IMPROVING IEEE 802.11 PERFORMANCE WITH POWER CONTROL AND DISTANCE-BASED CONTENTION WINDOW SELECTION

BY

BRIGHT CHU

B.S., University of Illinois at Urbana-Champaign, 2003

THESIS

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ABSTRACT

Wireless ad hoc networks have become increasingly popular in recent years. IEEE 802.11 is an international standard that specifies a wireless Medium Access Control (MAC) protocol. Significant research has been done to improve the performance of IEEE 802.11 MAC protocol. One area of research is in incorporating power control protocols into IEEE 802.11. Power control protocols can provide better spatial reuse and energy efficiency. However, the use of power control may create asymmetric links and unfairness in wireless networks. This thesis proposes a protocol that uses a distance-based contention window selection scheme to alleviate the unfairness caused by power control. We propose a few schemes to determine the initial contention window size for a transmission based on the distance traveled by the flow. Simulation results show that this approach achieves significant performance improvement.

ACKNOWLEDGMENTS

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LIST OF ABBREVIATIONS

AP Access point

CSMA Carrier sense multiple access

CTS Clear-to-send

CW Contention window

DCF Distributed coordination function

GPS Global Positioning System

IEEE Institute of Electrical and Electronics Engineers

MAC Medium access control

PCF Point coordination function

PCMA Power controlled multiple access

RTS Request-to-send

WLAN Wireless local area network

CHAPTER 1

INTRODUCTION

In recent years wireless communication networks have become increasingly popular. Many types of wireless services have become available, including cellular systems, satellite communication networks, and wireless local area networks (WLANs) [1, 2]. The increasing popularity of WLANs and wireless devices has led to greater interest in wireless ad hoc networks. An ad hoc network [3] is formed by wireless, potentially mobile hosts, without requiring the use of any fixed infrastructure, and can be set up in the environment where the wiring of a conventional network is difficult or not economically feasible.

Wireless ad hoc networks face challenges that are not present in wired networks. In wired networks, transmission errors typically occur at a low rate and interference among different communication flows is minimal. Collision detection is usually fast and easy in wired networks. Wireless communication, however, requires a shared transmission medium that is highly error-prone. Hence, in wireless communication, there is a much higher chance for collisions to occur. It is also more difficult to detect a collision in a wireless network. Often the lack of a reply message is the only way for a node to detect a collision. Therefore, compared to a wired network, a wireless network requires a different and more complicated medium access control (MAC) layer. This thesis focuses on the issues on MAC layer for wireless networks.

A popular international standard for MAC protocol in wireless networks today is the Institute of Electrical and Electronics Engineers (IEEE) 802.11 [4] standard. IEEE 802.11 standard gives specifications to the MAC and physical layers of wireless networks. The IEEE 802.11 standard consists of two components: point coordination function (PCF) and distributed coordination function (DCF). PCF is designed for centralized networks with an access point (AP), while DCF is a fully distributed scheme that is commonly used in ad-hoc wireless networks. This thesis focuses on the DCF scheme.

Much research has been done to improve the performance of basic IEEE 802.11 DCF. One important area of research is on power control – the adjusting of transmit and receiving power levels on wireless nodes to improve performance. There are two major benefits of power control:

- Energy Saving: By reducing transmit and receiving powers on wireless nodes, it is possible to reduce power consumption of the wireless nodes. A wireless node often operates on a battery. Hence it is important to preserve energy and potentially extend the lifespan of an ad hoc network.

- Spatial Reuse: Lower transmit power leads to shorter range of interference. As a result, multiple flows of transmission may occur in the vicinity of each other. This increase in spatial reuse could lead to increased capacity of the network.

This thesis combines the idea of power control with a scheme of distance-based contention window (CW) selection to improve the performance of IEEE 802.11 DCF. The rest of the thesis is organized as follows: Chapter 2 discusses background information on IEEE 802.11 DCF and related work in power control; Chapter 3 presents the details of our protocol; Chapter 4 presents and analyzes the results of simulations; Chapter 5 discusses future works and concludes the thesis.

CHAPTER 2

RELATED WORK

2.1 Overview of IEEE 802.11 DCF

The IEEE 802.11 DCF mechanism is a non persistent carrier sense multiple access (CSMA) scheme. In this scheme, nodes contend for channel access: a node that has data to transmit first senses the channel and transmits only if the channel has been free for some period of time (defined by DIFS in IEEE 802.11 standard). If this is not the case, the node defers the transmission and waits a certain period before the next attempt. There are two transmission modes in IEEE 802.11 DCF–the basic access mode (two-way handshake) and the request-to-send/clear-to-send (RTS/CTS) mode (four-way handshake). The basic access mode uses the exchange of data packets and acknowledgement (ACK) packets and is used when the size of the data packets is very small. The RTS/CTS mode consists of four-way handshakes of RTS/CTS/data/ACK. This mode is to be used in ad hoc networks where the sizes of data packets are large and is the mode in which the simulations in this thesis are done. The RTS/CTS exchanges serve two purposes: to coordinate the packet transfer between sender and receiver and to announce the duration of the packet transfer to nodes that are in range of the sender and receiver.

In this model, a sender node transmits a RTS packet to the intended receiver. If the RTS is successfully received, a CTS packet is sent from the receiver to the sender after a period of time (SIFS as defined in IEEE 802.11) to indicate that a data packet can be transmitted. A collision in the channel is detected by the absence of the CTS packet on the sender end. If a collision occurs, the sender goes into backoff. The period that a node spends in backoff is:

$$\text{Backoff\_time} = \text{rand}\,[0, \text{cw\_current}] \times \text{aSlotTime} \tag{2.1}$$

Backoff_time is defined as the product of a random integer between 0 and cw, the contention window size, and aSlotTime, which is a predefined time interval. In this scheme, cw starts at a predefined CW_{min} (with default value of 31 in IEEE 802.11) and is doubled every time on a collision until it reaches a predefined CW_{max} (with default value of 1023 in IEEE 802.11). This process is called exponential backoff as the increase in cw is exponential. After the backoff timer reduces to 0, the node attempts to retransmit the RTS packet. Upon a successful transmission, cw is reset to CW_{min}. If the sender receives CTS correctly, i.e., no collision, it transmits the data packet. After receiving the data packet, the receiver sends an acknowledgement (ACK) packet back to the sender. If the sender fails to receive the ACK, it assumes the Data packet is lost and retransmits the RTS. This scheme is illustrated in Figure 2.1.

IEEE 802.11 DCF is a fully distributed scheme. Every wireless node operates without the knowledge of the conditions of other nodes. The protocols proposed in this thesis try to maintain that characteristic of IEEE 802.11 DCF.

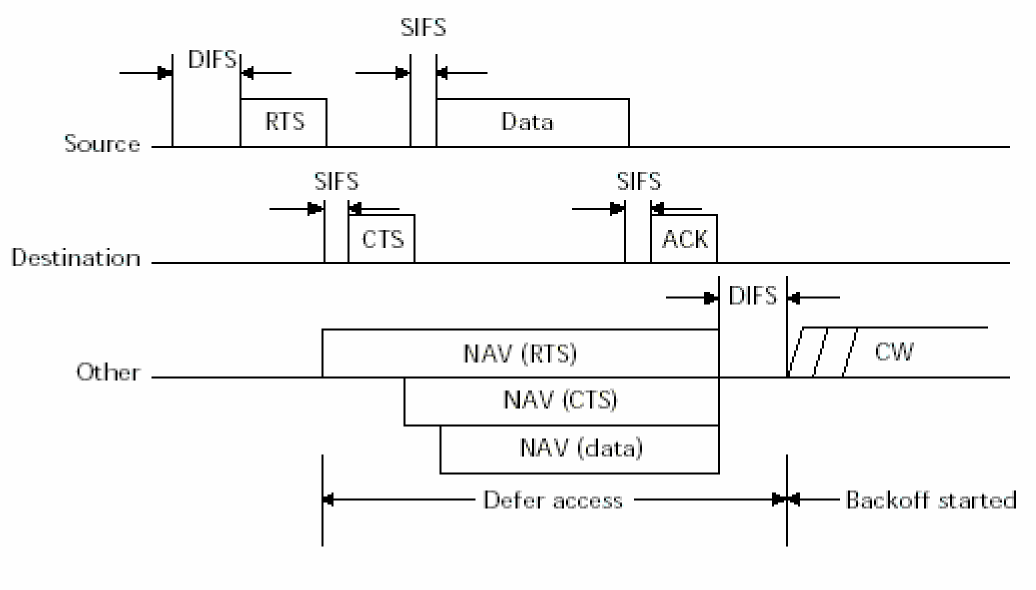


Figure 2.1 IEEE 802.11 DCF Four-Way Handshake

2.2 Survey of Power Control Protocols

Much research has been done to incorporate power control schemes into the basic IEEE 802.11 DCF. There are two possibilities for power control protocols—different nodes use different transmit powers or all nodes transmit with the same power level. If all the nodes use the same power level, it is possible for the resulting links to be "symmetric." That is, if node A can receive a packet from node B, node B is typically able to receive a packet from A, if the interference levels around the two nodes are similar. The work in [5] advocates for the use of identical transmit power at all nodes. However, there are limitations to this approach in reality. First, in this approach all the nodes in an ad hoc network must agree to share the same power level. These agreements take time to transmit in the network. Hence it is difficult for the nodes to quickly respond to the changes in physical channel characteristics. In addition, identical transmit power alone does not guarantee symmetry. Different nodes may experience different noise and interference levels in its surroundings. Further, the transmit power of the radios on the different nodes may not be identical due to manufacturing differences.

Because of these limitations of the identical-transmit-power approach, most power control protocols choose the approach of using different transmit powers on different nodes. The scheme in [6] allows a node A to specify its current transmit power in RTS, and allows the receiver node to include the desired transmit power in the corresponding CTS. Upon receiving the CTS, node A uses the specified desired transmit power to transmit the data packet. This scheme allows the receiver node to help the sender node to select appropriate transmit power level to maintain a desired signal-to-noise ratio. The work in [7] proposes a scheme where the RTS and CTS are sent at the highest possible power and the data and ACK packets are transmitted at lower power levels that are determined based on environment. The work in [8] shows that this scheme has some deficiencies. Since the transmit power for both data and ACK packets is small, this scheme may cause more collisions and hence reduce the overall throughput. The work in [8] proposes a way to overcome this deficiency by periodically transmitting a data packet with maximum transmit power. This allows nodes that can potentially interfere with the reception of ACK at the sender to periodically sense the channel as busy and hence defer their own transmission.

There are other power control approaches as well. Works in [9, 10] propose power-aware routing optimizations. They choose different metrics to analyze the cost of each possible route and determine a low energy-consuming route between a pair of nodes. The protocol proposed in [11] maintains a table of the minimum transmit powers necessary to communicate with neighbor nodes. This scheme allows each node to increase or decrease its power level dynamically. The protocol in [12] uses one control channel and multiple data channels. The RTS, CTS, broadcast, and special reservation packets are transmitted on the control channel in this scheme. By the RTS-CTS handshake, sender and receiver decide which channel and what power level to use. The sender then sends the special reservation packet to the receiver to reserve the channel. Then the data and ACK transmissions happen on the reserved data channel using the power level that is agreed upon in the RTS-CTS handshake. In [13, 14] the transmit power is controlled based on packet size. These works observe that reduced transmit power can lead to more bit errors and thus cause more retransmissions. Therefore, the protocols proposed in [13, 14] use an appropriate transmit power level based on packet size. The work in [15] is an adaptive scheme that chooses MAC frame size based on channel conditions.

There are other power control schemes that are based on the use of busy tones. The power controlled multiple access (PCMA) protocol [16] allows different nodes to select different transmit power on a per-packet basis. PCMA has two channels, one of which is for busy tones and the other is for all other packets. A busy tone is transmitted periodically after a node receives a data packet. The power level at which the busy tone is transmitted by a node is equal to the maximum additional noise the node can tolerate. Any node wishing to transmit a packet must first listen to the channel for busy tones from other nodes. The node then uses the signal strength of these busy tones to determine the highest power level at which it may transmit without interfering with other on-going transmissions. There are also other works on busy-tones with two separate channels [17-19].

The work in [20] proposes a scheme to keep the product of transmit power and carrier sense threshold to be constant in order to improve collision prevention. Power control is used for the purpose of topology control in [21, 22]. There has also been work [23, 24] to use power control to establish efficient spanning trees for multicasting and broadcasting.

CHAPTER 3

PROTOCOL DESCRIPTIONS

3.1 Motivation for the Protocol

As discussed in Chapter 2, most power control protocols use different transmit powers on different nodes. This often creates asymmetric links in the network and brings a problem of unfairness. Nodes that transmit at high power level can potentially capture the channel more often than nodes transmitting at low power level. This issue is demonstrated in Figure 3.1.

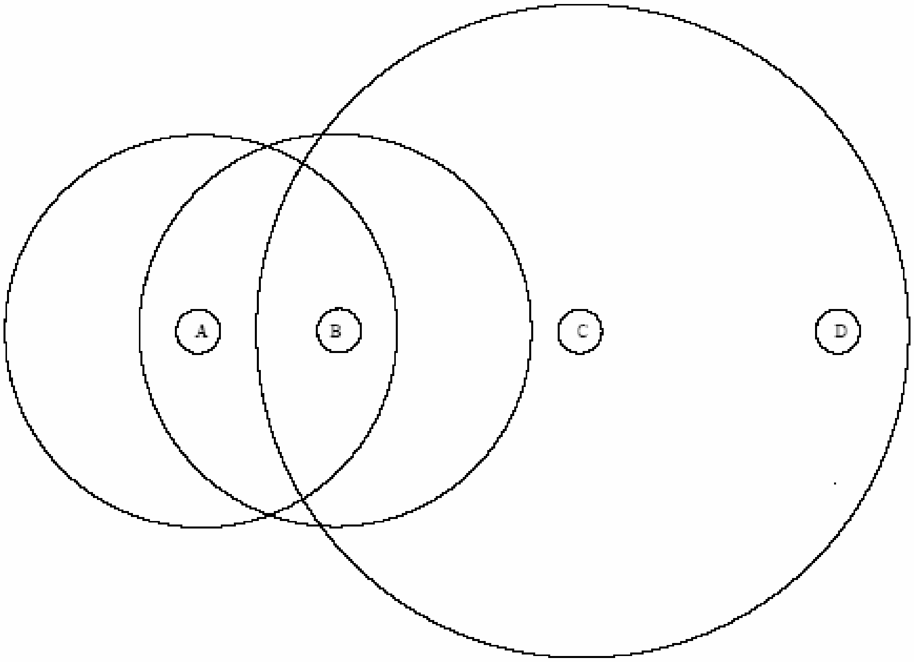


Figure 3.1 Asymmetric Links

In this setting, node C transmits at a higher transmit power than nodes A and B. When node C transmits, a transmission from node B, which is in the transmission range of node C, would collide with the transmission from node C. On the other hand, since node C is not in the transmission range of node B, it would not detect a transmission from B and would attempt to transmit even if B is transmitting. If both node B and node C are transmitting data at high rates, the flow from node C can potentially dominate the channel over the flow from node B.

This problem exists in general in ad hoc networks where different nodes use different transmit powers. A power control protocol improves the throughput over IEEE 802.11 by creating better spatial reuse in the network. However, this subtle unfairness issue makes data flows over longer links capture channel more often over data flows over shorter links.

In order to alleviate this problem, we need a scheme in which a shorter flow has a higher chance of capturing the data channel than a longer flow does. Our proposal is to use a distance-based backoff window selection scheme. In our scheme, we select initial backoff window size on each flow based on the distance of the flow. The general relationship is that the longer the flow, the bigger its starting backoff window must be. The later sections discuss a few schemes of selecting the backoff window size.

3.2 Protocol Overview

Our protocol is a power control protocol combined with a distance-based backoff window selection scheme. The power control protocol in our scheme is similar to the one proposed in [7] but also maintains memories of per-flow transmit powers. This protocol is a fully distributed scheme and can be easily implemented on top of the basic 802.11 MAC protocol.

The protocol requires the addition of certain fields to the packet headers and the local storage of each node. Table 3.1 illustrates the fields that need to be added to the packet headers.

Table 3.1 Additional Fields to Packet Header

Field Name	Size
Transmit_Power	4 bytes
Opposite_Transmit_Power	4 bytes
Send_Node_ID	2 bytes
X_Coord	4 bytes
Y_Coord	4 bytes
Z_Coord	4 bytes

The Transmit_Power field contains the transmit power at which the node sends this packet; Opposite_Transmit_Power field indicates the transmit power that should be used by the receiver on the returning packet; Send_Node_ID is the MAC address of the node; X_Coord, Y_Coord, and Z_Coord are the location coordinates of the node.

The fields that need to be added to the local storage space of each node are shown in Table 3.2.

Table 3.2 Additional Fields to Local Memory

Field Name	**Size**
Pt_app [num_flows]	4 bytes × num_flows
Pt_opp_app [num_flows]	4 bytes × num_flows
X [num_flows]	4 bytes × num_flows
Y [num_flows]	4 bytes × num_flows
Z [num_flows]	4 bytes × num_flows

Each array has the size of num_flows, which is the number of data flows that the node connects to. Pt_app array contains the appropriate transmit powers that the node should use on its flows; Pt_opp_app array contains the appropriate transmit powers that the nodes on the other end of the flows should use; X, Y, and Z arrays contain the location coordinates of the nodes at the other end of the node's flows.

These two structures do not require a lot of overhead to the 802.11 protocol. The additional fields to the packet header add 22 bytes to each packet, which is small compared to a data packet size, which is often hundreds of bytes. The additional local storage space required on each node depends on the number of flows that the node connects to, but in most cases is insignificant.

In our protocol, when a node starts to transmit to another node, it first transmits the RTS packet at the maximum power possible. It also sets all the fields in the packet header described in Table 3.1 to default values and updates its local storages as described in

Table 3.2 to default values. The default values for all transmit powers are the maximum power. A node can detect its location coordinates information using the Global Positioning System (GPS) [25]. At this point, the node should use the default starting contention window size, which is defined as CW_{min}, which is 32 as specified in IEEE 802.11.

Upon receiving the RTS, the receiver node uses the information in the packet header to update its local storage variables. It puts the Transmit_Power field in the packet header into its local Pt_opp_app array (the exact location in the array is determined by a hash table that converses the flow ID into an array index) and the location coordinates of the sending node into its local location arrays. In addition, the node updates its own transmit power based on the Opposite_Transmit_Power field in the packet header. The node then calculates the appropriate transmit power that the sender should be using, places it into the packet header by setting the Opposite_Transmit_Power field, and updates other fields of the header. The method with which this appropriate transmit power is determined is discussed in Section 3.3. The node then determines the contention window size that it should be using based on the length of the flow, which can be calculated locally based on the location information of the sender. Sections 3.4 to 3.6 discuss a few schemes to determine the contention window size. After these operations, the node transmits the CTS packet back to the sender.

Upon receiving the CTS packet, the sending node performs the same procedures as described in the previous paragraph, sets all the appropriate packet header fields and local memory arrays, and transmits the data packet back to the receiver. The receiving node then does the same thing with the ACK packet after receiving the data packet.

This scheme allows a node to update the transmit power for each flow on a per-packet basis. If the conditions surrounding a node change (for example the noise level increases), the information is reflected very quickly into the transmit power on the very next packet.

In our scheme we control the transmit power on a flow so that the packet can only be barely received at the receiver. This gives us the lowest transmit power possible (which leads to the lowest energy consumption) and the best spatial reuse. The next section discusses how we determine the transmit power for each flow.

3.3 Determine Appropriate Per-Flow Transmit Power

The transmit power at which a packet is sent and the receiving power at which the packet is received are related by the propagation model. In our simulations we use the two-ray ground model [26] as the propagation model. The relationship of the transmit Power, Pt, and the receiving power, Pr, in two-ray ground model is defined as follows:

$$\mathrm{Pr} = \frac{\mathrm{Pt} \times \mathrm{K}}{\mathrm{d}^4} \tag{3.1}$$

where K is a constant and d is the distance between the nodes. So we have the following relationship for a given d:

$$Pr = Pt \times Constant \tag{3.2}$$

In addition, in order for a node to successfully capture a packet, the following relationship must be satisfied:

$$Pr / Pn \geq SIR\_Thresh \tag{3.3}$$

where Pr is the transmit power, Pn is the total noise and interference that the node observes on the channel, and SIR_Thresh is the capture threshold, a constant value. Therefore, the minimum power at which a node can receive a packet is Pr*, which is defined as

$$Pr^* / Pn = SIR\_Thresh \tag{3.4}$$

Inserting Pr* into Equation (3.2), we get that the minimum power at which a node must be transmitting a packet in order for the receiver to receive it. We call this power level Pt* and it is defined as

$$Pr^* = Pt^* \times Constant \tag{3.5}$$

When a node receives a packet, it reads the field of Transmit_Power from the packet header. This is the power at which the sending node transmitted the packet (Pt). The node can detect the power level at which it receives the packet (Pr). Hence by Equation (3.2), we can find the constant that relates Pt to Pr. The node can also detect the total noise level on the channel (Pn). By Equation (3.4), we can find Pr*. Then by Equation (3.5), we get Pt*.

In our scheme we use 1.05 Pt* as our appropriate transmit power (slightly above Pt* to account for unexpected interference changes). The node puts this value into the packet header and into its local storage array. When the node on the opposite end of the flow receives the reply packet, it will use this calculated transmit power to send its next packet on this flow.

3.4 Two-Level Contention Window Scheme

After we determine the transmit power at which a node should be sending the packets, we use a distance-based selection scheme to determine the appropriate contention window size. This contention window size is the starting point of the exponential backoff scheme. In our protocol we do not disable the exponential backoff, i.e., the contention window is doubled every time a collision occurs.

In order to understand the relationship of the flow lengths and the optimal contention window sizes, we implemented a few different methods. First, we implement a two-level contention window scheme. This scheme does not use the "barely-reachable" transmit power selection procedures described in Section 3.3, but rather has only two transmit power levels and two contention window sizes associated with them. In this scheme, if the length of the flow is less than one third of the maximum transmission range in the network, the transmission power is set to be the power required to transmit exactly the distance of one third of the maximum range, and the contention window size is set to be 16. Otherwise, the transmission power is set to be the maximum transmit power and the contention window size is set to be 48. For the ns2 simulator [27] we used, the maximum transmission range has the default value of 250 m and the maximum transmit power is 0.2818 mW. The values of the parameters are listed in Table 3.3.

Table 3.3 Two-Level Scheme Setup

Length of the Flow	< 1/3 maximum range	> 1/3 maximum range
Transmit Power Level	0.0035 mW	0.2818 mW
Contention Window Size	16	48

3.5 Distance-Based Linear Relationship

For the schemes described in Sections 3.5 and 3.6, the "barely-reachable" transmission power selection scheme described in Section 3.3 is used.

It is intuitive to deduce that the contention window size should have a linear relationship with the distance between the two nodes on a link. A short link should have a small contention window and hence has its backoff timer expire faster than a long link with a large contention window size.

With the 250-m maximum transmission range in ns2 simulator, we set up the following linear relationship between the flow length and the contention window size. The maximum transmission range (250 m) has a contention window size of 48. We set a lower bound with contention window size 8 (corresponding to distance of flow of 47 m). This lower bound is necessary because a very small contention window size (i.e., a very short flow) would cause a lot more collisions and decreases overall throughput of the network in a high-traffic environment. This scheme is shown in Table 3.4.

Table 3.4 Linear Scheme Setup

Flow Length	Less than 47 m	Longer than 47 m
Contention Window Size	8	0.192 × distance

In this work we assume that there is no obstruction between nodes in the network. If there is obstruction in the network, a flow may need large amount of power to go around the blockage. This would affect the relationship of transmission power and flow distance.

3.6 Distance-Based Nonlinear Relationship

We would also like to explore if a nonlinear relationship between the contention window size and the flow length would give better performance. With a power control scheme the short flows in a network tend to be dominated by long flows. Therefore, we choose to use a scheme that biases toward shorter links.

Table 3.5 Nonlinear Scheme Setup

Flow Length	Less than 25 m	Between 25 and 83.3 m	Longer than 83.3 m
Contention Window Size	4	0.132 × distance	0.216 × distance − 7

We choose a scheme that is shown in Table 3.5. This scheme has a lower bound of distance 25 m (1/10 of the maximum range) with contention window size 4. We then divide up the flows with other lengths to two sets of linear relationships. The flows with length between 25 m and 1/3 of the maximum transmission range (83.3 m) have a linear CW function with a slope that is less steep than the slope of flows with lengths between 1/3 of the maximum transmission range (83.3 m) and the maximum transmission range (250 m). This scheme biases towards shorter flows by giving them a smaller increase rate in their contention window sizes than that for the longer flows. A plot representing this scheme is show in Figure 3.2.

Obviously this is only one particular setting of nonlinear relationships between contention window size and flow length. More complicated relationships may improve the performance more. That is part of the future work.

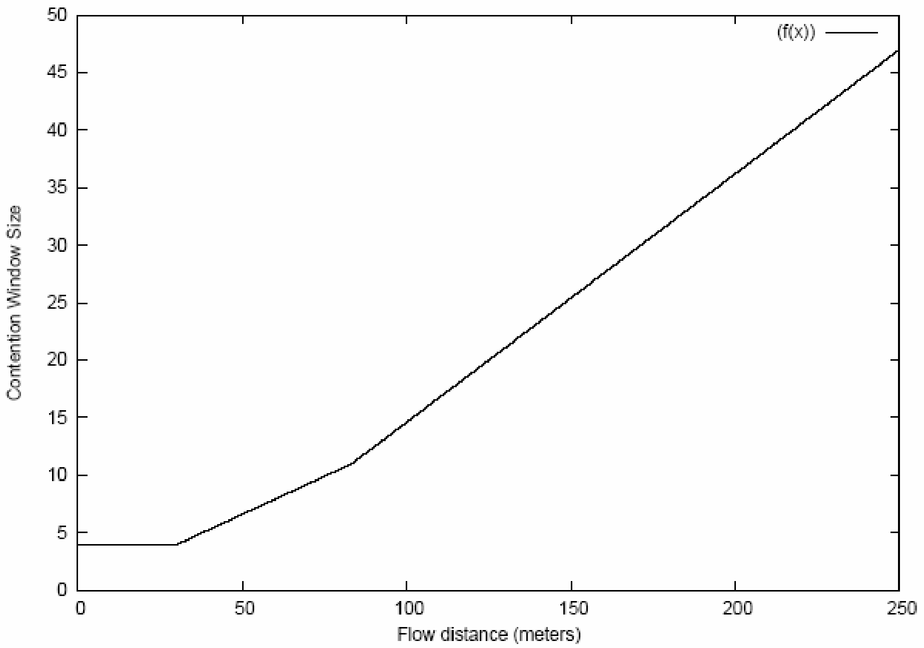


Figure 3.2 Nonlinear Distance-Based Contention Window Selection

CHAPTER 4

ANALYSIS OF RESULTS

4.1 Simulation Setups

We implemented the power save protocols and the distance-based contention window selection schemes described in Chapter 3 in ns2 simulator [25]. The version of ns2 that we used is ns2.26.

The IEEE 802.11 version simulated here uses a data channel rate of 2 Mbps. We choose to use data packets with size of 1 kbyte. We want every flow in the network to be backlogged so that the channel is used at its full capacity. Hence, we decide to transmit at a rate of 250 packets per second on each flow.

We set the experiment space to be a 500 m × 500 m square and place nodes uniformly at random in the space. In these simulations we do not consider mobility. Having mobility could introduce new issues for distance-based contention window selection schemes. It is further discussed in Chapter 5. To eliminate the overhead of routing, we use hardwire routing schemes where every flow is within one hop of its destination. The scheme can be extended for multihop situations, as discussed in Chapter 5.

The metrics that we are interested in studying include:

- Total throughput in the network.

- Total throughput-distance in the network: Throughput-distance is the product of throughput and the transmission distance of the flow. It is a better metric than throughput in measuring network performance in this situation because it takes into account of the disparity of link distances among different flows.
- Maximum vs. minimum throughput-distance: This metric gives insights to the fairness measures in the network.
- Average per-node power consumption.
- Average amount of throughput delivered per watt.

We run the simulations and compare the performance of basic IEEE 802.11, the proposed power control schemes with distance-based contention window selection, and only the power control schemes with default contention window schemes. We vary the number of nodes in the network, with the number of flows in the network equal to half of the number of nodes. The placement of the nodes is done with random seeds in ns2 scenario generation scheme. These simulation results are averaged over 15 different random topologies.

In our simulations a flow is formed between a destination node and a source node that are within one hop (250 m). We used two schemes for the selection of sources and destinations of flows:

- In Section 4.2, we choose a source node and then pick its nearest neighbor as the destination node. The number of sources is equal to the number of flows, which is half the total number of nodes in the network.
- In Sections 4.3 and 4.4, we randomly choose the location of a source node, pick the link distance from a uniform distribution between 0 and 250, and randomly select an angle between 0 and 2π and use that to determine the location of the destination node. Again, the number of sources is half the total number of nodes.

We run simulations on several different schemes in the following sections. They are represented in the plots and tables by the following notations:

- 802_11: IEEE 802.11 DCF.
- two_power: The two-level contention window selection scheme described in Section 3. 4
- two_power_no_cw: The two-level scheme with default contention window size (initial value of 32).
- pr_ctr_cw: The “barely-reachable” power control scheme with linear distance-based contention window selection mechanism, as described in Section 3.5.
- pr_ctr: The “barely-reachable” power control scheme with default contention window size (initial value of 32).
- pr_ctr_7: The “barely-reachable” power control scheme with initial contention window size of 7.

- pr_ctr_cw_nl: The “barely-reachable” power control scheme with nonlinear distance-based contention window selection mechanism, as described in Section 3.6.

4.2 Limitations of Two-Level Contention Window Schemes

We find that a simple two-level contention window selection scheme does not work well in certain situations. Since the two-level scheme treats a flow as either short or long, it does not work well in a setting consisting almost entirely of one type of the flows but not many of the other. For example, it is known that power control schemes improve the performances of IEEE 802.11 in a network consisted of mostly short flows [8]. IEEE 802.11 uses maximum transmit power on all flows. This is equivalent to considering all flows as long flows, and hence causes a lot more unnecessary collisions and delays in backoffs in such a setting. A power control scheme allows flows to transmit at the power that it requires (which in this case is a lot lower than maximum transmit power) and creates better spatial reuse in the network. To create such a setting, we set up a topology where short links are formed between nearest neighbors, as described in Section 4.1. The comparisons of throughput and throughput-distance are shown in Figures 4.1 and 4.2, respectively. As expected, these results show that power control schemes improve throughput and throughput-distance dramatically over 802.11 in this setting. However, the scheme with two different levels of contention windows does not do significantly better than the scheme with just the default contention window selection scheme. This is because almost all the flows in the network transmit at the low power level in the two-level scheme and use the small contention window (size 8) as the starting point. Therefore, the scheme with different contention windows does not provide better spatial reuse or fairness over the scheme with only power control and a initial contention window size of 32. The slight improvement is achieved due to the smaller initial contention window size.

Hence we conclude that the two-level scheme is not a very good approach due to its over-simplification of flow types (either long or short) and does not work well in certain settings. More complicated distance-based schemes should be considered.

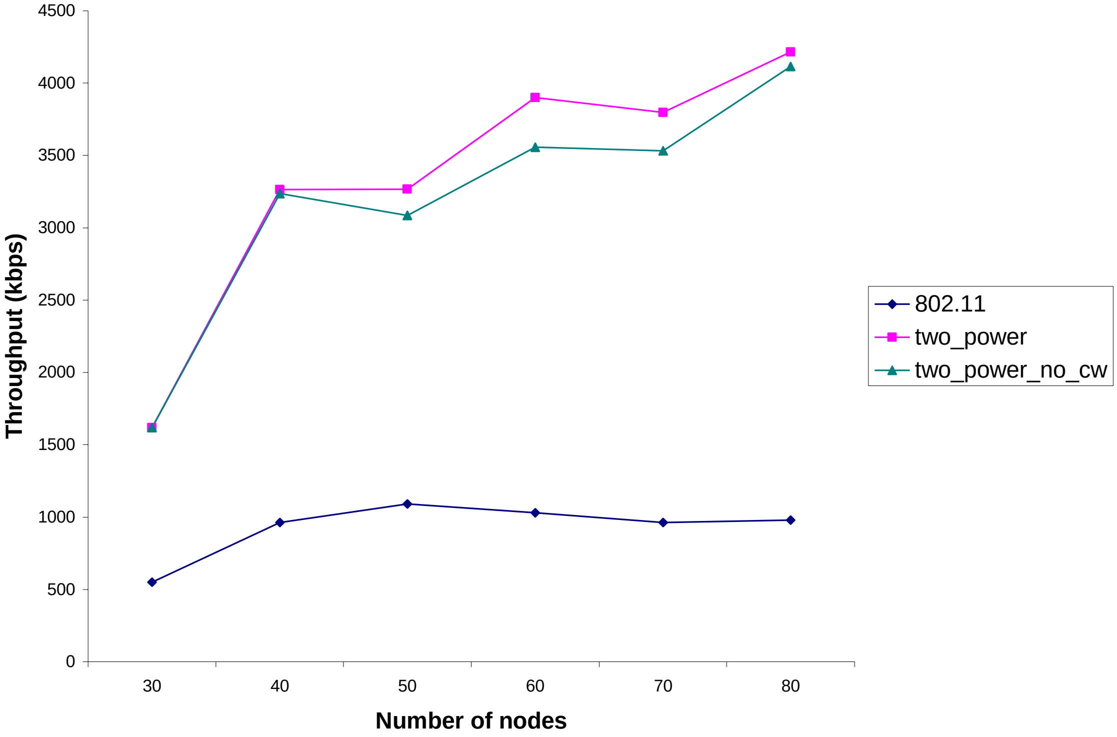


Figure 4.1 Two Power-Level Throughput Comparisons

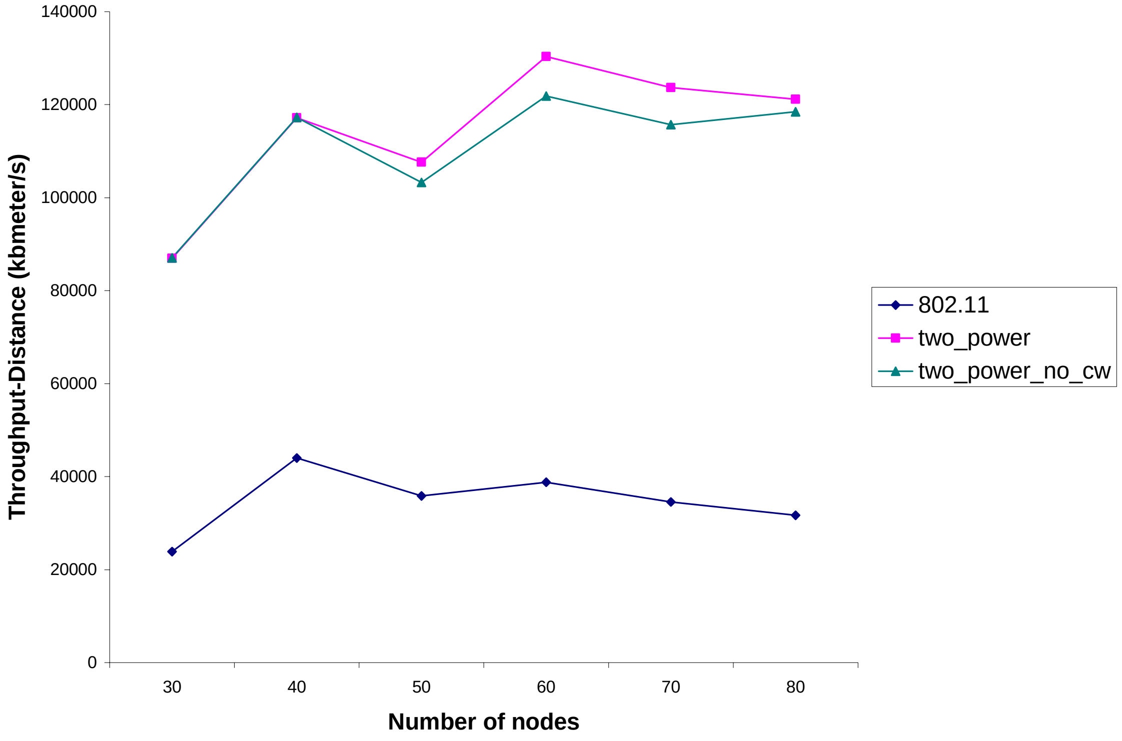


Figure 4.2 Two Power-Level Throughput-Distance Comparisons

4.3 Analysis of Linear Scheme

Most real-world networks do not consist of only long or short flows, but rather a mixture of links of various lengths. Hence for the simulations in this and next sections, we set up a network with the flows whose lengths are randomly chosen from a uniform distribution between 0 and 250 m, as described in Section 4.1. The simulation results suggest that our linear scheme shows a significant performance improvement not only over IEEE 802.11 but the schemes with only power control protocols.

The four schemes that we compare in this section are the default 802.11, power control scheme with default contention window size, power control scheme with a smaller initial contention window of size 7, and the power control with linear distance-based window selection scheme.

The reason that we choose the power control scheme with a smaller contention window is to show that the improvement in performances in our scheme over power control-only scheme is not due to smaller initial contention window size. The scheme with initial contention window size of 7 has an advantage over our linear distance-based scheme, in which the flows' contention window size starts from 7 to 48 based on the link distance. Yet still as the results show, it does not achieve better throughput than our scheme.

From Figure 4.3 the linear CW selection scheme consistently has 30-40% more overall throughput than 802.11 as the number of nodes in the network increases. It is interesting to notice that the power control only protocol does even worse than 802.11 in overall throughput. This is due to the fact that since all flows have the same initial contention window sizes under the power control-only scheme in such a high-traffic network, the shorter flows tend to collide more often than the longer flows and hence increase their contention window to very large sizes. As a result the shorter links spend a lot of time in backoffs waiting to retransmit. Therefore, although the power control scheme improves spatial reuse, the collisions that it causes negate those improvements and the overall impact of the power control-only scheme is negative on throughput. The linear distance-based CW scheme, on the other hand, gives shorter links smaller contention window to begin with. Hence when a collision happens a shorter link gets to retransmit before a longer link. This prevents the contention window sizes on short flows from getting very large and reduces unnecessary waiting time. The power control-only scheme with starting contention window sizes of 7 does slightly better than the scheme with contention window 32, but not nearly as good as the linear distance-based scheme.

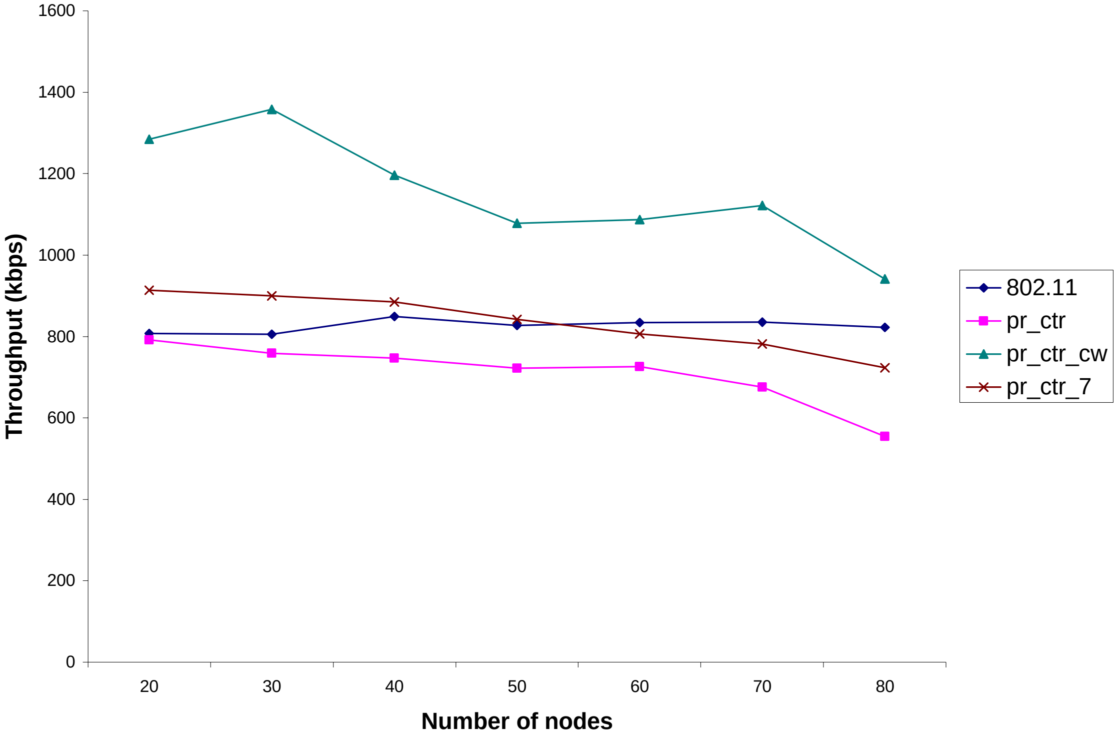


Figure 4.3 Linear Scheme Throughput Comparisons

Figure 4.4 is the comparison of results in throughput-distance. This plot shows that power control only scheme with default CW size has a 20 - 30% improvement on overall throughput-distance over 802.11. The scheme with default CW of 7 is around 15% better than the scheme of 32. The linear scheme has an improvement of 40% on the power control-scheme with default CW and about 25% on the scheme with CW as 7. Since the metric of throughput-distance takes into account the factor of link length, it suggests that the distance-based CW scheme improves performance on flows of all lengths. This is further demonstrated next.

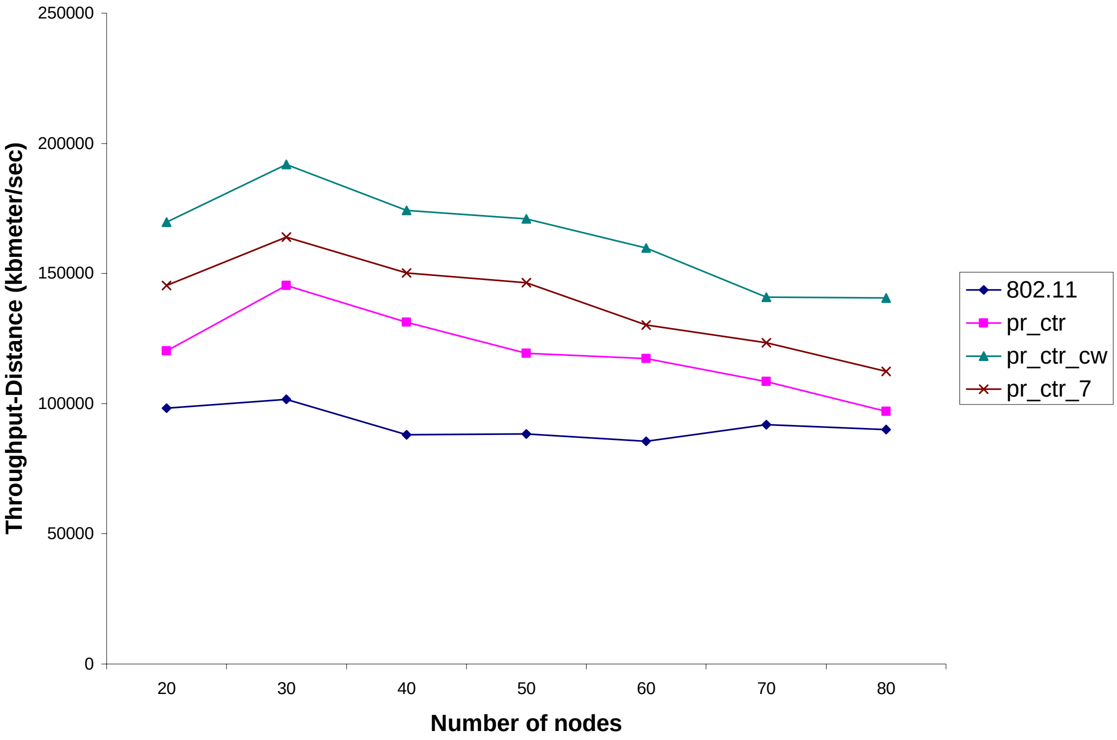


Figure 4.4 Linear Scheme Throughput-Distance Comparisons

Tables 4.1 and 4.2 show the maximum and minimum single-flow throughput-distances of the power control only schemes (with initial contention window sizes of 7 and 32) and the distance-based linear CW selection scheme.

The results in these tables show that the linear scheme improves the throughput-distance on both long and short flows and links compared to the power control-only schemes. The small contention window sizes on short links give them shorter waiting time on collisions. This leads to better spatial reuse and reduces the number of collisions on long flows, which increases throughput-distance on the long flows as well.

Table 4.1 Comparisons of Maximum Single-Flow Throughput-Distance

Number of Nodes	Pr_ctr (in kbmeter/s)	Pr_ctr_7 (in kbmeter/s)	Pr_ctr_cw (in kbmeter/s)
20	55987	63949	86795
30	42067	58394	80316
40	33735	41023	51465
50	22604	32034	48258
60	29071	34543	41158
70	22347	30134	38049
80	17586	28343	47079

Table 4.2 Comparisons of Minimum Single-Flow Throughput-Distance

Number of Nodes	Pr_ctr (in kbmeter/s)	Pr_ctr_7 (in kbmeter/s)	Pr_ctr_cw (in kbmeter/s)
20	11.2	15.0	23.6
30	5.3	7.1	18.4
40	3.8	5.2	10.2
50	2.0	4.6	7.6
60	1.1	2.2	4.2
70	0.3	0.9	2.1
80	0.4	0.8	1.5

As discussed earlier, power control has the dual purposes of improving spatial reuse and saving energy. We are interested to see the impact of distance-based CW selection scheme on power consumption. Hence we also analyzed the average per-node power-consumption in the network for different schemes. We record the total energy consumed in the network during the simulation, find the average energy consumed on each node, and divide it by the simulation time to find the average power consumption of a node. This power is the total power consumption on a node, including transmission, receiving, and idle powers.

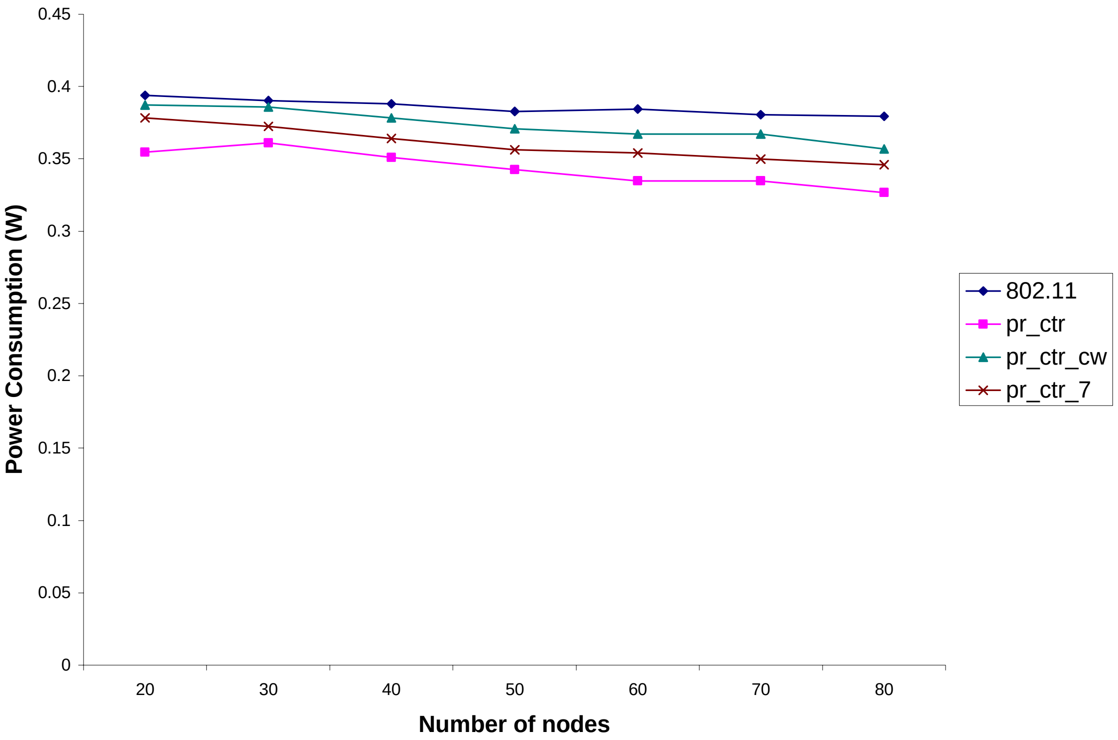


Figure 4.5 Linear Scheme Power Consumption Comparisons

From Figure 4.5, IEEE 802.11 consumes the most power and the power control-only (with default CW) scheme has the lowest power consumption level. This demonstrates the purposes of power control protocols. 802.11 uses maximum transmit power on all flows while power control schemes use only the power necessary to reach the receiver. This plot shows that the distance-based linear scheme consumes less power than 802.11

but more than power control. The reason for that is because the linear scheme is able to transmit more packets than power control only scheme and thus consumes more power. We believe that the distance-based scheme is in fact more power efficient than the power control-only scheme. Figure 4.6 shows the number of kilobits delivered per watt:

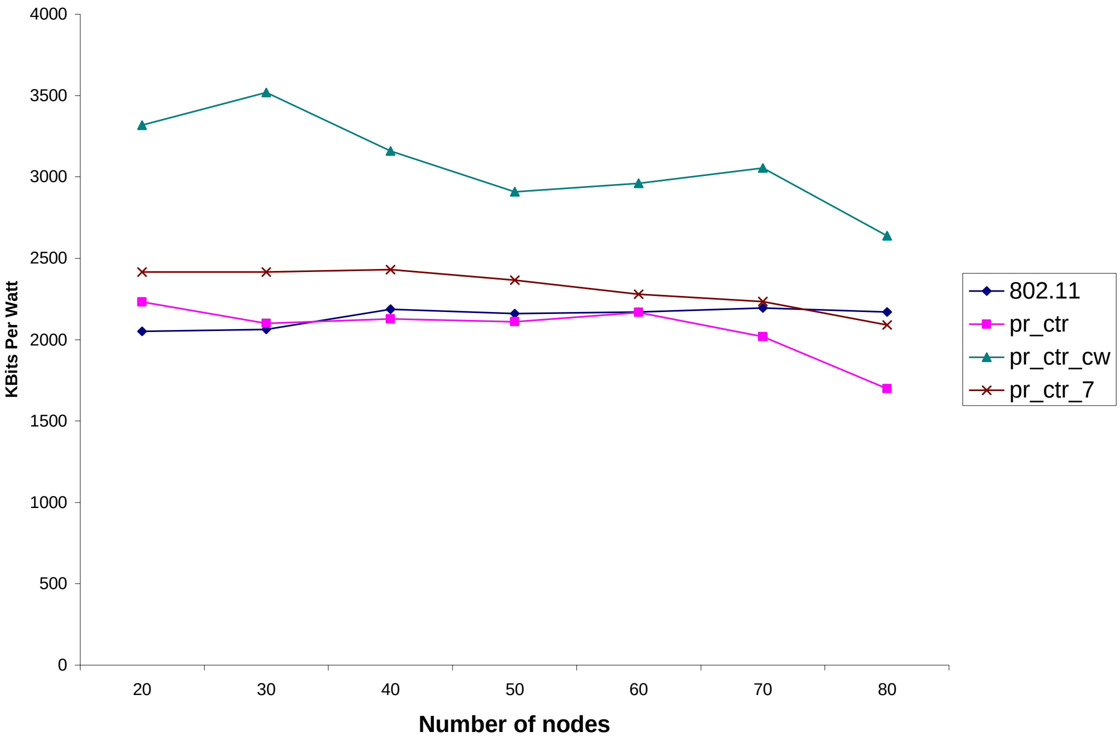


Figure 4.6 Throughput-Distances Per Watt Comparisons

This suggests that the linear scheme is able to transmit 40 – 50% more data with the same amount of power as the power control only scheme. It is due to the fact that the distance-based scheme reduces the number of collisions on the network. When a collision happens, power is wasted. The reduction in number of collisions allows power to be used on actually transmitting packets. Therefore, the power efficiency improves.

4.4 Analysis of Nonlinear Scheme

We also analyzed the nonlinear distance-based contention window selection scheme described in Section 3.6. This scheme performs slightly better than the linear scheme. This suggests that future work could be done to find an even better relationship between flow lengths and contention window sizes.

We run simulations of the linear, nonlinear, and power control-only schemes (with default CW) to compare their throughput and throughput-distance, as shown in Figures 4.7 and 4.8.

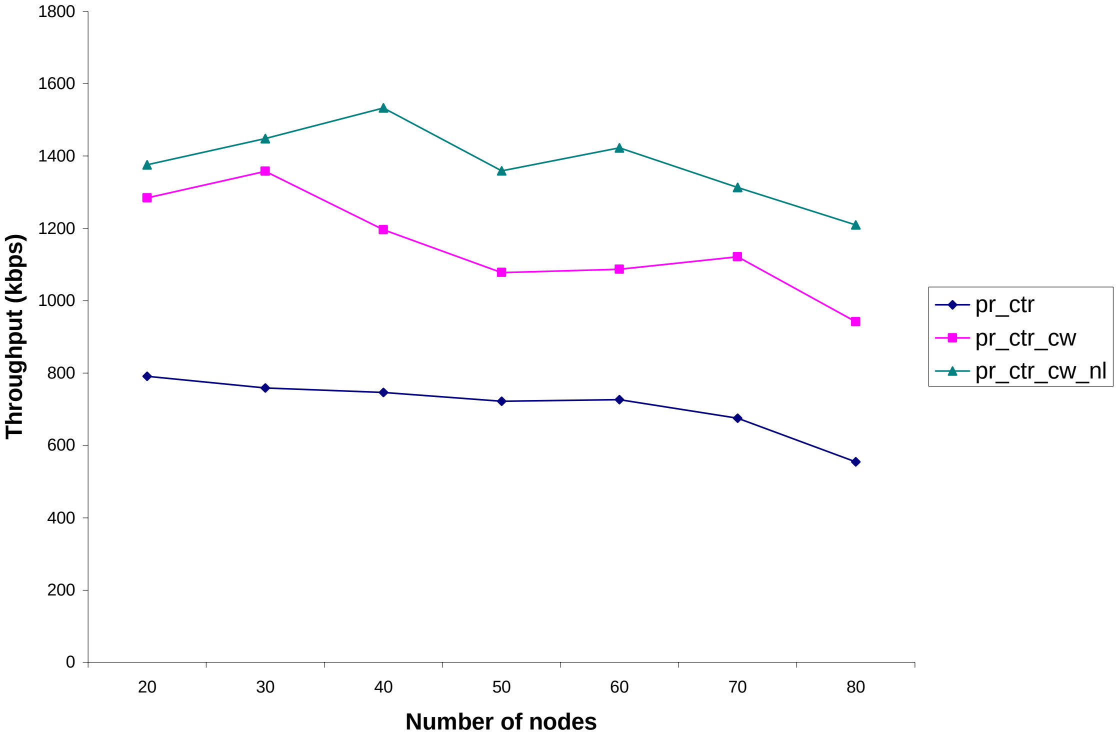
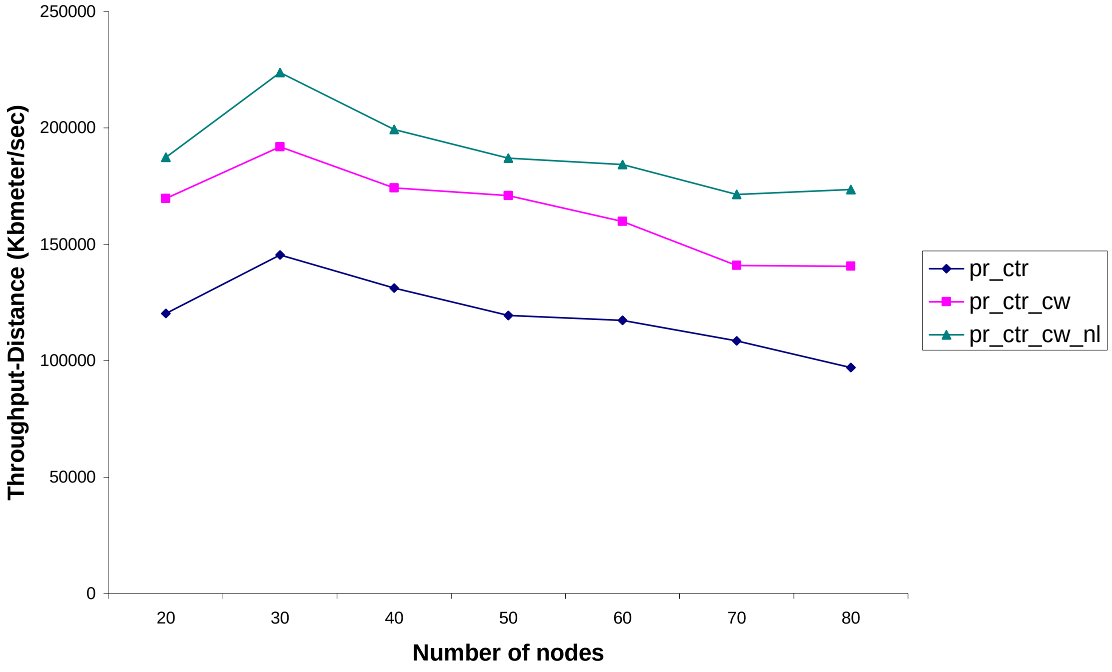


Figure 4.7 Nonlinear Scheme Throughput Comparisons



4.8 Nonlinear Scheme Throughput-Distance Comparisons

Figure 4.7 shows the comparison of throughput of these schemes and Figure 4.8 shows the comparison of throughput-distance of these schemes. On throughput the nonlinear scheme performs 10-15% better than the linear scheme; on throughput-distance the nonlinear scheme does 20 – 30% better than the linear scheme. These results suggest that in the linear scheme the short links do not get enough bias. This is further demonstrated in Tables 4.3 and 4.4.

Table 4.3 shows that the maximum single-flow throughput-distance for the nonlinear scheme increases by around 10% over the linear scheme. On the other hand, Table 4.4

Table 4.3 Linear vs. Nonlinear Maximum Single-Flow Throughput-Distance

Number of nodes	Linear Scheme (in kbmeter/s)	Nonlinear Scheme (in kbmeter/s)
20	86795	87952
30	80316	94753
40	51465	60601
50	48258	51145
60	41158	45763
70	38049	43534
80	47079	48920

Table 4.4 Linear vs. Nonlinear Minimum Single-Flow Throughput-Distance

Number of nodes	Linear Scheme (in kbmeter/s)	Nonlinear Scheme (in kbmeter/s)
20	23.6	45.3
30	18.4	34.8
40	10.2	17.4
50	7.6	13.6
60	4.2	8.0
70	2.1	5.1
80	1.5	3.8

shows that the minimum single-flow throughput-distance for the nonlinear scheme almost doubles over that for the linear scheme. This suggests that the nonlinear scheme improves the performance of short links a lot more than the long links. This confirms that the short flows need a contention window selection scheme that is more biased than a linear scheme. Future work is needed to find a more optimal scheme.

Overall, the results in this chapter show that a power control protocol combined with a distance-based contention window selection scheme significantly improves performance of an ad hoc network. Such a protocol not only provides better spatial reuse and energy efficiency than the IEEE 802.11 DCF, but also a power control-only protocol.

CHAPTER 5

CONCLUSION AND FUTURE WORK

In this thesis we propose a scheme that combines power control with distance-based contention window selection to improve the performance of IEEE 802.11 DCF. Like other power control protocols, this scheme reduces energy consumption and provides better spatial reuse in an ad hoc network. In addition, our protocol provides a method to use distance-based contention window selection schemes to alleviate the subtle unfairness caused by asymmetric links created in power control. Simulations show that this scheme achieves significant performance improvement over 802.11 and power control-only protocols.

One area to explore in the future is to develop a better relationship between flow distance and contention window size. The nonlinear scheme in this thesis suggests that a more optimal relationship can be found. The short flows in an ad hoc network using power control protocols need to be given more advantages over long flows.

The simulations that we conduct in this thesis are for single-hop flows where hardwired routing is used. However, the scheme proposed in this thesis should work for a multihop network as well. Since all the information that a node needs to keep in this scheme is its next hop information, no special changes need to be made to the wireless routing protocols in order to incorporate this scheme into a multihop environment. However, work needs to be done to explore the impact of wireless routing protocols on power control and contention window size selection.

One of the issues that we do not address in this work that needs to be studied in the future is mobility. The protocol presented in this work needs the location information of the sending/receiving node and it attains this information from the header of the packet that it receives. This scheme works well in a network where nodes are not moving very fast. However, if a node is moving at very high speed, the location information that the node advertises in the last packet that it transmitted may be significantly different than its current location. More research needs to be done to address the impact of mobility on a distance-based scheme.

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