “ideal” transceiver (determined by Equation 3.1) against results obtained from the Aironet radio. Figure 3-11 confirms that the Aironet PC4800 transceiver can only approximate the performance of the ideal transceiver.

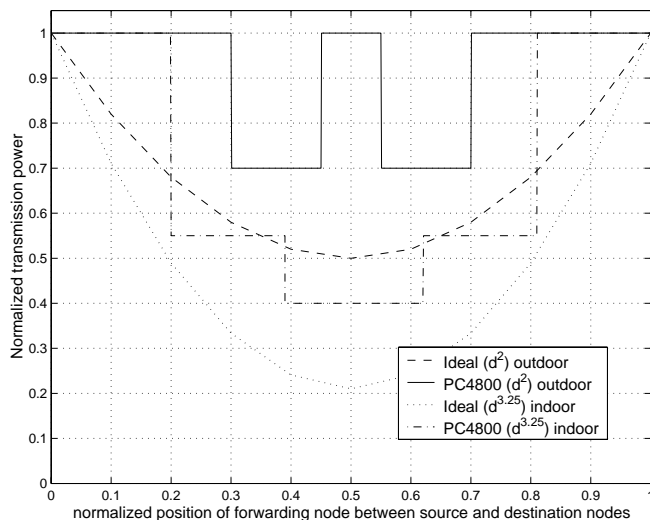


Figure 3-11: Experimental Results for Transmission Power versus the Position of a Redirector between a Source-Destination Pair for Indoor and Outdoor Environments

Table 3.1 shows the aggregate transmission power needed to transmit a single packet between nodes A and B using not one but several intermediate redirector nodes. In all cases we evenly distributed the forwarding nodes between source and destination pairs. For both outdoor and indoor environments we separated the source and destination nodes to the maximum distance allowed while transmitting

at 100 milliwatts. From Table 3.1, we observe that power optimization is better for stronger path attenuation conditions (i.e., indoor versus outdoor). This result is expected since the strength of radio waves decay faster under strong path attenuation settings. Thus, nodes in indoor environments benefit much more of the presence of redirector nodes.

	number of forwarding nodes					
	0	1	2	3	4	5
$n = 2$ (outdoor)	100	100	60	80	25	30
$n = 3.25$ (indoor)	100	40	15	20	5	6

Table 3.1: Aggregate Transmission Power versus Number of Nodes for Outdoor and Indoor Settings

3.7.3 Discussion

The experimental results show that PARO can be partially implemented using off-the-shelf radio technology providing transmission power savings. However, due to a number of limitations with existing radio and software support technology the full power savings of PARO are difficult to attain today. In what follows, we discuss our implementation experiences and the impact of these limitations on the potential gains of PARO. Much of these comments are driving our future work.

Some radio anomalies are highlighted in Figure 3-11. For example, when the redirector is positioned at the mid-point between the source and destination nodes the ideal transceiver offers significant savings. However, in the case of the outdoor experiment using the Aironet PC4800 radio, positioning the redirector at the mid-point provides no power savings. Such anomalies are mainly the product of the operational granularity (i.e., the number of transmission power levels available) of the radio used.

Almost as important as having a larger set of transmission power levels is the manner in which these different levels are spaced with respect to each other. Transmission power levels for the Aironet PC4800 radio are exponentially spaced at 1, 5, 20, 50 and 100 mW. Therefore, the Aironet PC4800 is capable of using 1 mW for destinations that are a short distance from the transmitter, and 100 mW when the receiver is far away for example. Separating transmission levels in such an exponential fashion allows for a better approximation of the minimum transmission power at both near and far distances within the maximum transmission range of the transceiver. In contrast, a linear spacing of transmission power levels provides good accuracy only at either near or far distances but not at both near and far distances.

Regarding the delay involved in switching between transmission powers, ideally the transceiver should be capable of switching transmission power at the RTS-CTS time-scale. Whether or not this is possible in the future strongly depends on how much transmission power savings would improve the overall power consumption of a device, thus, motivating transceiver designers to improve this switching speed. For the PC4800 radio this delay is approximately 7 milliseconds. During this period the radio transceiver is neither capable of receiving nor transmitting packets. As we discussed in Section 3.5., RTS-CTS packets need to be transmitted at maximum transmission power to guarantee the operation of the IEEE 802.11 MAC. This constraint means that PARO cannot fully operate using the Aironet radio because it is not possible to switch the transmission power between RTS-DATA packets (transmitting node) nor CTS-ACK packets (receiver node) given the slow switching time. The only scenario where PARO could be deployed using current IEEE 802.11 Aironet PC4800 radios is in the case where the network operates at low traffic loads. In this case, the probability of a node finding hidden terminals while transmitting a packet would be small, thus RTS-CTS is unnecessary.

The Aironet PC4800 radios permit switching RTS-CTS mode ON and OFF depending on an RTS threshold. This threshold determines the minimum size of a transmitted data packet that requires the use of RTS/CTS. When the transmitted packet is equal to, or larger than the RTS threshold, an RTS packet is sent. This threshold ranges from 0 to 2400 bytes with a default value of 2048 bytes. The rationale behind this threshold is that the presence of hidden terminals is more disruptive for larger, rather than smaller data packets. This is because a transmitting node does not learn that a collision (due to hidden terminals) has occurred until the end of transmitting a data packet. Therefore, for larger data packets a transmitting node waits longer before it retransmits a packet. RTS-CTS packets are smaller in size and, if lost due to collision, can be retransmitted quickly with little overhead in comparison to data packets. The disadvantage of using RTS/CTS is that for each data packet transmitted that is larger than the threshold size, another packet must be transmitted and received, thereby reducing throughput.

The current RTS threshold does not relate to the network load and, therefore, it cannot be used to PARO's advantage. What is needed is a threshold that switches RTS-CTS on, when the traffic load is high, and off, when the traffic load is low; this operation is equivalent to switching PARO's operation off and on, respectively. A module implementing this functionality could take advantage of the number of collisions that data packets experience (which relates to network load) in order to switch the RTS-CTS mechanism on or off. It is important to note that because packets being forwarded between a source and destination may interfere with each other, switching RTS-CTS off may work only if the inter-packet delay is longer than the end-to-end delay of the path. Such a restriction is very limiting. As we discussed earlier the introduction of new MAC protocols such as Power Controlled Media Access Protocol (PCMAP) [55] can help overcome many of these limitations.

We are studying how new MAC protocols can best offer the necessary dynamic power control support for PARO as part of our future work.

PARO proposes a cost function that makes the assumption that power consumption during the transmission mode is dominant and outweighs the collective power consumption during reception, idle and sleep modes. Therefore, in this work we only consider transmission power during data communication. We refer to a radio with these characteristics as an *ideal* radio. The full realization of an ideal radio is not possible because devices consume power during other radio operations. For example, some IEEE 802.11 radios have a power consumption of 1400mW in the transmission mode, 1000mW in the reception mode, 830mW in the idle mode, and 130mW during sleep mode [77]. Therefore, when IEEE 802.11 radios are used, applying PARO route optimization has little impact on the resulting power savings of the network interface. PARO introduces redirectors between source-destinations nodes that otherwise can communicate with each other directly. Introducing redirectors increases the number of times that a packet is received and transmitted before reaching its final destination. Until new radios are developed where the power consumption during reception is significantly smaller in comparison to power consumption during transmission then power optimization protocols such as PARO will show limited benefit.

3.8. Related Work

Previous work in the area of power optimization in wireless networks has mainly focused on reducing the power of devices at the hardware level [3] [2] [4] or at the MAC level [15] [72]. This goal is generally achieved by allowing devices to operate in low-power modes, sleeping during periods when no packets are destined for reception at a particular device.

Transmission power control in wireless networks has mainly addressed the control of the amount of interference that wireless devices operate in. In [68] work on joint power control between the base station and mobile devices determines the minimum transmission power for each mobile device for the uplink in a manner where the SIR thresholds for each communication link is met. In [34] microeconomics concepts and game theory are applied to power control in a distributed CDMA wireless system. In [55] transmission power control is used to improve the throughput capacity in a wireless packet network. In [67] power control is used to shape the topology of a multi-hop wireless network in a way that balances network-partitioning resilience versus spatial reuse.

In [49] a wireless ad-hoc network is divided into several clusters with a cluster-head responsible for handling most of the routing load in a power-efficient manner. In [39] micro sensor nodes use signal attenuation information to route packets towards a fixed destination known to all nodes in a energy-efficient way. In [81] different algorithms to discover energy-efficient broadcast and multicast trees are presented. Work presented in [73] uses a shortest-hop routing algorithm to discover the route with the lowest total cost among alternative paths from a source to a destination. The cost of each segment of the path is determined by the remaining lifetime of each forwarding node. The energy consumed in transmitting and receiving one packet over one hop is assumed to be constant in this work. In [22] an energy efficient routing protocol balances the traffic load in the network in order to maximize the lifetime of forwarding nodes.

A routing protocol addressing a similar problem space as PARO is discussed in [69]. In [69] wireless-enabled nodes discover energy-efficient routes to neighboring nodes and then use the shortest path Bellman-Ford algorithm to discover routes to any other node in the network. PARO differs from [69] in several ways. PARO

devices do not rely on the availability of GPS to track the location of mobile nodes but uses signal attenuation to discover energy-efficient routes to neighboring nodes (i.e., those nodes located within the maximum transmission range). In addition, PARO does not only target finding energy-efficient routes as a goal. Rather, PARO attempts to achieve this goal using the minimum energy. Finally, PARO is designed to operate below standard layer 3 ad-hoc routing protocols to provide wide area coverage support in mobile environments.

Development of routing protocols capable of operating in wireless ad-hoc networks is the goal of the MANET working group in the IETF [53]. Little attention, however, has been placed on power conservation by the group. Rather, MANET routing protocols [11] attempt to “minimize” the number of intermediate hops (thereby minimizing delay) between any source-destination pair in the network [64] [65] [43]. MANET protocols are based on broadcast flooding schemes and, therefore, suffer of the same drawbacks as MLSR in order to discover power-efficient routes.

3.9. Conclusion

In this chapter, we have presented the design, implementation and evaluation of PARO, a dynamic power controlled routing scheme for wireless ad hoc networks. We evaluated PARO and compared its performance to MLSR. We found that PARO consumed less power in order to find power-efficient routes compared to MLSR due to its variable-range transmission support and its point-to-point on-demand design. An implementation of the PARO system using a commercial IEEE 802.11 radio showed a basic proof of concept even though some inefficiencies and anomalies were identified. Future work needs to study the performance of Internet applications and transport protocols operating over PARO. Future work should also investigate complementary techniques that help save reception and idle power in PARO-based

wireless ad hoc networks.

The main contribution of the chapter is the design, implementation, analysis and evaluation of PARO in an experimental wireless ad hoc testbed. To our best knowledge PARO represents the first deployed routing protocol in wireless ad hoc networks that is based on the foundation of variable-range transmission control. The main goal of PARO is to reduce the overall transmission power in the network in a simple and scalable manner. Adding or removing redirectors to accomplish this goal, however, impacts traditional QoS metrics such as throughput and end-to-end delay. While PARO is not designed to provide QoS assurances it is important to understand its impact on these performance metrics. Clearly, the introduction of one or more redirectors may have a negative impact on some of these metrics (e.g., end-to-end delays). In the next chapter, we address this challenge and study application-level QoS issues (e.g., delay and throughput) under such a power-conserving regime promoted by PARO. We propose a set of enhancements to baseline PARO design presented in this chapter, called QOS-PARO, which enables applications to tradeoff application-specific QoS performance and energy conservation. QOS-PARO represents to our best knowledge the first energy efficient routing scheme that can also support this QOS-power tradeoff at the network layer.

Chapter 4

QoS-PARO: Trading-off Energy-Savings for Better Application QoS

4.1. Introduction

The impact of transmission power control on network throughput has been widely studied in the literature in the context of cellular networks [68] [34], and more recently in the case of wireless ad hoc networks [37] [7]. The later analysis focuses on the maximum capacity of the network as a function of the transmission range, node density, and average distance between source-destination pairs. In [37] the authors show that the end-to-end throughput available to each node is $O(\frac{1}{\sqrt{n}})$ for random traffic patterns where n is the number of nodes.

The main trade-off involved in a power controlled wireless ad hoc network is related to the average number of times a packet is forwarded versus the average number of interfering nodes per attempted transmission. Increasing the transmission range reduces the number of times a packet needs to be forwarded by intermediate nodes en-route to its final destination. However, increasing the transmission range increases the interference, and therefore, the channel contention every time a node attempts to transmit, thus, increasing transmission delays. An inverse trade-off

applies when the transmission range is reduced. In [37] it is shown that reducing the transmission range is a better solution in terms of increasing the traffic carrying capacity of wireless ad hoc networks. The analysis presented in [37] only considers the physical capacity of the network, and not, the inefficiency of the MAC protocol used to transport data on top of the physical network. Unfortunately, MAC protocols used in wireless ad hoc networks provide only limited performance in particular those protocols developed for shared medium access control operations [82].

4.2. QoS Performance of PARO

. In addition, the main design goal of PARO is to reduce the overall transmission power consumed by network devices. Adding and removing redirectors to accomplish this goal, however, impacts the observed application-level performance, (e.g., throughput and end-to-end delay). As a result, the performance of the MAC and PARO can impact the delivered application QoS.

The goal of this chapter is to study the interplay between power conserving networking protocols such as PARO and the observed QoS delivered at the applications. Based on the results from this study we investigate whether an enhanced PARO protocol can be designed to capture this *QoS/power trade-off* for applications that want to tradeoff better QoS performance at the expense of sub-optimal energy-savings.

The specific contributions of this chapter are as follows. We first study the performance limitations of using PARO with IEEE 802.11 and the power controlled medium access protocol (PCMAP) [55] for single and multihop wireless ad hoc operations. Next, we propose, design, implement, and evaluate an enhanced version of the PARO protocol introduced in Chapter 3 called *QoS-PARO*, which is capable of trading off application QoS and energy conservation in wireless ad hoc networks. To

our best knowledge QoS-PARO represents the first routing scheme that integrates control algorithms to realize this QoS/power trade-off in wireless ad hoc networks. QoS-PARO can also be used to establish a set of differentiated service classes in wireless ad hoc networks. For example, wireless ad hoc networks could offer two types of service classes to devices/applications: (i) a power-savings class, which optimizes power-savings at the expense of potentially poorer throughput and delay; and (ii) a controlled throughput class, which attempts to improve the throughput observed by applications/devices at the expense of sub-optimal power-savings. QoS-PARO offers a number of strategies and policies that make different services classes simple to implement. Under such a regime, applications that need preferential throughput or delay performance would subscribe to the controlled throughput class while all other applications seeking to optimize their power-savings would use the default power-savings class. Such a partitioning of applications in power controlled wireless ad hoc networks represents a new direction. We argue that future wireless ad hoc networks based on variable-range power control would need to provide service differentiation to possibly different classes of applications. These applications are yet to emerge but we anticipate that existing applications such as real-time streaming and transactional data applications would benefit from wireless ad hoc networks built on QoS-PARO techniques.

The structure of this chapter is as follows. Section 4.3. evaluates the QoS performance of a PARO network using IEEE 802.11. The limitations of the IEEE 802.11 implementation of PARO are contrasted with the performance delivered when using the PCMAP power controlled MAC [55], as discussed in Section 4.4.. A detailed discussion of the motivation behind QoS-PARO is presented in Section 4.5.. In addition, the detailed design of QoS-PARO is also presented. Following this, we study the performance of QoS-PARO using the ns-2 simulator in Section 4.6.. Related

work is discussed in Section 4.7.. Finally, we present our conclusion in 4.8..

4.3. PARO QoS Performance

In order to analyze how adding and removing redirectors in PARO impacts applications QoS we performed some experiments on a simple PARO “chain” network and a more complex “random” network using CBR/UDP traffic. In both experiments we use the same simulation environment presented in the analysis of the baseline PARO protocol discussed in Chapter 3.

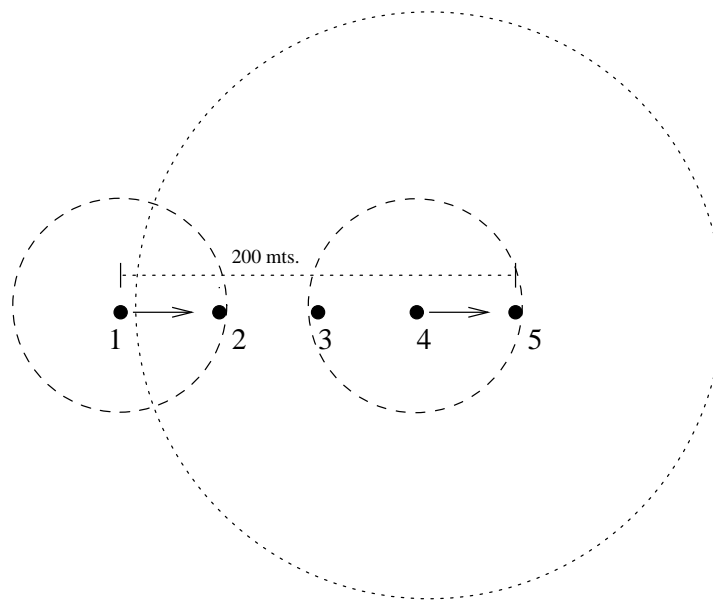


Figure 4-1: An Example of a Simple Chain Network Showing 3 Redirectors for a Source (1) and Destination (5) Pair

Definition: The *transmission range* in CSMA/CA, denoted R_x , is defined as the maximum distance from the transmitter where an overhearing node can still decode the received signal correctly. For WaveLAN IEEE 802.11 radios the receiving threshold correspond to $3.652e-10$ watts, or about 200 meters when the radio

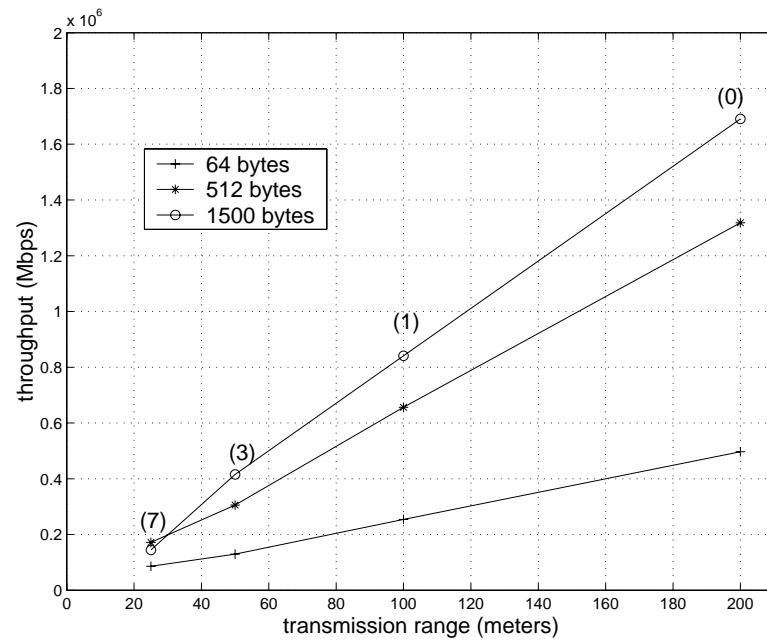


Figure 4-2: Throughput Performance of PARO

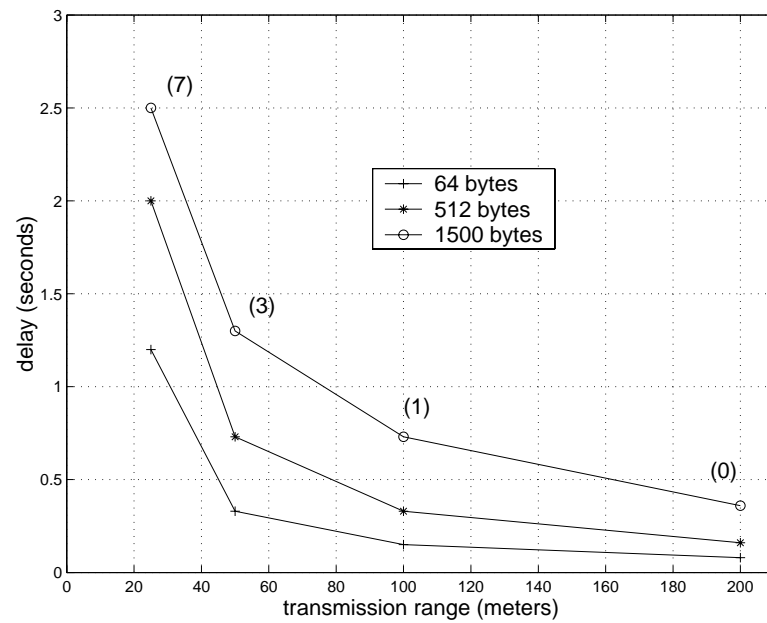


Figure 4-3: Delay Performance of PARO

transmits at nominal transmission power (0.28 watts).

Definition: The *sensing range* in CSMA/CA, denoted S_x , is the maximum distance from the transmitter where an overhearing node considers the channel busy, independent of whether or not this node can decode the received signal correctly. This sensing threshold corresponds to 1.559e-11 watts, or about 550 meters away from a radio transmitting at nominal transmission power (0.28 watts) for WaveLAN IEEE 802.11 radios.

Figure 4-1 shows the simulation scenario of a simple static chain network with the source (node 1) and destination (node 5) nodes set 200 meters apart, with three redirectors set 50 meters apart between them. A chain network refers to a network where all the forwarding nodes are located in a straight line connecting the source and destination nodes (see Figure 4-1). The dashed line in the figure corresponds to the transmission range and the dotted line to the sensing range. Figures 4-2 and 4-3 show simulation results for a varying number of redirectors between the source-destination nodes and packet sizes (viz. 64, 512 and 1500 bytes). In each case we manually locate redirectors in the simulator at equal distances between the source-destination nodes. There are no other nodes in the network beyond the nodes in the chain. As Figure 4-2 and 4-3 show, the channel utilization drops sharply and the end-to-end delay increases as the number of redirectors increase. Because all redirectors are located at equal distances between the source-destination nodes, the transmission power levels used for RTS-CTS and data packets are the same. Therefore, it is not necessary to transmit RTS-CTS packets at maximum transmission power in this scenario, as described in Chapter 3 on PARO operations. As a result, the performance results shown in figures 4-2 and 4-3 are better than the normal case where the range between redirectors is different and RTS-CTS packets are transmitted at maximum transmission power in order to maintain MAC

operations, thus, further degrading the performance.

Figure 4-4 shows the throughput performance of a wireless ad hoc network with multiple simultaneous connections and randomly positioned nodes. In this experiment there are 300 nodes in a 200x200 meters network. This network size is chosen such that nodes are capable of communicating with any other node without the need of forwarding nodes when the maximum transmission power is used. There are 20 UDP/CBR connections randomly chosen among the 300 nodes and each packet is 1500 bytes in length. All nodes transmit with the same power so RTS-CTS and DATA packets are transmitted with the same transmission power level. This is similar to the previously discussed chain network experiment. The results in Figure 4-4 show that adding forwarding nodes (e.g., reducing transmission power) significantly reduces the throughput seen by flows in the network (the number in parenthesis shows the average number of forwarding nodes along a particular path). Figure 4-4 also compares the throughput obtained by each flow with respect to the offered load per flow. When flows transmit at low rates (e.g., 1 pkt/sec), the network is able to carry the aggregate traffic load when nodes use 100 and 200 meters transmission ranges. Note, that even for a load of 1 pkt/sec the network can not accommodate the aggregate traffic load for low transmission range levels (e.g., for 25 and 50 meters transmission range levels). For higher offered loads (e.g., 5 and 20 pkt/sec), the network is able to accommodate a portion of the aggregate offered traffic load for higher transmission ranges, but it is severely limited to carry the same amount of traffic at lower transmission range levels. This limitation is mainly associated with the poor channel utilization exhibited by CSMA MAC protocols.

An important observation not shown in Figure 4-4 is that there is a high variation in the throughput obtained by flows located at either short (e.g., 0-50 meters) or longer ranges (e.g., 150-200 meters) during the same experiment. We found that

when nodes use low transmission ranges (e.g., 25, 50 meters), source-destination pairs located far away from each other achieve much lower throughput compared with source-destination pairs located near to each other. This is because source-destination pairs located far away (e.g., over longer ranges) require more forwarding nodes to communicate, severely reducing their throughput as observed in the simple chain network example.

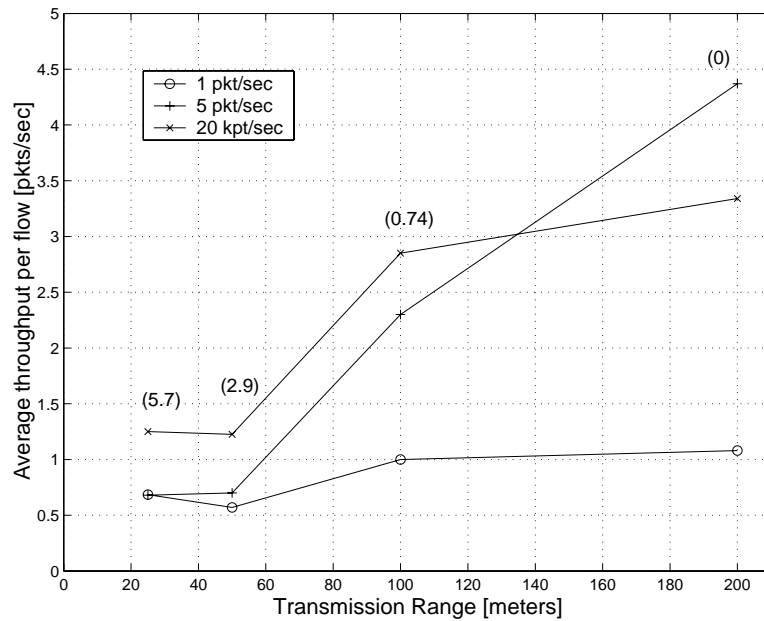


Figure 4-4: Throughput Performance of Random Ad Hoc Network versus Transmitted Power

Several factors contribute toward the observed degraded performance in both the simple chain network and the random network examples. It is widely known that IEEE 802.11 is not the best MAC protocol for multihop wireless ad hoc networks [82] and results in lower throughput and increased end-to-end delays experienced by applications [26] [7]. Referring to Figure 4-1, when node 4 transmits to node 5 no other nodes in the network can transmit during this period. This is because when node 2 senses an ongoing transmission between node 4 and node 5, it inhibits node

1 from transmitting to node 2; that is, node 2 will not send a CTS after receiving an RTS from node 1. A similar situation occurs when nodes 1, 2 and 3 transmit. As a result, the theoretical channel utilization of this simple chain network is $\frac{1}{4}$ of the maximum capacity. In fact Figure 4-2 shows that only $\frac{1}{5}$ of the maximum throughput is achieved. Similar results are discussed in the literature [26]. Decreasing the transmission range not only reduces the number of transmission opportunities that redirectors can use for their own transmissions, but every time a node attempts a transmission and senses the medium busy, it backs off an exponentially increasing period of time after each failed transmission attempt before trying again to transmit using the CSMA/CA access protocols. We now discuss two main factors that contribute toward the poor performance of CSMA/CA protocols in multihop operations.

4.3.1 Sensing and Reception Ranges

Sensing and transmitting ranges impact the performance of CSMA/CA based (e.g., IEEE 802.11) multihop wireless ad hoc networks. An ongoing transmission by a node inhibits any other node transmitting within its sensing range. Table 4.1 shows the equivalent sensing range for a given transmission range using the carrier sense and reception thresholds for the WaveLAN IEEE 802.11 radio. Table 4.1 shows this for different numbers of redirectors. In each case the transmission power is the minimum transmission power between adjacent redirectors. Table 4.1 also shows the ratio between sensing and transmission ranges ($\frac{S_x}{R_x}$). This ratio is a very important parameter not only for the performance of PARO but also for the performance of any multihop routing protocol (e.g., DSR, AODV, TORA, etc.). This is because whenever a forwarding node is actively transmitting it inhibits $\frac{S_x}{R_x}$ other forwarding nodes from transmitting at the same time. A high $\frac{S_x}{R_x}$ ratio limits the number of

simultaneous transmissions along a given route, thus reducing the overall channel utilization. The $\frac{S_x}{R_x}$ ratio does not remain constant but increases as the number of redirectors increase, as shown in Table 4.1. Thus, reducing the overall channel utilization as the number of redirectors increase.

number of redirectors	transmission range (Rx) [meters]	sensing range (Sx) [meters]	Sx/Rx ratio
0	200	550	2.75
1	100	220	2.2
3	50	144	2.88
7	25	102	4.08

Table 4.1: Sensing Range/Reception (Sx/Rx) Range Ratio for the IEEE 802.11

4.3.2 Spectral Reuse

As discussed in Section 3.3.1 most propagation models assume the strength of the received signal to be $\sim \frac{1}{d^\gamma}$ fraction of the strength of the transmitted signal. The higher the value of γ the faster the signal strength decays with distance, and therefore, the closer two transmitting nodes can be to each other without interfering with each other's transmissions. For indoor environments most propagation models assume an attenuation proportional to $\sim \frac{1}{d^4}$, thus, contributing toward a higher spectral reuse in the wireless network. In the case of outdoor environments some propagations models consider an attenuation of $\sim \frac{1}{d^2}$ or consider a two path loss model. The later model considers two regions: a first region where the signal attenuation is proportional to $\sim \frac{1}{d^2}$ (inside the Fresnel Zone), and a second region outside the Fresnel Zone where the signal attenuation is proportional to $\sim \frac{1}{d^4}$. Because the distances between redirectors in the PARO protocol are mostly within the $\sim \frac{1}{d^2}$ zone instead of the $\sim \frac{1}{d^4}$ zone there is less spectral reuse when using PARO in outdoor environments. Ideally, it is desirable to have the sensing range closer to the

transmission range in order to increase the spectral reuse in the network. This goal can be achieved by lowering the minimum signal to interference ratio (SIR) that a node can tolerate when receiving a packet correctly. However, such a change would increase the complexity of the hardware and similarly its cost.

In the previous chapter we show why RTS-CTS packets must be transmitted at maximum transmission power in order to guarantee MAC operation of IEEE 802.11 based PARO networks. Such operations cannot exploit the spectral reuse potential in the network, however. A node transmitting a packet to another node in close proximity at the minimum transmission range has to use RTS/CTS at full transmission range for correct operation of the communication system.

While IEEE 802.11 does not exhibit good performance in wireless ad hoc networks, there may be other MAC protocols for shared media that may offer better performance for multihop wireless ad hoc operations. The power controlled media access protocol (PCMAP) [55] [55] is one such protocol. PCMAP solves the common RTS-CTS high transmission power limitation found in IEEE 802.11 based multihop networks. In contrast to the IEEE 802.11 protocol where all nodes must transmit RTS-CTS packets with a common agreed transmission power, PCMAP allows nodes to transmit RTS-CTS with any transmission power without disrupting the operation of other nodes in the network, thus increasing spectral reuse in comparison to IEEE 802.11. While PCMAP improves the performance of shared medium multihop networks, its performance is still limited by the use of CSMA/CA links.

4.4. Power Controlled Media Access Protocol (PCMAP)

PCMAP provides spectral reuse gains in shared channel wireless networks where nodes use power control to communicate. PCMAP is based on two fundamental design principles: (i) *power conservation principle*, which dictates that each source

must transmit using the minimum transmission power necessary to reach the intended receiver (representing the same meaning of the minimum transmission power as in the case of PARO; and (ii) *cooperation principle*, which dictates that no source that initiates a new transmission can disrupt on-going transmissions by transmitting too “loud”.

PCMAP uses two separate frequency channels for its operation. One channel is used for the data traffic while the other channel is used for signaling. The packet exchange on the data channel uses a request-power-to-send (RPTS) acceptable-power-to-send (APTS) DATA-ACK packet handshake, which is similar to the RTS-CTS-DATA-ACK sequence used in IEEE 802.11. The purpose of the RPTS-APTS exchange that precedes data transmission is similar to the RTS-CTS, except that its purpose is not to force hidden terminals to back off. Rather, it is to let source and destination nodes compute the minimum transmission power to communicate with each other (the power conservation principle). In PCMAP, active receivers advertise a periodic busy tone on a signaling channel to other potential transmitters including their maximum tolerance to admit extra noise (e.g., interference). A node intending to transmit a packet must first sense the busy tone signal on the signaling channel. If a busy tone exists, then the node adjusts its transmission power such that it does not disrupt on-going transmissions prior to communication with its intended receiver (the cooperation principle).

Performance results shown in [55] indicate that PCMAP allows for a greater number of simultaneous transmissions than IEEE 802.11 by reducing the transmission power levels to the minimum levels necessary to guarantee successful reception by the intended destination, thus improving the channel utilization. The benefits of using PCMAP over IEEE 802.11 increase as the traffic becomes more localized (e.g., when nodes communicate with other nodes in their neighborhood only).

A negative property of the performance of PCMAP is that it favors short-range transmissions over long-range ones under high traffic loads [55]. We highlight this observation because it is this unfairness that we use to our advantage in the QoS-PARO proposal discussed in Section 4.5. in support of QoS differentiation. We implemented PCMAP in a network simulator in order to first understand this unfairness behavior, and second, in order to experiment with PARO using PCMAP.

4.4.1 PCMAP Simulation Environment

We use the *ns* network simulator with the CMU wireless extension [1] to simulate the operation of PCMAP, as defined in [55]. The simulator supports physical, link, and routing layers for single/multi hop wireless ad hoc networks. The propagation model is based on a two-ray model, which is appropriate for outdoor environments where a strong line of sight signal exists between the transmitter and receiver nodes, and where the antennas are omnidirectional. The two-ray propagation model assumes there are two main signal components. This model computes the strength of the received signal at the destination nodes as:

$$R_{j,i} = \frac{T_{i,j}G_tG_rh_t^2h_r^2}{d^4} \quad (4.1)$$

where $R_{j,i}$ is the received power at node j when node i transmits with power $T_{i,j}$, d is the distance separating transmitter from the receiver over, and G_t h_t^2 and G_r h_r^2 are the antenna gain and antenna height of the transmitter and receiver nodes, respectively.

After receiving a packet each node invokes the propagation model to determine the power at which the packet is received. If a node determines that the packet was successfully received (e.g., the received power was above a certain threshold) it passes the packet to the MAC layer. If the MAC layer receives an error-free packet

it passes the packet to the link layer, and so on.

In the evaluation discussed in Section 4.6, we consider static networks only. We did not consider mobility here because mobility adds another dimension and complexity to the problem, as we discussed in Chapter 3. The same ideas and solutions presented in the baseline PARO to support mobile nodes such as keeping a minimum rate of packets flowing between source-destination pairs and increasing the minimum transmission power of each transmission are applicable to both IEEE 802.11 and PCMAP access protocols.

Similar to IEEE 802.11, a packet is successfully captured by a node's wireless network interface in PCMAP if the sensed power of the received packet is above a certain minimum value¹ otherwise the packet cannot be distinguished from background noise/interference. Communication between two nodes in PCMAP uses RPTS-APTS packet handshake signaling before the actual data transmission takes place. We reuse the same module to compute the minimum transmission power used in the baseline PARO protocol and compute the minimum transmission power in PCMAP (refer to Chapter 3 Section 3.3.1 to see how PARO computes the minimum transmission power between two nodes). In the PCMAP implementation, however, we add a local copy of the noise to the packet header of each transmitted packet, as defined in the specifications of PCMAP [55]. This addition is necessary for PCMAP because the noise (or interference) levels are not negligible as is the case with the baseline PARO evaluation. PCMAP operations including the conservation and cooperation principles are implemented according to [55].

Figure 4-5 shows the performance of PCMAP using a 250 meters connectivity range. There are 100 nodes in a 1000x1000 meter network with a 100 flows each

¹For Wavelan, this value corresponds to 0.2818 watts for the normal power transmission; 1.559e-11 watts for the carrier sense threshold to detect a collision; and 3.652e-10 watts for the sensitivity of receiver.

sending 2 kB packets. Only 1 hop exists between source and destination nodes, for a connectivity range of 250 meters. Each source selects a destination at random within its 250 meters range. Figure 4-5 shows the fraction of total packets received by destinations over five distance ranges (viz. 0-50, 50-100, 100-150, 150-200, and 200-250 meters, respectively) from their associated sources (we use the same 5 intervals used in [55] for comparison), which transmit either 1 or 64 packets per second. A fair MAC protocol would result in a linearly increasing number of packets transmitted at each range since the number of receivers at each range increases by $2\pi R$, where R is the range from the source node. In Figure 4-5, we can observe that for 1 packet per second PCMAP supports fair behavior because the fraction of packets sent increases linearly with range. In the case where the network operates under heavier traffic conditions, the fraction of the packets sent over longer distances decreases due to the unfairness behavior of power-controlled MACs toward longer range transmissions, as discussed earlier.

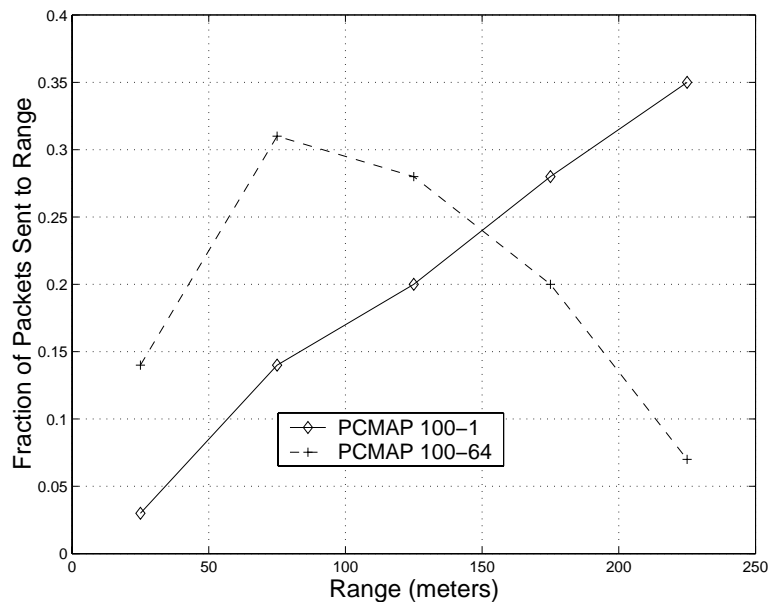


Figure 4-5: PCMAP: Fraction of Packets Sent to each Range and Traffic Load

In Table 4.2 we show the number of destinations and the unfairness factor over each range used for the same network setup as shown in Figure 4-5. The unfairness factor in this case expresses the transmission opportunities to destinations located within different transmission ranges. For example, one of the 14 destination nodes located within the 100-150 meters range from their respective sources has 7 times more transmission opportunities than any of the 36 destinations located within the 200-250 meters range from their respective sources. An extreme example of this unfairness phenomena exhibited by PCMAP is reflected in that any of the 3 destinations located within the 0-50 meters range have 23 times more transmission opportunity than any of the 36 destinations located in the 200-250 meters range. In fact, in the setup for the experiment shown in Figure 4-5, the 3 destination nodes located in the 0-50 meters range have an aggregate throughput higher than the aggregate throughput of the 36 destinations located in the 200-250 meters range. These results best illustrate the inherent unfairness of PCMAP.

Range [meters]	Number of Flows	Unfairness Factor
0-50	3	x23
50-100	14	x10
100-150	19	x7
150-200	28	x3
200-250	36	x1

Table 4.2: Throughput unfairness of PCMAP

Figure 4-6 further illustrates the root of this unfairness. In this example several sources transmit to destinations located at different transmission ranges. The solid circles shown in Figure 4-6 correspond to the sensing ranges of the on-going transmissions. Nodes A and B attempt to initiate new transmissions to nodes C and D, respectively (shown as dotted circles in Figure 4-6). The cooperation principle of PCMAP dictates that no new transmission can disrupt any of the on-going trans-

missions. Therefore, node B is likely to find the medium busy and backoff more often than the source node A, which only needs to sense if the medium is free in a much smaller area in comparison with source node B.

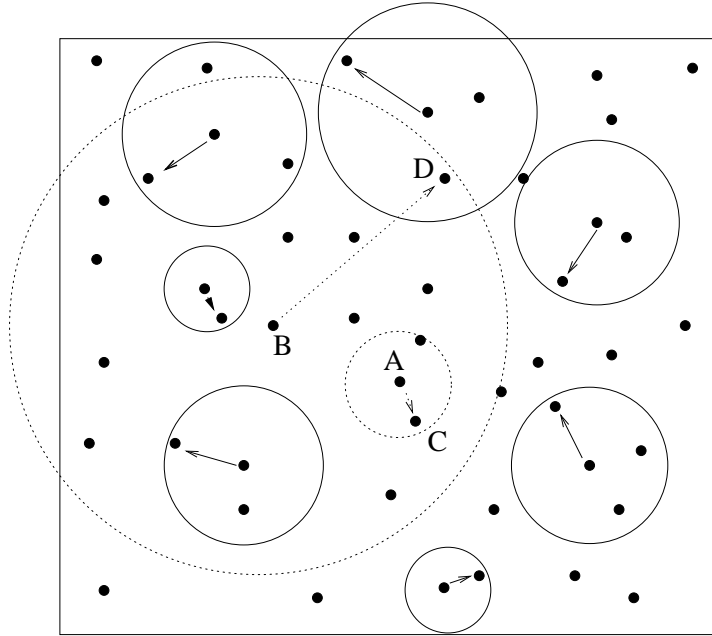


Figure 4-6: Example of the Transmission Unfairness of Long-range Transmissions in a Power-controlled MAC

The inherent unfairness toward long-range transmission is not specific to PCMAP, but is a common behavior of power-controlled MACs that provide higher spectral reuse in the network. Counter intuitively, we use this unfairness as a basis for providing service differentiation in wireless ad hoc networks. The intuition is as follows. If we break a long-range transmission into shorter-range transmissions, as the baseline PARO is capable of doing, then we can likely increase the transmission opportunity of the resulting shorter-range transmissions, improving the end-to-end QoS observed by a particular flow. Such an approach, however, may be detrimental to other flows and to the overall capacity of the network to carry traffic. In what

follows, we study this tradeoff. We call this tradeoff “QoS-PARO” and discuss its benefits in more details in the next section.

Without this unfairness toward long-range transmissions exhibited by power-controlled MACs, adding redirectors to a flow/path would degrade the throughput and delay performance observed, impacting other flows in the network. For range-independent type of MACs, the addition of redirectors makes sense when the performance metric of interest is solely energy-savings. The availability of power-controlled MACs on the other hand provides a window of opportunity for research into the design of systems that can target energy-savings, and, possibly QoS differentiation. We study these issues and open questions in what follows.

4.5. QoS-PARO: Realizing the QoS-Power Trade-off

In the previous discussion we showed how adding redirectors to routes impacts application layer QoS such as throughput and delay. Now we consider building QoS mechanisms into a baseline PARO system for specific applications that wish to trade-off better QoS performance for sub-optimal power-savings. This tradeoff, to our knowledge, has not been discussed in the wireless ad hoc literature. This tradeoff could be achieved by simply limiting the number of redirectors introduced between a source-destination pair, thereby enabling certain coarse control of the throughput and delay performance seen by the applications. When enabling the addition or removal of redirectors to achieve QoS control, however, we need to pay particular attention to which users can add or remove redirectors in order to assure “stable” and meaningful operations for the wireless network as a whole. This is because adding one redirector to one flow impacts the QoS performance of possibly (in the worst case) all other flows in the network. Allowing all flows to add or remove redirectors may result in an unstable solution where each flow attempts to

optimize its own QoS/power constraints at the same time. As an example, consider a flow X that determines that no redirectors should be added to its path because it has a minimum delay requirement. Because flow X has no control over the number of redirectors introduced by neighboring flows, other flows around flow X can severely degrade the QoS performance obtained by flow X , without flow X being able to do anything in response. We call this phenomenon the *domino effect*. The domino effect can be seen as the global impact of a local greedy strategy by a node/application/user. In order for session X to have certain control over its QoS, it is insufficient to control the number of redirectors used by flow X only. Rather, it is necessary to control the number and the position of redirectors in the network in a certain manner.

In order to control the impact of the domino effect in the network it is necessary to limit the number and rate of adding or removing redirector operations in the network. The simplest way to accomplish this objective is to limit the number of flows that are allowed to add or remove redirectors. For example, *gold plan* users can have such control to optimize their application performance while *silver plan* users cannot. This policy essentially differentiates between the population of nodes/users/applications in the network. Such a policy would help to limit the number of gold service users by an ISP in order to support the differentiated service quality over the silver users. QoS-PARO is motivated by this model. As the name suggest, QoS-PARO tradeoffs transmission power and QoS performance for flows in wireless ad hoc networks. In QoS-PARO, we propose that only a subset of flows/applications is given the capability of adding or removing redirectors. The remaining applications would use a commonly agreed transmission power without redirectors. Flows with the flexibility of adding or removing redirectors in this manner would be more sensitive than other flows in terms of their QoS requirements.

For example, some applications may be transmitting rate-sensitive information such as low-rate audio or important alarm messages, while other applications may transmit delay-insensitive information such as local temperature measurements as in the case of sensor networks. More specifically, let's define “Q-P sensitive” for flows (high priority) that are QoS and power sensitive and “Q-P insensitive” (low-priority) for flows that tolerate best effort QoS. Separating flows using different priorities is not a limitation of QoS-PARO, but a common property of protocols that attempts to improve the average performance or a certain set of flows in detriment to others, as is the case of the DiffServ model discussed in the IETF [24].

4.5.1 Protocol Description

QoS-PARO protocol is defined by the *monitoring-control* and *positioning* operational phases. During monitoring-control periods, Q-P sensitive receivers monitor the continuous flow of packets from their respective sources and may decide to take QoS-Power control actions or not based on a user/application specific policy. During the positioning period, redirectors can be dynamically added or removed from routes of Q-P sensitive flows. Positioning redirectors is concerned not only with adding or removing redirectors from the network path, but also with the location where redirectors are positioned in relation to Q-P sensitive flows.

Figure 4-7 illustrates the operational cycle of QoS-PARO. In this figure, we show an example trace of the performance behavior for a QoS metric (e.g., throughput, delay, etc.) for a “hypothetical flow” over time. The QoS-PARO cycle has *active* and *normal* operational periods. During active periods, Q-P sensitive flows can add or remove redirectors from their paths in order to coarsely modify their QoS/power performance trade-off. Different Q-P sensitive flows may have different QoS/power policy objectives. However, there are several base policies that Q-P sensitive flows

must obey while adding or removing redirectors in order to assure the stable operation of the wireless network (we will explain these baseline policies below). After a Q-P sensitive flow finishes adding or removing redirectors from its path, it moves into a “normal” operational mode for an interval when no redirectors can be either added or removed even if during that interval the observed QoS performance changes. The motivation for having active and normal periods in QoS-PARO is to make unlikely that two Q-P sensitive flows in the same neighborhood add or remove redirectors from their paths at the same time. The reason why this is important is because having two Q-P sensitive flows modifying the number of redirectors in such a manner would interfere with the QoS performance values that are being monitored by each user, possibly leading to unstable measurements. The duration of active and normal intervals is discussed below.

Active intervals are composed of several monitoring and positioning periods. Figure 4-7 focuses in on one active interval for further elaboration. A destination node monitors the performance of a metric (e.g., end-to-end packet delay, energy-savings, etc.) for sometime before a specific policy being used would trigger the addition or removal of redirectors. The duration of monitoring periods should allow for the reception of multiple packets to compute the average value of the metric being measured or controlled (e.g., average end-to-end delay). The duration of active periods depends on the specific policy being used and may extend over several monitoring/positioning intervals. Let us define the average duration of an active period as \bar{T}_{active} and let U_{Q-P} be the number of Q-P sensitive flows in the network. We compute the duration of normal intervals T_{normal} as a random variable uniformly distributed between $[\frac{1}{2}U_{Q-P}\bar{T}_{active} \quad 2(U_{Q-P}\bar{T}_{active})]$. The constant $U_{Q-P}\bar{T}_{active}$ is the non-overlapping sum of the active periods for all Q-P sensitive flows. The factor $\frac{1}{2}U_{Q-P}\bar{T}_{active}$ in the brackets bounds the minimum interval between two active

periods, while the factor $2U_{Q-P}T_{active}$ reduces the probability of two or more Q-P sensitive flows having overlapping active periods.

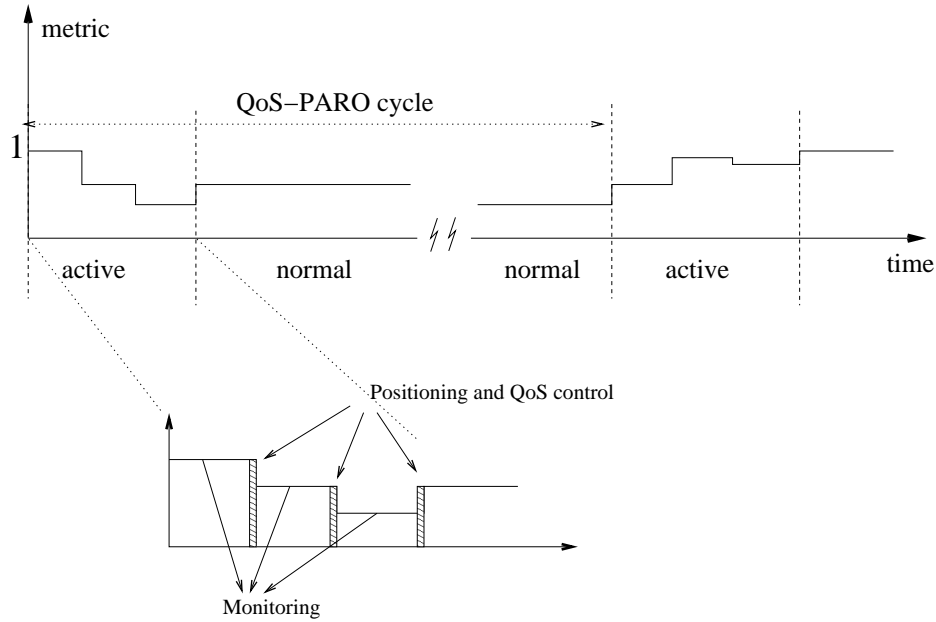


Figure 4-7: QoS-PARO Life Cycle

In what follows, we discuss the QoS-PARO operational periods in more detail. Because IEEE 802.11 does not have good spectral reuse performance due to its lack of power control support, we will assume a power-controlled MAC protocol such as PCMAP [55] in the rest of this chapter. However QoS-PARO would be capable of operating over any power-controlled MAC [25].

4.5.2 Monitoring-Control Phase

Figures 4-9(a) and 4-10(a) illustrate an example of a network with a source node S transmitting to a destination node D . In both figures node D monitors the continuous reception of packets from source S and computes the observed performance using certain performance metrics. In the design of QoS-PARO we consider the fol-

lowing metrics: packet delay (PD), packet throughput (PT) and transmission power (TP). However, other metrics could also be monitored depending on a particular application/policy. Based on the monitoring of one or more metrics at the receiver (e.g., node D in this example), the receiver decides whether the observed QoS/power performance is satisfactory based on the user-specific policy being used, and may take further action to modify the number of redirectors in its path during this active period.

4.5.3 User Policy

Optimizing a metric to achieve a certain performance (e.g., minimize PD or maximizing PT) level by adding or removing redirectors is difficult and it is not always feasible due to the “domino effect” discussed earlier. In addition, multihop wireless networks have a maximum traffic carrying capability and the upper bound capacity is shared by all active flow sessions in the network. Optimizing throughput and delay, as well as transmission power, simultaneously is extremely challenging because optimizing throughput and delay is orthogonal to optimizing transmission power in most circumstances.

Adding redirectors impacts and reduces the overall capacity of the network to carry traffic, as we discussed in Section 4.3.. This property applies to both IEEE 8022.11 and PCMAP MAC protocols. Adding redirectors, however, does not necessarily degrade the QoS performance observed by “all” flows in the network. During the discussion of PCMAP we showed that a session transmitting over a long-range link has less opportunity to transmit under power-controlled MACs [55] in comparison to sessions transmitting over shorter-range links. Therefore, under certain conditions breaking a longer-range link into shorter-range links by adding redirectors improves QoS performance in comparison to the same flow having no redirectors

along the path.

In QoS-PARO, gold users have no performance goals restrictions. What QoS-PARO does restrict on the other hand, are the policies (e.g., mechanisms or rules) that gold users can use while attempting to reach their individual QoS and energy savings goals. These policies are necessary to limit the inherent QoS degradation in the network resulting from the addition and removal of redirectors by gold users. In QoS-PARO we identify three stable operational points or policies that are feasible for Q-P sensitive flows (gold users):

- *No Power Control (NPC)*: This is the default behavior of IEEE 802.11 or PCMAP based networks without redirectors (e.g., packets are transmitted directly between source-destination pairs). This case corresponds to transmitting with the maximum transmission power in IEEE 802.11, or with the minimum transmission power between source-destination pairs in PCMAP based networks. We have already shown that under such conditions the best QoS in terms of throughput and delay is achieved because no costly packet forwarding is involved. We also discussed earlier that use of PCMAP under such conditions provides improved performance over IEEE 802.11 due its better spectral reuse properties [55]. However, applying no power control means that more transmission power is used in comparison to alternative routes using forwarding nodes. This policy favors traditional QoS performance but is detrimental to the transmission power and energy power savings in the network.

- *Metric Saturation Point (MSP)*: Under this policy gold users (or all users if the performance metric is transmission power) are allowed to actively add or remove redirectors. We define the metric saturation point, as the point where the action of adding one more redirector to a path would not provide any significant improvement in the performance of a particular metric being controlled. The reader

my recall that we make a similar point in Chapter 3 where we analyzed the power optimization performance of the baseline PARO protocol. In that experiment, we show that the addition of a fourth redirector to flows in networks where nodes are positioned randomly only provides a 3% power savings increase. We therefore define the parameter δ_{metric} as the minimum metric improvement that makes the addition of a redirector worth it in terms of additional performance improvement. The idea behind limiting the number of redirectors is to limit the potential negative effect of adding more redirectors in terms of additional QoS degradation observed by other flows (both Q-P sensitive and insensitive flows) in the wireless network.

- Greedy-PARO: Under this policy a subset of nodes in the wireless network would be allowed to add or remove redirectors in order trade sub-optimal power savings for improved QoS. We believe that there is an emerging need for such a service in energy-conserving wireless networks, as new applications appear (e.g., distribution of control information in sensor networks). Each of the selected flows (e.g., Q-P sensitive flows) is capable of adding and removing redirectors in order to achieve their QoS/power performance tradeoff in a greedy fashion (e.g., each node may have different QoS/power tradeoff objectives). We define the targeted performance of such a flow as $QoS/Power^{target}$. This target could be application specific, service class specific or a default for all Q-P sensitive applications in the network. We define monitored performance of supporting N redirectors in a path as $QoS/power_N^{measured}$. During the monitoring-positioning periods, a Q-P sensitive flow will add or remove redirectors in order to bring the observed performance $QoS/power_N^{measured}$ closer to the target performance $QoS/Power^{target}$. In all cases Q-P sensitive flows can add redirectors as long as the metric saturation point policy described above has not been reached, which is a necessary requirement to maintain the operation of the network.

The performance of application QOS metrics such as throughput or delay could be improved by either adding or removing redirectors, depending on the specific operational conditions experienced. Under certain conditions the throughput and delay performance may improve by adding redirectors due to the unfairness behavior of power controlled MAC, as discussed earlier. However, in other situations removing redirectors could improve the throughput and delay performance because less costly packet-forwarding takes place. As a result Q-P sensitive flows may need to determine experimentally whether adding (*adding-search*) or removing (*removing-search*) redirectors leads to better performance or not as the case may be. The following algorithms control the addition and removal of redirectors during an active period determining this tradeoff point.

Adding-search {# Currently N redirectors in the pathif ($QoS|Power_N^{measured} < QoS|Power^{target}$)

⊙ add redirector

if($QoS|Power_{N+1}^{measured} > QoS|Power^{target}$)

stop // begin quite interval

elseif($QoS|Power_{N+1}^{measured} > QoS|Power_N^{measured}(1 + \delta_{metric})$)

N ++

goto ⊙

else remove redirector

}

Removing-search {# Currently N redirectors in the pathif ($QoS|Power_N^{measured} < QoS|Power^{target}$)

⊙ remove redirector

if($QoS|Power_{N-1}^{measured} > QoS|Power^{target}$)

stop // begin quite interval

elseif($QoS|Power_{measured}^{N-1} > QoS|Power_{measured}^N(1 + \delta_{metric})$)

N --

goto ⊙

else add redirector

}

It is important to note that even if a flow is able to reach its target performance level during an active period, we cannot guarantee that the performance level can be maintained during preceding normal operational periods. This is because during these periods other flows may attempt to optimize their own performance metrics thereby affecting by some magnitude the QoS performance observed by all other flows in the network, as is the case with the domino effect.

4.5.4 Redirector Positioning Phase

We show how the number of redirectors between source-destination pairs impacts QoS performance. The manner in which redirectors are positioned (i.e., distributed in the network) between source-destination pairs also impacts the QoS performance observed by flows and energy savings. In what follows, we discuss how redirectors can be positioned between source-destination pairs in QoS-PARO based networks.

4.5.4.1 Optimal versus Incremental Positioning of Redirectors

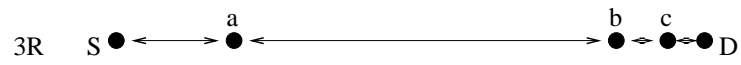
Figure 4-8(a) illustrates an example of how 3 redirectors could be positioned on a straight line between nodes S and D . We use this simple scenario to illustrate the impact of positioning redirectors in different locations. Since the transmission energy necessary to reach a receiver increases exponentially with range, the power savings performance of a route (as discussed in chapter 3) is dominated by the longest link of the final route, which in this example corresponds to link $a \leftrightarrow b$. Because link $a \leftrightarrow b$ is almost as long as the original link $S \leftrightarrow D$ (with no redirectors), little power is saved in this example.

QoS performance is more difficult to analyze in comparison to the transmission power case because of all the simultaneous interference interactions among transmitting nodes in the network (domino effect). In general, however, one important factor that impacts QoS performance is the combination of both the number and the location of redirectors in the network. Because link $a \leftrightarrow b$ in the figure is as long as the original link $S \leftrightarrow D$ without redirectors, there is an insignificant reduction in the overall interference generated by a packets traveling between node S and node D . In addition, the two redirectors located near node D do not help reducing the interference significantly. Rather, they add costly packet forwarding that can severely degrade the QoS performance, as shown in the simple chain network example.

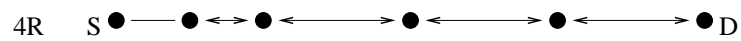
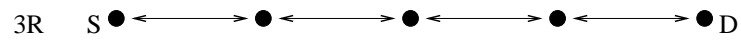
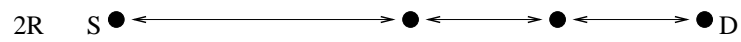
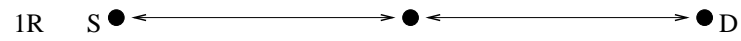
It is intuitive from Figure 4-8(a) that the “optimal” way to position redirectors between source-destination pairs is to position redirectors at equal distances from each other. This positioning of nodes is illustrated in Figure 4-8(c) for 0, 1, 2, 3 and 4 redirectors, respectively. Positioning redirectors in this manner minimizes the length of the longest link, thus contributing toward lower interference and transmission power levels along the route.

In practice, however, optimal positioning of nodes in this manner is difficult to achieve in real networks. This is because wireless ad hoc networks represent distributed computing environments where location information is difficult to obtain or inaccurate, if available. In addition, low node density may not provide the opportunity to find potential redirector nodes located at the positions where optimization is possible. Another drawback of the optimal positioning of redirectors (best illustrated by Figure 4-8(c)) is related to the fact that redirectors on row N do not belong to the route when one redirector is added to the route (row $N + 1$), or when one redirector is removed from the route (row $N - 1$). In other words, adding or removing one redirector from an optimum path requires finding a new set of redirectors altogether. Finding and positioning redirectors may be also costly in terms of the signaling overhead and the delays associated with these operations. This is certainly true in wireless networks where QoS variations require the continuous adjustments of the number of redirectors per flow. These drawbacks suggest that “incremental” positioning of redirectors, such that redirectors found in row N can be “recycled” in rows $N + 1$ and $N - 1$ would be more appropriate from a practical network implementation perspective.

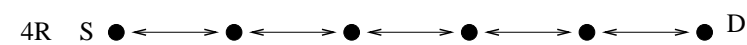
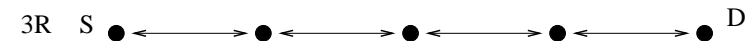
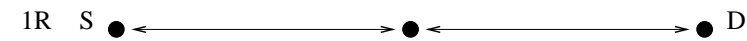
The most appealing method of implementing incremental positioning of redirectors is to break the longest link in a route into two equal-size links anytime a new redirector needs to be added to a route. As discussed in Chapter 3, the baseline



(a) Example of 3 Redirectors



(b) Incremental Positioning of Redirectors



(c) Optimum Positioning of Redirectors

Figure 4-8: Optimum and Incremental Location of Nodes

PARO protocol supports this operational principle. Figure 4-8(b) illustrates such an incremental positioning of redirectors between nodes S and D for 0, 1, 2, 3 and 4 redirectors, respectively.

Incremental positioning of redirectors, however, introduces some inefficiencies in the system in comparison with the optimal solution discussed earlier. Table 4.3 quantifies both the interference and the transmission power generated while transmitting a single packet between node S and node D using the incremental and optimal solutions as is illustrated in Figures 4-8(b) and (c), respectively. The interference and transmission power in this example is the summed over all hops visited by a packet between the source and destination nodes including the source node. We assume a path attenuation of $\frac{1}{d^4}$. The values of both interference and transmission power are normalized for the case of no redirectors (0R). Table 4.3 highlights the inefficiency of using an incremental versus optimal positioning scheme. Optimal and incremental positioning of nodes overlap for 0, 1 and 3 redirectors so there is no performance degradation when using incremental positioning of redirectors in these cases. Similarly, there is only a 5% and 2% interference increase, and 4% and 1% transmission power increase when using incremental positioning of 2 and 4 redirectors, respectively. These results suggest that an incremental positioning of nodes does not degrade the performance of the system significantly. For real networks where nodes are located at random locations the difference in performance may be lower. In the evaluation section we compare optimal and incremental positioning of redirectors for random networks and finite node density. The fact that the incremental positioning of redirectors is easier to deploy provides a better foundation to built interference and power-aware systems in wireless ad hoc networks. Because the baseline PARO protocol is based on the incremental positioning of nodes, it can be used to control both QoS and energy savings (as discussed in Chapter 3) using

the same basic protocol operations.

Number of Redirectors	Interference			Tx Power		
	Opt.	Inc.	% Inc. Error	Opt.	Inc.	% Inc. Error
0R	1	1	0%	1	1	0%
1R	0.5	0.5	0%	0.125	0.125	0%
2R	0.33	0.38	5%	0.035	0.07	4%
3R	0.25	0.25	0%	0.016	0.016	0%
4R	0.20	0.22	2%	0.008	0.012	1%

Table 4.3: Optimum versus Incremental Positioning of Nodes

4.5.4.2 Positioning Redirectors

We have shown how the baseline PARO protocol has the ability to efficiently position redirectors in an incremental manner. In order to support QoS-PARO redirector positioning we require a modification of the baseline PARO protocol, however. This requires controlling the addition and removal of redirectors in order to enable some control over the QoS performance and energy savings based on a certain QoS/power trade-off policy.

In order to explain how QoS-PARO controls the positioning of redirectors, we first review the baseline PARO operations, as illustrated in Figure 3-3 in Chapter 3. The figure illustrates a route taken by data packets after each iteration of the PARO protocol where the intermediate nodes are selected as redirectors after transmitting route-redirect requests. The basic PARO protocol adds as many redirectors to a route as is possible. In the example shown in the figure, one redirector is added during iteration 1, two redirectors are added during iteration 2, and finally, one more redirector is added during iteration 3. The example shown represents a low node density scenario so no more redirectors are available after the third iteration. It is very likely that for networks with higher node densities many more redirectors

would be available to routes compared with the example shown in Figure 3-3. As a result, for QoS-PARO it would be necessary to add control over the specific number of redirectors introduced into the route.

Since more than one redirector can be added to a route during one iteration, it is insufficient to send a signaling packet requesting the addition of one redirector to the current path. This would lead to ambiguous behavior because it would not be clear which redirector among all the potential redirectors found along a path in one iteration offers the best interference and power optimization performance. In the case of iteration 2 (in Figure 3-3), the redirector on the right-hand side is the one that should be selected because it achieves a lower end-to-end interference and transmission power compared to the redirector on the left-hand side. Because of this potential ambiguous behavior, we modify the baseline PARO protocol in a manner where all potential redirectors found in one iteration are first evaluated at either the source or destination points before a decision is made about selecting which specific redirector to select. This is an enhancement to the baseline PARO operation. Once the source or destination node selects a specific redirector based on some policy decision (which could be flow/application/node specific), a packet can be sent along the path to dynamically activate a selected redirector on-demand.

4.5.4.3 Adding and Removing Redirectors

Figures 4-9 and 4-10 illustrate the basic operation of adding and removing a redirector from a path, respectively. For ease of presentation, we use the same topology used to discuss the operation of the baseline PARO protocol, shown in Figure 3-3. Figure 4-9 illustrates the different steps involved in adding a redirector. At the start under initial conditions there exists a route without any redirectors positioned between nodes S and D (see Figure 4-9(a)). Once packets are exchanged

between S and D , other nodes overhearing these transmissions can compute if a route-redirect operation is needed. In case more than one redirector is available, only the best-positioned redirector (e.g., node h in this example) sends a route-redirect message to both S and D , as in the case of the baseline PARO protocol. Reception of route-redirect messages at S and D nodes creates route-redirect entries in their route-redirect tables (the label NH in route-redirect tables in 4-9 refers to the next hop in routes as defined in the baseline PARO protocol).

The operation of QoS-PARO is different to the baseline PARO protocol in the actions taken after the reception of a route-redirect request from potential redirectors. Reception of a route-redirect request by a potential redirector in QoS-PARO does not trigger the immediate redirection of the flow of packets, as occurs in the baseline PARO protocol. Rather, QoS-PARO creates entries in route-redirect table and marks their state as *dormant* (e.g., not active). Dormant state entries in route-redirect tables remain inactive until a signaling message explicitly changes the state to the active state. When entries are made active, they behave exactly like route-redirect entries in a baseline PARO system. Figure 4-9(a) illustrates the state of the redirect tables after node h transmits route-redirect messages to nodes S and D . The state flag in the route-redirect tables indicates whether an entry is dormant (flag=0) or active (flag =1).

In the example shown in Figure 4-9(a), new packets generated by node S copy information about dormant state entries from each visited node as packets move toward node D . This information includes the pair $[ID, Opt]$ of each dormant redirector visited along the path. The ID field is a unique identifier (e.g., MAC address) while the Opt field relates how much energy is saved. Using the example of 4-9(a), let d_{ij} be the distance between nodes i and j , then the value of Opt for dormant

redirector h , Opt_h , can be computed as follows:

$$Opt_h = d_{SD}^2 - (d_{Sh}^2 + d_{hD}^2) \quad (4.2)$$

Equation 4.2 computes the amount of energy that can be saved by adding node h to forward packets between nodes S and D . Therefore, the Opt value can be seen as a measure of how much a path benefits from adding a specific redirector. The values of d_{SD}^2 , d_{Sh}^2 and d_{hD}^2 are provided to redirector h by the baseline PARO protocol (refer to Chapter 3 Section 3.3.1 to see how PARO computes the minimum transmission power between transmitting and overhearing nodes). In cases where more than one dormant redirector is found, node D can select the best redirector based on which dormant redirector has the highest Opt value.

Once node D selects a dormant redirector based on certain policy (e.g., node D tries to meet specific energy-saving target), it sends a packet back to node S with a request to add the selected redirector to the path. This signaling packet could be an explicit signaling packet if no data packets are available, or it could be a data packet with the information associated with the selected redirector included in the packet header. We call this signaling packet a *route-redirector*, it contains the ID of the redirector being requested to be added or removed from the path. This signaling packet activates the selected dormant redirector (i.e., sets the state flag=1 in the route-redirect table) of any node along the path having the selected dormant redirector in the route-redirect table. This is illustrated in Figure 4-9(b).

Adding node h to the path in Figure 4-9(b) triggers the beginning of a new monitoring period. In this example, the insertion of node h along the path triggers two new potential redirectors (viz. nodes e and f) to send route-redirect messages. Packets traveling from node S toward node d copy information about dormant redirectors in each node along the path. As a result each packet received by D

carries a list of all redirectors and their corresponding *Opt* values. Node *D* can then monitor QoS performance and determine whether or not to add another redirector if it requires to further optimize the QoS/power tradeoff.

An example of removing a redirector in QoS-PARO is illustrated in Figure 4-10. In this figure, a route exists having two redirectors (nodes *h* and *f*). When node *D* wants to remove a redirector from the path based on a certain policy (e.g., node *D* is attempting to meet a throughput performance that is currently below its desired value), it sends a route-redirector packet toward the source with the ID of the selected redirector. This operation is illustrated in Figure 4-10(b). Removing a redirector from a route follows the inverse operation to adding redirectors. The last redirector added to a path is also the first redirector to be removed from the path. This is because among of all the redirectors already in the path the last redirector is the one with the lower *Opt* value. In the example shown in Figure 4-10(a) this corresponds to redirector *f*. Node *D* sends a route-redirector packet toward node *S* requesting the removal of node *f* from the path. Nodes along the path forwarding this request and having node *f* as their next hop in the route, forward the request to the node in the route two hops ahead. This results in a new route bypassing redirector *f*. In the example shown in Figure 4-10(b) node *D* sends a signaling packet directly to node *h*, which then forwards the packet toward node *S*. The route-redirector packet sets the corresponding entry for redirector *f* in the redirect table back to the dormant state again. Figure 4-10(b) shows the resulting route between nodes *S* and *D* now only using redirector *h*. At this point a new monitoring period begins and node *D* continuously measures QoS and power and may determine whether or not further optimization is necessary, as shown in Figure 4-10(c).

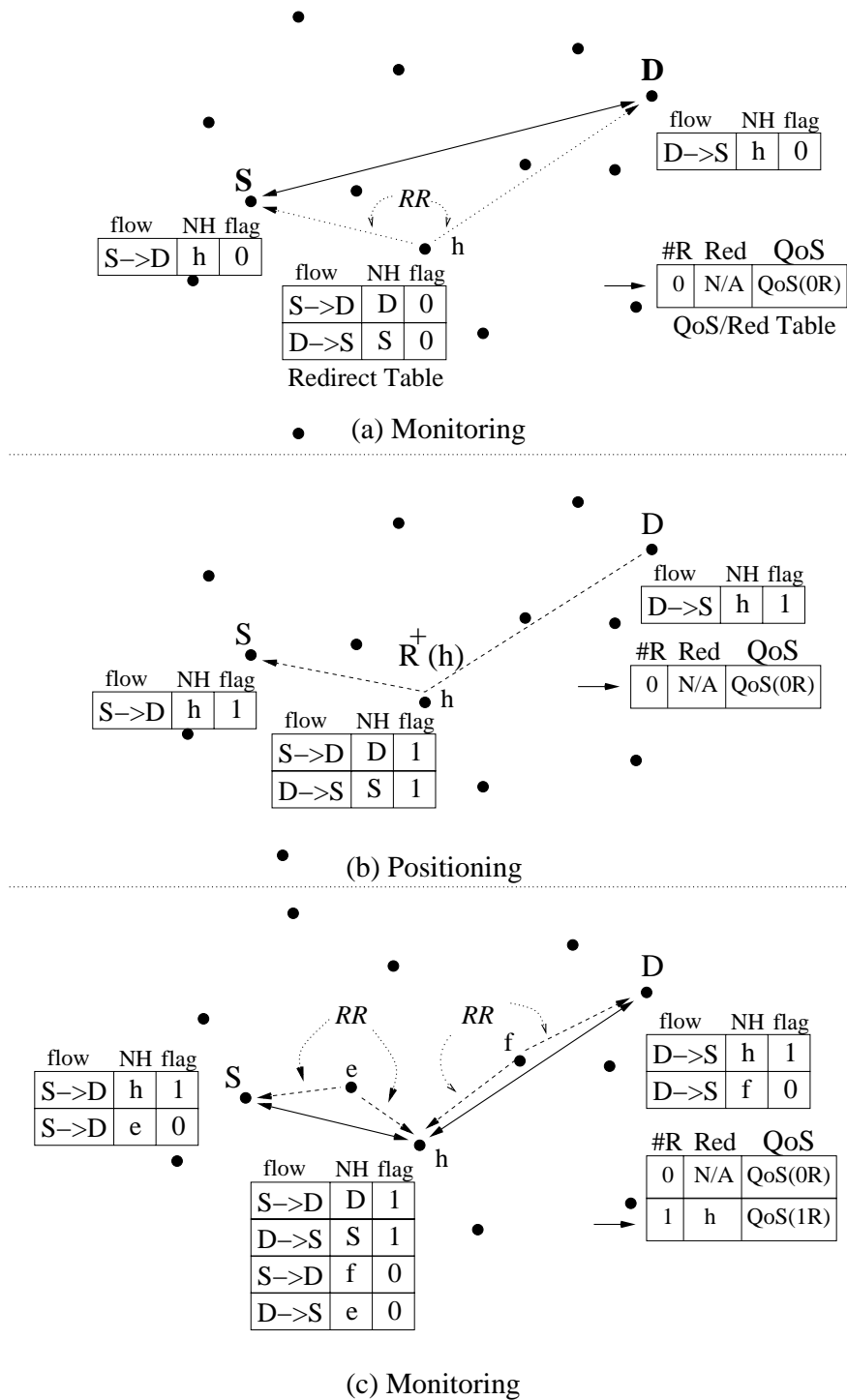


Figure 4-9: Adding a Redirector in QoS-PARO

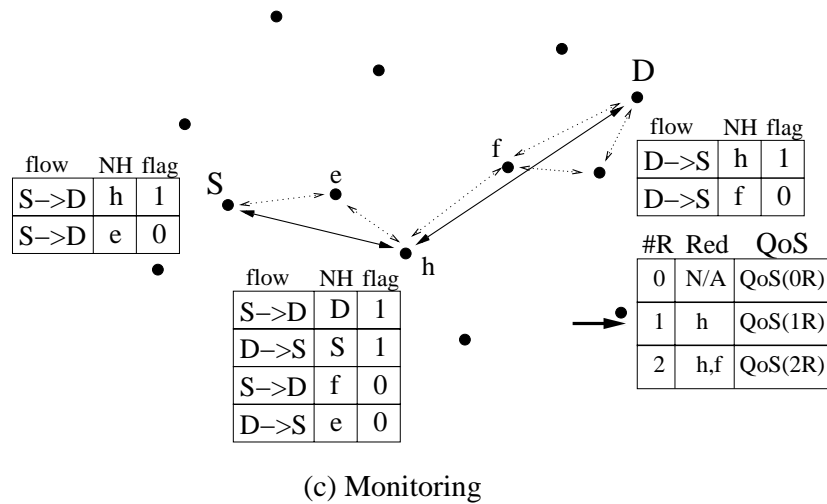
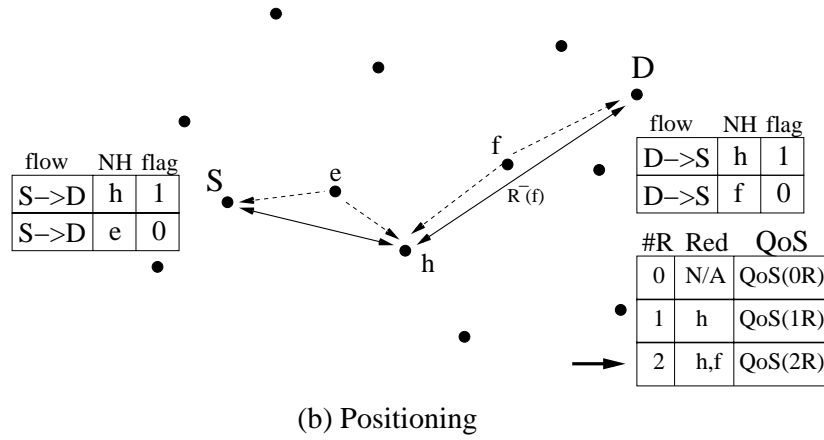
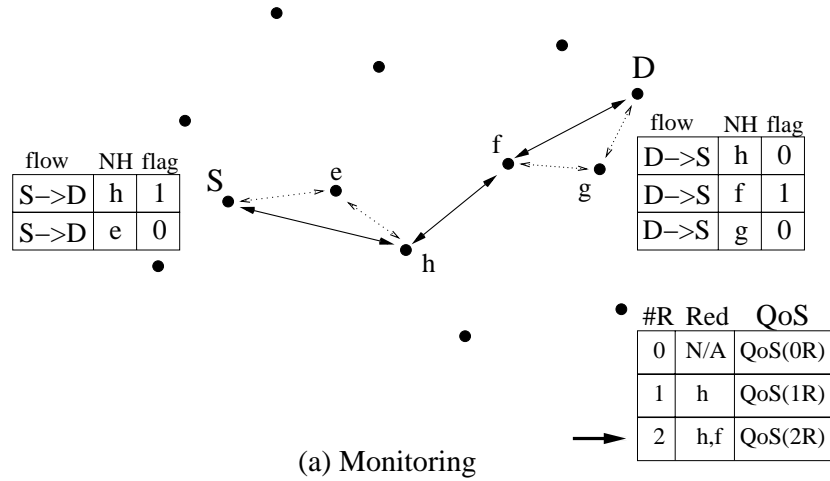


Figure 4-10: Removing a Redirector in QoS-PARO

4.6. Evaluation

In what follows we present an evaluation of QoS-PARO. First, we analyze the error involved while positioning nodes in an incremental manner. We then experiment with different operational aspects of QoS-PARO and show how flows/applications/nodes can add or remove redirectors to dynamically modify their observed QoS and power performance trade-off. We use PCMAP as the MAC protocol for QoS-PARO. We implement QoS-PARO using the ns simulator with the CMU wireless extensions. We extend our implementation of the baseline PARO protocol to implement the positioning and monitoring components of QoS-PARO, as described in Sections 4.5.2 and 4.5.4, respectively. We used UDP/CBR traffic sources for the experiments discussed below. Each point in the presented graphs are the average of 10 experiments, each of them using a different seed number while locating nodes in the network.

4.6.1 Incremental Positioning Error

Figure 4-11 shows the percentage error generated by positioning redirectors incrementally. This percentage error is obtained by the interference value associated with an incremental positioning of redirectors divided by the minimum interference value obtained by optimum positioning of redirectors. We contrast this percentage error for various node densities in a 200x200 meters wireless network for the two cases when flows add 2 and 3 redirectors to their paths, respectively. Results from Figure 4-11 show that the error generated by not using the optimum positioning of redirectors is small in general (i.e., below 5 %). We observe that the incremental positioning approach is therefore a simple and efficient method to position redirectors. In addition, the error decreases for low node density. The reason for this is the unavailability of nodes at the optimum locations for an optimum positioning of redirectors to occur.

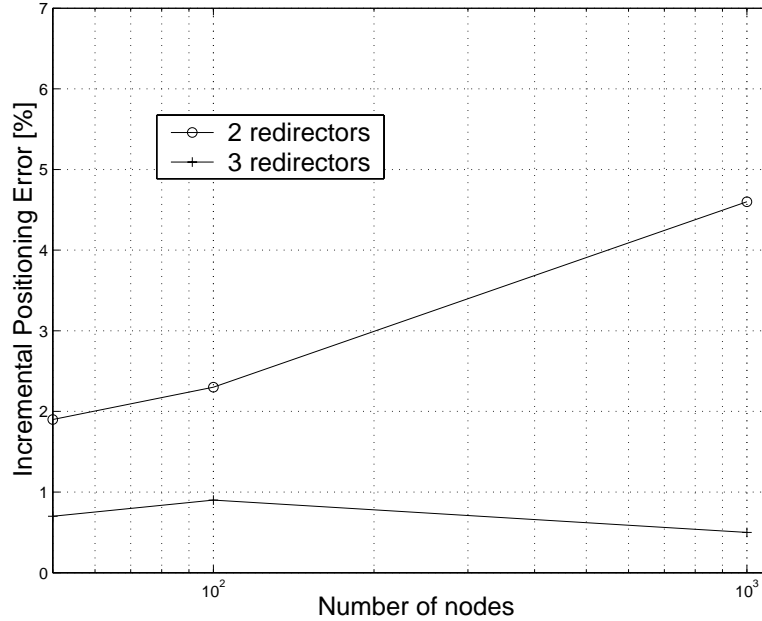


Figure 4-11: Incremental Positioning of Redirectors Error

4.6.2 QoS-PARO Performance

In what follows, we evaluate several aspects of the performance and behavior of the proposed QoS-PARO protocol. We first analyze the impact of different network conditions on the performance QoS-PARO, and evaluate the metric saturation point and Greedy-PARO policies.

4.6.2.1 Domino and Unfairness Effects

First, we examine the two extremes operational points of QoS-PARO based on the network conditions experienced. On one end of the spectrum there is the unfairness effect (i.e., a long-range flow may benefit by adding redirectors in the presence of few shorter-range flows), while on the other end of the spectrum, there is the domino effect (i.e., many competing shorter-range links).

Figure 4-12 shows the transmission power and throughput performance for differ-

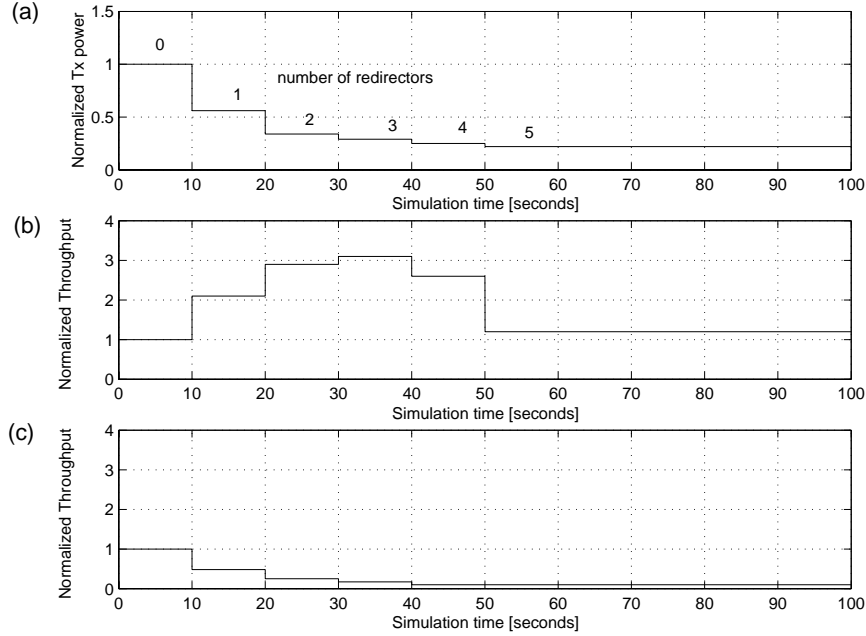


Figure 4-12: Throughput Performance of a Flow Running QOS-PARO

ent numbers of redirectors. We evaluate a 100 nodes in a 1000x1000 meter network with a 100 flows each sending sixty four 2kB packets every second with a connectivity range of 250 meters. Each source picks a destination at random within its 250 meters range. Initially there are no redirectors between sources and destinations. Figure 4-12 shows the transmission power and throughput performance for one test flow in the 200-250 meters range for 0, 1, 2, 3, 4 and 5 redirectors. The number of redirectors is shown above the trace line). All performance metric values are normalized to the case where no redirectors are present. The test flow adds redirectors at 10 seconds intervals in this experiment.

Figure 4-12(a) shows the transmission power of the route used by the test flow. The transmission power of a flow depends on the number of redirectors along the path only, and thus, it is not affected by other flows adding redirectors. As Figure 4-12(a) shows, transmission power consumption decreases as more redirectors are

added to the route. This is the same behavior shown in Chapter 3 where we analyzed the energy saving performance of the baseline PARO. As shown in the trace, energy savings are less significant after each new redirector is added to the route.

Figure 4-12(b) corresponds to the scenario where only the test flow is allowed to add redirectors, and Figure 4-12(c) corresponds to the case where 30 flows are allowed to add redirectors. We choose 30% of the flows to be gold users in this experiment because it results in many short-range interfering links that severely degrade the throughput performance of all flows. Q-P sensitive flows add but do not remove redirectors in these experiments in order to stress the negative effect of adding redirectors in the network. We study the aggregate impact on the performance of the network in more detail later on in this chapter. As Figure 4-12(b) shows, giving a single long-range flow the capability to add redirectors can improve both the power savings and the throughput performance of the test flow under consideration due to the inherent unfairness behavior of PCMAP toward long-range flows under this network conditions. Note that after 3 redirectors have been added the negative impact of a CSMA type of channel access outweighs the unfairness behavior of the MAC and the throughput performance degrades accordingly. The behavior shown in Figure 4-12(b) can be considered a best-case scenario because only one flow is allowed to add or remove redirectors (e.g., no domino effect exists).

Figure 4-12(c) shows the throughput performance of the test flow when the test flow and 29 other long-range flows are allowed to add redirectors. In this case, the selected 30 flows have the same number of redirectors along their paths at any time during the experiment. Results shown in Figure 4-12(c) show the same performance previously seen for the *chain* and *random* network experiments, shown earlier in Section 4.3. for IEEE 802.11. The reason why we observe similar degraded QoS performance for an increase number of redirectors is because an increase number of

shorter-range links begin interfering and competing for resources with each other. Breaking flows into smaller flows decreases the unfairness factor presented in Figure 4-12(b). In Figure 4-12(c), the results make the network look more like a IEEE 802.11 wireless network with a common transmission power.

4.6.2.2 Metric Saturation Policy

Figure 4-13 shows the transmission power and throughput when the operational behavior of the network exhibits the metric saturation point policy with transmission power as the metric. Because transmission power savings are not affected by other flows adding redirectors, all flows can add or remove redirectors in this scenario (in this experiment $\delta_{power} = 10\%$). In the experiment shown in 4-13(a), the addition of the third redirector does not reduce the transmission power of the path significantly compared with the initial transmission power when the source node transmit directly to the destination node. In this case the flow removes two redirectors where it remains for the next active interval. Again, the number of redirectors is shown above the trace line.

4.6.2.3 Greedy-PARO Policy

Figure 4-14 shows the throughput performance when nodes operate under the Greedy-PARO policy trading QoS for sub-optimal power savings. For the experiment shown in Figure 4-14, 10 flows randomly selected among all flows can add or remove redirectors while the remaining 90 flows transmit without making use of redirectors. Each of the 10 sensitive flows have a target throughput objective while at the same time they use as little energy as possible. The dashed line in Figure 4-14(a)-(c) denotes the target performance for one of the 10 flows allowed to use redirectors under consideration (called test flow below). Monitoring intervals are set to 10 seconds. The

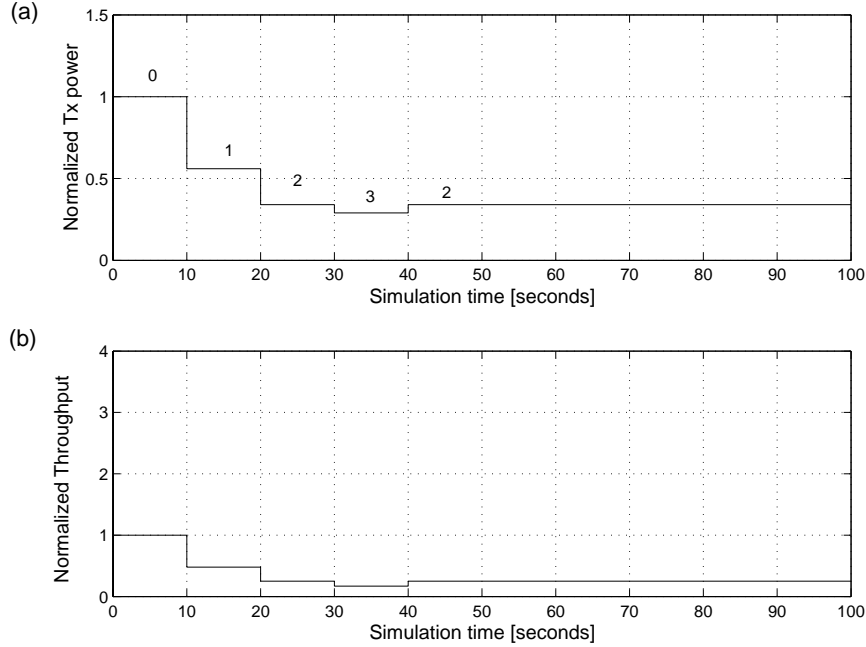


Figure 4-13: Behavior of the Power Saturation Point Policy of QOS-PARO

duration of normal periods after an active period is uniformly distributed between 150-800 seconds. The three graphs shown in Figure 4-14 contrast the Greedy-PARO operation of one test flow when the target throughput performance is above the initial throughput performance (a), and when the target throughput performance is below the initial throughput performance (b)(c), but with energy-saving constraint.

Figure 4-14(a) shows the Greedy-PARO behavior when the targeted performance is higher than the initial performance. In this case, the test flow uses the adding-search algorithm (detailed in Section 4.5.2) anticipating that there are fewer short-range flows in the neighborhood and thus the unfairness behavior of the MAC improves throughput. Because there are many active links in this experiment, adding redirectors degrades the observed performance. The test flow then uses the removing-search algorithm (detailed in Section 4.5.2) and waits for the next active

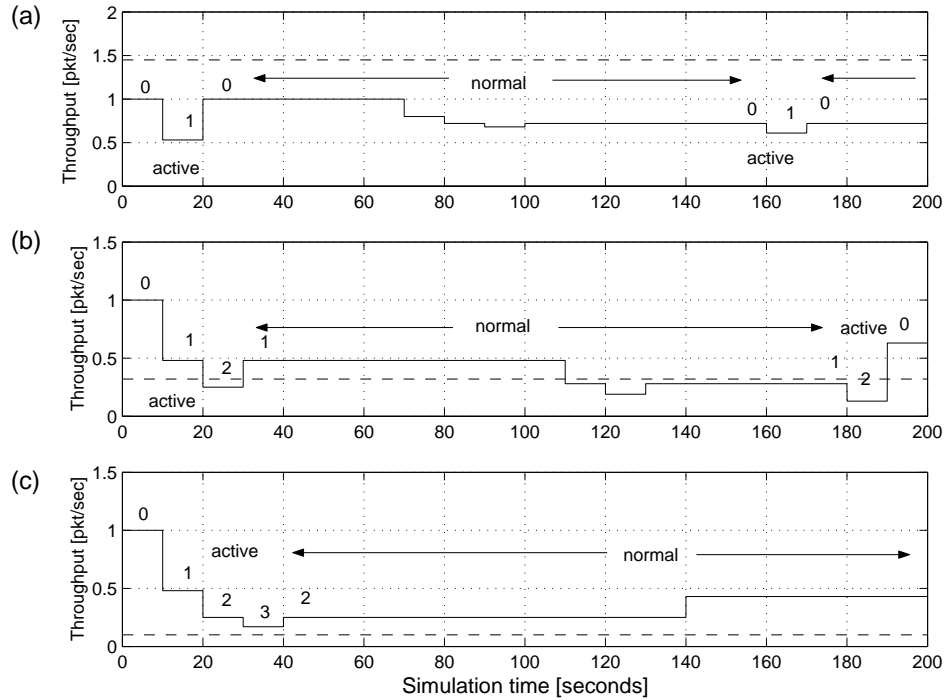


Figure 4-14: Throughput Performance of a Flow Operating in Greedy-PARO

period to try again. Active and normal periods are shown above the trace line in addition to the number of redirectors being used in the path.

Figure 4-14(b) shows the Greedy-PARO behavior when the target throughput performance is lower than the initial performance without redirectors. The test flow then tries to add redirectors to reduce the energy-consumption while always maintaining the throughput performance above the desired performance point. In this case the test flow uses the adding-search algorithm. In this experiment adding one redirector to the path keeps the performance above the target performance, before the flow moves into a normal period. Note that during the normal interval the monitored throughput performance drops below the target throughput performance level, as a result of the domino effect. During the next active period (approximately 180 seconds into the trace) the flow first uses the adding-search algorithm, and if

the desired performance is not met, then the test flow uses the removing-search algorithm, which in this experiment brings the performance back above the target operational level.

Figure 4-14(c) shows the behavior of Greedy-PARO when the targeted throughput performance is lower than the initial throughput without redirectors and lower than the power saturation point where $\delta_{power} = 10\%$. We have already discussed that a common rule of QoS-PARO is that flows do not add redirectors if the metric saturation point has been reached to avoid unnecessary interference for other nodes in the wireless network. This corresponds to 2 redirectors for the test flow as shown in Figure 4-14(c).

4.6.3 Aggregate Performance

In the previous experiments we have shown the performance of QoS-PARO for individual flows. Now we analyze the aggregate impact on QoS when a subset of flows in the network is allowed to add and remove redirectors. In this experiment we selected 10% of the flows to be Q-P sensitive (subset of flows A) while the remaining 90% of the flows are Q-P insensitive and transmit packets from source to destination directly without any intermediate forwarding hops or redirectors (subset of flows B).

We evaluate a 100 nodes in a 1000x1000 meter network with 100 flows each sending sixty four 2kB packets per second. Each source picks a destination at random within its 250 meters range. Figure 4-15 shows the fraction of the total packets received by destinations for each subset of flows over five distance ranges (0-50, 50-100, 100-150, 150-200, and 200-250 meters, respectively) from their sources. For Q-P sensitive flows we introduce redirectors to the paths in a way that all the resulting links for those flows fall within the 0-50 meters range. This arrangement corresponds to adding 4, 3, 2, 1, and 0 redirectors to the original high priority flows

in the 200-250, 150-200, 100-150, 50-100 and 0-50 meters range, respectively.

Figure 4-15 compares the performance of Q-P sensitive and Q-P insensitive flows. As a reference, this figure also shows the expected performance if no redirectors were to be used by the Q-P sensitive flows. Under this conditions, the 10 Q-P sensitive flows without redirectors are called subset A^* while the 90 Q-P insensitive flows are called subset B^* . We do this to show the “fair-share” of the received throughput if no redirectors were added by any flow. Where fair share refers to the throughput or delay obtained when no node is allowed to add or remove redirectors (e.g., normal operation). As Figure 4-15 shows, addition of redirectors for flows in subset A increases the QoS performance of this subset compared with their fair share (subset A^*). We observe the improvement is more significant for longer-range flows, the reason for this is that original shorter-range Q-P sensitive flows without redirectors already benefit from the unfairness behavior of the MAC.

Figure 4-15 also compares the sum of the fraction of packets received for subsets A and B with those of subsets A^* and B^* . When no redirectors are used by Q-P sensitive flows, the sum of the fractions of packets received within each range is equal to 1. This is an indication that all transmitted packets are received in one hop without redirectors. In the second scenario where redirectors can be used by high priority flows, a fraction of the packets transmitted go to intermediate redirectors, therefore, the sum of the fraction of the packets received end-to-end not counting those packets transmitted to intermediate nodes is less than 1. This shows that a fraction of transmitted packets go to intermediate nodes (i.e., redirectors), reducing the end-to-end throughput. This behavior means that improving the QoS performance of flows in subset A by adding redirectors is achieved at the expense of reducing the overall end-to-end throughput seen by the network (about 66% in this experiment), and more specifically, by a severe QoS degradation observed by flows

in subset B .

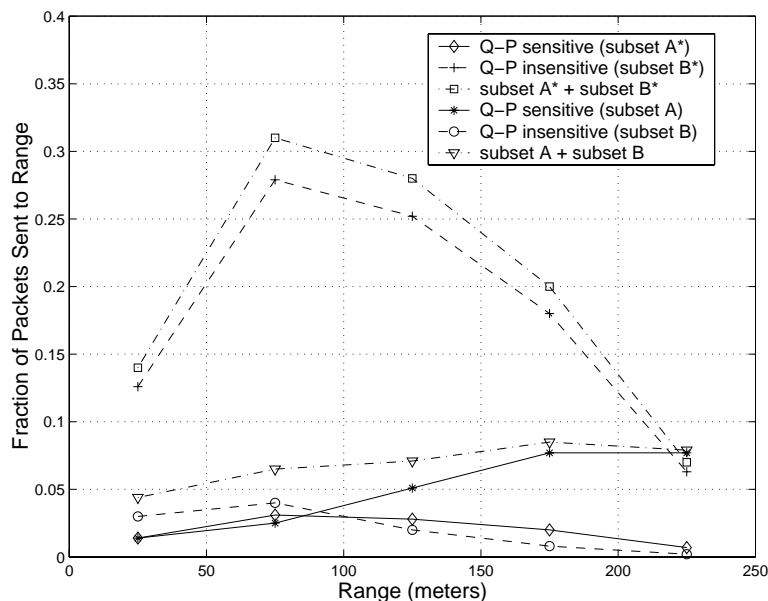


Figure 4-15: Aggregate Performance of QoS-PARO

4.7. Related Work

To our best knowledge QoS-PARO represents the first QoS/power-aware controlled routing protocol for wireless ad hoc networks that is based on the foundation of variable-range transmission control.

The state of the art in QoS control for wireless ad hoc networks is best represented by the COWPOW system [56]. In [56], the authors present a system where mobile nodes are capable of switching the value of the common-range transmission power they use at the same time. Mobile nodes in this system periodically reduce this value and stop right before the first partition of the network occur. As we mention in Chapter 2, this method consumes more power and reduces the capacity compared with a method based on variable-range transmission principles. Another

important difference of QoS-PARO and the COMPOW proposal is that in contrast to common-range transmission based proposals where users get a similar QoS performance, QoS-PARO supports service differentiation with multiple policies. We believe that such a system is better suited to support different types of emerging applications that may require different QoS-power trade-off being supported by the network.

A signaling system supporting QoS in mobile ad hoc networks is discussed in the INSIGNIA project [50]. The INSIGNIA system creates QoS reservation at intermediate nodes visited by the data packets/flows en-route toward destinations. The transmission range used by the INSIGNIA protocol is based on the maximum common-range (e.g., like other MANET systems). An advantage of this system is that it is capable of locally restoring reservations in cases where intermediate hops move out of the route, thus it avoids costly end-to-end QoS re-adaptation.

Another example of QoS provisioning in ad hoc networks is the SWAN system. In [6], the authors present a service differentiation system for stateless wireless ad hoc networks. This system is based on the notion that provisioning QoS to applications inside ad hoc networks is rather difficult and end-to-end QoS adaptation results more appealing in such environments. In [6], flows monitor end-to-end performance and adjust their transmitting rates according to the service class they belong to. This system uses common-range transmission principles.

In the work described in [7], the authors discuss the impact on TCP throughput on the number forwarding nodes, or the equivalent common-range transmission value used, in static wireless ad hoc networks for unreliable links. Results presented in [7] show that there is an optimum transmission range that maximizes TCP throughput. Other examples of TCP behavior over wireless links, not necessarily related to wireless ad hoc networks but wireless networks in general include [9] [10] [41].

Examples of QoS adaptation systems for wireless links (not necessarily related to wireless ad hoc networks) include modifications to the link schedulers [13] [33] [52]. The main feature of these adaptation systems is that they react to link errors and compensate affected flows when links conditions improve.

The performance of IEEE 802.11 over wireless ad hoc networks is studied in [82]. Results from [82] show that one of the main reasons for the poor utilization of IEEE 802.11 over wireless ad hoc networks is its long sensing range. This issue is also studied in [26].

4.8. Conclusion

In this chapter we studied the impact of adding or removing redirectors in a PARO based network on traditional QoS metrics such as throughput and end-to-end delay. We first study this impact for IEEE 802.11 and PCMAP [55] MACs based wireless ad hoc networks and showed the severe limitations of these MAC protocols for single and multihop wireless operations. We discussed the unfairness performance of source-destinations pairs based on location under PCMAP based wireless networks. We showed how this behavior can be used as a foundation for service differentiation in wireless ad hoc networks. We proposed QoS-PARO, which builds QoS mechanisms into the baseline PARO system for specific applications that wish to tradeoff better QoS performance for sub-optimal energy savings. In QoS-PARO, selected flows add or remove redirectors from their paths in order to coarsely modify their observed QoS performance an energy savings. We also showed that modifying the QoS performance and energy savings of selected flows is at the expense of potentially severe QoS degradation observed by non selected flows (i.e., flows/applications that do not use redirectors in their paths). The poor performance observed by flows in wireless ad hoc networks mainly a product of the nature of channel sense multiple

access protocols (CSMA) (i.e., Ethernet type of these MAC protocols). It is well known that CSMA access protocols have poor link utilization, and when combined with multihop packet forwarding across of multiple wireless links significantly reduces the overall observed performance of the system. Moreover, the theoretical work by Gupta and Kumar [37] shows that reducing the transmission power to a minimum by means of adding forwarding hops between source-destination pairs increases the physical traffic carrying capacity of the wireless network. In order to obtain better QoS performance in PARO based networks, it is necessary to develop new access protocols that departs from channel sensing in single frequency systems. This is an open area of research.

Chapter 5

Conclusion

Effective transmission power control is a critical issue in the design and performance of future wireless ad hoc networks, including system design metrics such as physical connectivity, network connectivity and reachability, power savings and application QoS. The manner in which each of these performance metric is affected by transmission power control and the resulting interaction and interdependencies between these different system metrics is complex to model and understand, and is the subject of this dissertation.

There has been little analysis in the past to show the differences between the performance of common-range and variable-range routing protocols for wireless ad hoc networks. The proposals by [69] [29] [30] [67] have in the past intuitively suggested that a variable-range approach could outperform a common-range approach in terms of power savings, however, no definite analytical results backed this claim up.

This dissertation presents a strong argument for the use of variable-range routing protocols in future wireless ad hoc networks. In Chapter 2, we derived an asymptotic expression for the computation of the average variable transmission range in wireless ad hoc networks. We showed that the use of a variable-range routing protocol uses lower transmission power compared with common-range based solutions, thus,

variable-range approaches have the potential to increase the capacity and power savings of wireless ad hoc networks. We also derived expressions for the route-discovery and maintenance phases of an ideal on-demand routing protocol for wireless ad hoc networks. We showed that there is an optimum setting for the transmission range (not necessarily the minimum), which maximizes the capacity available to nodes in the presence of mobility.

The results presented in Chapter 2 provide a formal proof of the advantage of a variable-range transmission policy versus common-range one. Our results provide justification for the development of new routing schemes that can provide capacity and power-savings enhancements for nodes in wireless ad hoc networks. More specifically, these results point to development of new routing protocols based on variable-range transmission control. Such a paradigm overcomes most of the limitations of common-range routing protocols that are prevalent today. The results presented in this chapter assume that nodes are homogeneously distributed in the network. We are currently investigating new bounds for both variable-range and common-range transmission policies where nodes are not distributed in this way. Furthermore, we plan to use real traces of nodal positioning in future analysis. Because the average length of variable-range links is less affected by the distribution of nodes compared to the length of common-range links, we believe results from this study will highlight other benefits of using variable-range routing protocols over common-range ones.

Chapter 3 introduced PARO, a dynamic power controlled routing scheme for wireless ad hoc networks based on variable-range transmission control. PARO uses a packet forwarding technique where immediate nodes can elect to be *redirectors* on behalf of source-destination pairs with the goal of reducing the overall transmission power needed to deliver packets in the network, thus, increasing the operational

lifetime of networked wireless devices. PARO is not only applicable as a local area routing technology where all nodes are within the direct transmission range of each other (e.g., personal area networks, home networks, sensor networks, WLANs) but it can also perform power optimization as a layer 2.5 routing technology operating below wide-area MANET routing protocols. In this case, PARO provides wide-area routing protocols with local energy-conserving routes. Wide-area routing is used to forward packets when the source and destination nodes are outside the maximum transmission range of each other.

We evaluated PARO and compared its performance to a modified common-range link state routing protocol (MLSR). We found that PARO consumed less power in order to find power-efficient routes compared to MLSR due to its point-to-point on-demand design. An implementation of the PARO system using a commercial IEEE 802.11 radio showed a basic proof of concept even though some inefficiencies and anomalies were identified. Currently, we are studying the performance of Internet applications and transport protocols operating over PARO. We are particularly interested in studying QoS issues such as delay, “goodput” and packet error rates under such regimes. Furthermore, we are investigating complementary techniques that help save reception and idle power in PARO-based wireless ad hoc networks.

Adding and removing redirectors to reduce the transmission power in PARO based wireless ad hoc networks impacts traditional application-level QoS metrics such as throughput and end-to-end delay. In Chapter 4, we studied the impact of adding and removing redirectors in a PARO based network on these QoS metrics. We first studied this impact using IEEE 802.11 and PCMAP [55] MACs and showed the limitations of these MAC protocols for single and multihop wireless operations. We discussed unfairness issues and their performance impact on source-destinations pairs when located at far distances using PCMAP based wireless networks. We

showed how this behavior could be used as a foundation for service differentiation using power-aware routing schemes. Based on these insights we proposed QoS-PARO that builds QoS mechanisms into the baseline PARO system for applications that wanted to tradeoff better QoS performance for sub-optimal energy-savings. Selected flows/applications can add and remove redirectors along their paths in order to coarsely control their observed QoS-power trade-off. We showed that modifying the QoS performance and energy-savings of these selected flows comes at the expense of the QoS degradation observed by non selected flows (i.e., flows that do not use redirectors in their paths).

In Chapter 4, we showed that the poor performance observed by flows in wireless ad hoc networks is mainly a product of channel sense multiple access (CSMA) protocols. It is well known that CSMA access protocols have poor link utilization, and when combined with multihop packet forwarding across multiple wireless links significantly reduces the overall performance observed by the system. Moreover, the theoretical work by Gupta and Kumar [37] shows that reducing the transmission power to a minimum by means of adding forwarding hops between source-destination pairs increases the physical traffic carrying capacity of the wireless network. In order to obtain better QoS performance in PARO based networks, it is necessary to develop new access protocols that departs from channel sensing in single frequency systems. This is an open area of research.

Network solutions based on a common, maximum transmission power approaches improve the physical connectivity of wireless ad hoc networks. However, we have shown in this dissertation that this goal is achieved at the expense of sacrificing network capacity and wasting transmission power in wireless ad hoc networks. We argued in this dissertation that the existing systems design based on a common-range transmission approach that favors connectivity at the detriment of capacity,

power conservation, and application QoS is limited; and furthermore, not the best foundation for the development of future wireless ad hoc networks. In this thesis we have attempted to make the case for a different approach. We proposed that the design of wireless ad hoc networks should be based on variable-range transmission power control, which we believe is more suited to the needs of these emerging networks, their devices and applications. We hope that this thesis has contributed to that overall argument.

Chapter 6

My Publications as a PhD Candidate

The following publication list represents published journal, conference and workshop papers during my period as a PhD candidate in the Department of Electrical Engineering over the period 1997-2002.

6.1. Journal Papers

J. Gomez-Castellanos, A. T. Campbell, M. Naghshineh, C. Bisdikian “PARO: Supporting Transmission Power Controlled Routing in Wireless Ad Hoc Networks”, *ACM/Kluwer Journal on Wireless Networks (WINET)*, 2003. (to be published)

A. T. Campbell, J. Gomez-Castellanos, S. Kim, Z. Turanyi, C-Y. Wan, and A. Valko “Experiences with Cellular IP”, *Journal of High Speed Networks (JHSN), Special Issue on Multimedia in Wired and Wireless Environment*, invited paper, September 2002. (to be published)

X. Zhang, J. Gomez-Castellanos, and A. T. Campbell, “Design and Performance of Mobile IP Paging,” *ACM Mobile Networks and Applications (MONET), Special issue on Modeling Analysis and Simulation of Wireless and Mobile Systems, Vol. 7, No. 2, pp 127-141*, March 2002.

Javier Gomez., Andrew T. Campbell, “Supporting Application and Channel De-

pendent Quality of Service in Wireless Networks”, *ACM/Baltzer Journal on Wireless Networks (WINET)*, Vol. 9, No. 1, January 2003.

6.2. Magazine and Review Articles

A. T. Campbell, J. Gomez-Castellanos, S. Kim, Z. Turanyi, C-Y. Wan, and A. Valko “A Comparison of IP Micromobility Protocols”, *IEEE Wireless Communications Magazine*, Vol. 9, No. 1, pp 72-78, February 2002.

Andrew T. Campbell, Javier Gomez-Castellanos, “IP Micro Mobility Protocols”, ACM SIGMOBILE Mobile Computing and Communications Review, October 2000, Volume 4, Number 4, pp 45-53.

Andrew T. Campbell, Javier Gomez, SanghyoKim, Zoltan Turanyi, Chieh-Yih Wan, and Andras G. Valko, “Design, Implementation, and Evaluation of Cellular IP”, *IEEE Personal Communications, Special Issue on IP-based Mobile Telecommunications Networks*, pp. 42-49, August 2000.

6.3. Conference Papers

Javier Gomez, Andrew T. Campbell, Mahmoud Naghshineh and Chatschik Bisdikian, “Conserving Transmission Power in Wireless ad hoc Networks”, *IEEE 9th International Conference on Network Protocols (ICNP’01)*, Riverside, California. November 2001.

X. Zhang, J. Gomez-Castellanos, and A. Campbell, “P-MIP: Paging in Mobile IP,” *ACM Fourth International Workshop on Wireless Mobile Multimedia (WOW-MOM’01)*, Rome, Italy, July 2001.

Javier Gomez, Andrew T. Campbell, “A Channel Predictor for Wireless Packet Networks”, *IEEE International Conference on Multimedia and Expo (ICME 2000)*,

New York, NY July-August 2000.

Javier Gomez, Andrew T. Campbell, Mahmoud Naghshineh, Chatschik Bisdikian “Power-aware Routing in Wireless Packet Networks”, *Sixth IEEE International Workshop on Mobile Multimedia Communications (MoMuC’99)*, San Diego, California, November 1999.

S. Kim, C-Y. Wan, W. B. Paul, T. Sawada, A. T. Campbell, J. Gomez, A. G. Valko, “A Cellular IP Demonstrator”, *Sixth IEEE International Workshop on Mobile Multimedia Communications (MoMuC’99)*, San Diego, California, November 1999.

J. Gomez, A. T. Campbell and H. Morikawa, “The Havana Framework for Supporting Application and Channel Dependent QOS in Wireless Networks”, *IEEE 7th International Conference on Network Protocols (ICNP’99)*, November 1999, Toronto, Canada.

Andrew T. Campbell, Javier Gomez, Andras G. Valko, “An Overview of Cellular IP”, *IEEE Wireless Communications and Networking Conference (WCNC’99)*, New Orleans, September 1999.

A. G. Valko, J. Gomez, S. Kim, A. T. Campbell, “On the Analysis of Cellular IP Access Networks”, *IFIP Sixth International Workshop on Protocols for High Speed Networks (PfHSN’99)*, Salem Massachusetts, August 1999.

J. Gomez, A. T. Campbell, “Supporting Adaptive-QOS over Multiple Time Scales in Wireless Networks”, *DIMACS Workshop on Mobile Networks and Computing*, Piscataway, NJ, March 1999.

J. Gomez, A. T. Campbell and H. Morikawa, “A Systems Approach to Prediction, Compensation and Adaptation in Wireless Networks”, *ACM First International Workshop on Wireless Mobile Multimedia (WOWMOM ’98)*, Dallas, Texas, October 1998.

A. G. Valko, A. T. Campbell, J. Gomez, “Cellular IP - A Local Mobility Proto-

col,” *IEEE 13th Annual Computer Communications Workshop*, Oxford, Mississippi, October 1998.

J. Gomez, M. Naghshineh, “Link error impact on MPEG video over Wireless Broadband Networks”, *Proc. of IFIP Fifth International Workshop on Quality of Service (IWQOS’97)*, New York, NY, May 21-23 1997.

J. Gomez, A. T. Campbell “Delivering Adaptive Flows to Mobile Hosts over the Internet”, *Advance Project Report*, Columbia University, January 1997.

6.4. Workshop Presentations

Javier Gomez, Andrew T. Campbell, “Power-Aware Routing Optimization for Wireless ad hoc Networks”, *High Speed Networks Workshop (HSN’2001)*, Balatonfured, Hungary, June 2001.

Javier Gomez, Andrew T. Campbell, “Building a Cellular IP Testbed”, *IP Based Cellular Network Conference (IPCN 2000)*, Paris, France, May 2000.

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