A Power Control MAC Protocol for Ad Hoc Networks *

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ABSTRACT

This paper presents a power control MAC protocol that allows nodes to vary transmit power level on a per-packet basis. Several researchers have proposed simple modifications of IEEE 802.11 to incorporate power control. The main idea of these power control schemes is to use different power levels for RTS-CTS and DATA-ACK. Specifically, maximum transmit power is used for RTS-CTS, and the minimum required transmit power is used for DATA-ACK transmissions in order to save energy. However, we show that these schemes can degrade network throughput and can result in higher energy consumption than when using IEEE 802.11 without power control. We propose a power control protocol which does not degrade throughput and yields energy saving.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless communication; C.2.2 [**Network Protocols**]

General Terms

Algorithms, Design, Performance

Keywords

Power control, energy saving, medium access control, ad hoc network

1. INTRODUCTION

Wireless hosts are usually powered by batteries which provide a limited amount of energy. Therefore, techniques to reduce energy consumption are of interest. One way to conserve energy is to use *power saving* mechanisms. Power saving mechanisms allow a node to enter a *doze state* by powering off its wireless network interface when deemed reasonable [2, 8, 19, 27]. Another alternative is to use *power control* schemes which suitably vary transmit power to reduce energy consumption [1, 4, 5, 6, 25, 26]. In addition to providing energy saving, power control can potentially be used to improve spatial reuse of the wireless channel. In this paper, we study *power control* for the purpose of energy saving.

A simple power control protocol has been proposed based on an RTS-CTS handshake in the context of IEEE 802.11 [1, 6, 10, 15]. Different power levels among different nodes introduce asymmetric links. Therefore, in the above scheme, RTS and CTS are transmitted using the highest power level and DATA and ACK are transmitted using the minimum power level necessary for the nodes to communicate. In this paper, we show that this scheme has a shortcoming, which increases collisions and degrades network throughput. We present a new power control protocol which does not degrade throughput.

The rest of this paper is organized as follows. Section 2 reviews the related work. Background on IEEE 802.11 is given in Section 3. Section 4 describes a previously proposed power control scheme and its shortcoming. Section 5 presents our proposed power control MAC protocol. We will refer to the proposed scheme as PCM (Power Control MAC). Section 6 discusses simulation results. Section 7 concludes the paper.

2. RELATED WORK

A power control mechanism that can be incorporated into the IEEE 802.11 RTS-CTS handshake is proposed in [10, 15]. The scheme in [15] allows a node, A, to specify its current transmit power level in the transmitted RTS, and allows receiver node B to include a desired transmit power level in the CTS sent back to A. On receiving the CTS, node A then transmits DATA using the power level specified in the CTS. This scheme allows B to help A choose the appropriate power level, so as to maintain a desired signal-to-noise ratio. A similar protocol is utilized in [6], wherein the RTS and CTS packets are sent at the highest power level, and the DATA and ACK may be sent at a lower power level. We

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refer to this scheme as the *BASIC* power control MAC protocol. We found that the BASIC scheme has a shortcoming that can degrade the throughput. Furthermore, the BASIC scheme may potentially increase the energy consumption, instead of decreasing it. We elaborate on this in Section 4.2.

PARO [6], a power-aware routing optimization, determines routes which consume low energy. PARO chooses a cost function based on the transmit power level at each hop on a route, to determine a low energy-consuming route between a pair of nodes. PARO also uses a power control MAC protocol similar to BASIC. Several other routing metrics are also proposed in [20, 23].

A power control protocol presented in [1] is also similar to the BASIC scheme. It maintains a table for the minimum transmit power necessary to communicate with neighbor nodes. This scheme allows each node to increase or decrease its power level dynamically. However, different power levels among nodes result in asymmetric links, causing collisions.

A power control protocol proposed in [28] uses one control channel and multiple data channels. A control channel is used to assign data channels to nodes. An RTS, CTS, RES (a special packet), and broadcast packets are transmitted through the control channel using the highest transmit power. By an RTS-CTS handshake, source and destination nodes decide which channel and what power level to use for data transmissions. On the reception of CTS, the source sends an RES to the destination to reserve a data channel. Then, DATA and ACK transmissions occur on the reserved data channel using the negotiated power level from the RTS-CTS handshake.

Transmit power is controlled according to packet size in [4, 5]. The proposed scheme is based on the observation that reducing transmission power can result in energy savings, but can also result in more errors. A higher bit error rate can lead to increased retransmissions, consuming more energy. Thus, the protocol in [4, 5] chooses an appropriate transmission power level based on the packet size. An adaptive scheme is also presented in [11] to choose MAC frame size based on the channel conditions.

IEEE 802.11 may result in unfairness (performance degradation) for nodes which use lower transmission power than their neighbor nodes. Poojary *et al.* [14] propose a scheme to improve the fairness.

COMPOW [13] selects a common power level at all nodes in the network to ensure bi-directional links. Each node runs several routing daemons, each at a different power level. The power level is chosen to be the smallest power level which achieves the same level of network connectivity as the highest power level.

The Power Controlled Multiple Access (PCMA) protocol [12] allows different nodes to have different transmission power levels (and allows per-packet selection of transmit power). PCMA uses two channels, one channel for "busy tones", and the other for all other packets. PCMA uses busy tones, instead of RTS-CTS, to overcome the hidden terminal problem. While a node is receiving a DATA packet, it periodically sends a busy tone. The power level at which

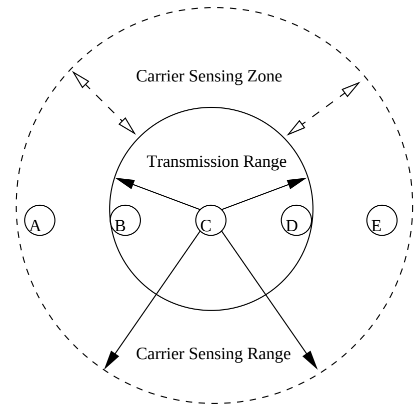


Figure 1: Nodes in transmission range can receive and decode packet correctly, whereas nodes in the carrier sensing zone can sense a transmission, but cannot decode it correctly.

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 first waits for a fixed duration (determined by the frequency with which nodes transmit busy tones when receiving data), and senses the channel for busy tones from other nodes. The signal strength of busy tones received by a node is utilized to determine the highest power level at which this node may transmit without interfering with other on-going transmissions. Busy tones with two separate channels are also used in [3, 7, 20, 29].

In [16, 17, 18, 24], power control is used for the purpose of topology control. Power control has been also used to establish energy efficient spanning trees for multicasting and broadcasting [25, 26].

3. IEEE 802.11 MAC PROTOCOL

IEEE 802.11 specifies two medium access control protocols, PCF (Point Coordination Function) and DCF (Distributed Coordination Function). PCF is a centralized scheme, whereas DCF is a fully distributed scheme. We consider DCF in this paper.

We now define the terms *transmission range, carrier sensing range* and *carrier sensing zone* which are used in the rest of the paper. (These terms are illustrated using Figure 1.)

- *Transmission range*: When a node is within transmission range of a sender node, it can receive and correctly decode packets from the sender node. In our simulations, the transmission range is 250 m when using the highest transmit power level.

- *Carrier sensing range*: Nodes in the carrier sensing range can sense the sender's transmission. Carrier sensing range is typically larger than the transmission range, for instance, two times larger than the transmission range [9]. In our simulations, the carrier sensing range is 550 m when using the highest power level. Note that the carrier sensing range and transmission

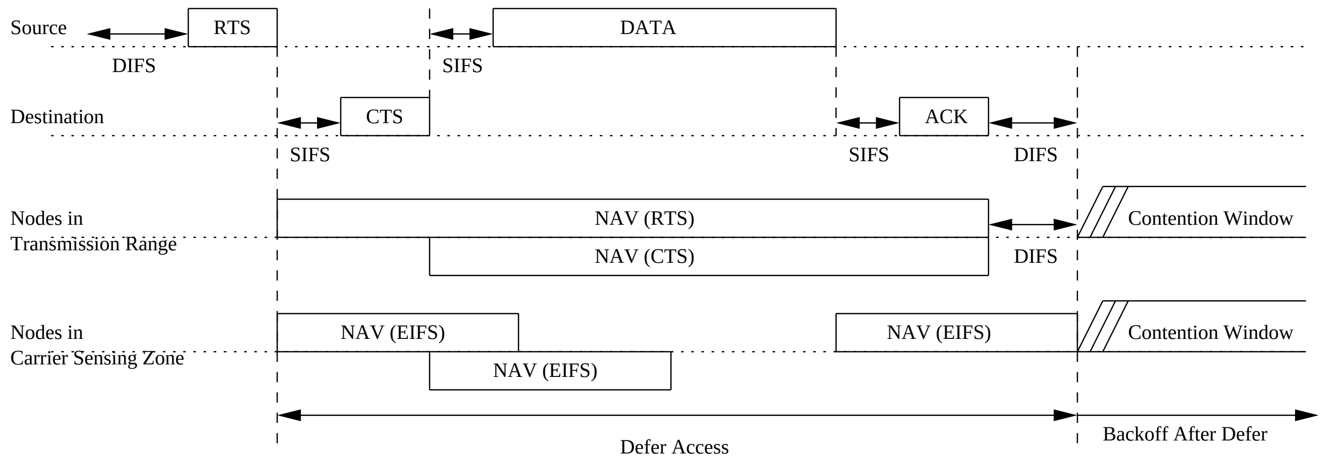


Figure 2: When source and destination nodes transmit RTS and CTS, nodes in transmission range correctly receive these packets and set their NAVs for the duration of the whole packet transmission. However, nodes in the carrier sensing zone only sense the signal and cannot decode it correctly, so these nodes set their NAVs for EIFS duration (when they sense the channel changing state from busy to idle). The purpose of EIFS is to protect an ACK frame at the source node.

range depend on the transmit power level. Since carrier sensing range includes the transmission range, we now define *carrier sensing zone* which excludes the transmission range from the carrier sensing range.

- *Carrier sensing zone*: When a node is within the carrier sensing zone, it can sense the signal but cannot decode it correctly. Note that, as per our definition here, the carrier sensing zone does not include transmission range. Nodes in the transmission range can indeed sense the transmission, but they can also decode it correctly. Therefore, these nodes will not be in the carrier sensing zone as per our definition. The carrier sensing zone is between 250 m and 550 m with the highest power level in our simulation.

Figure 1 shows the transmission range, carrier sensing range, and carrier sensing zone for node C[1]. When node C transmits a packet, B and D can receive and decode it correctly since they are in transmission range. However, A and E only sense the signal and cannot decode it correctly because they are in the carrier sensing zone.

The DCF in IEEE 802.11 is based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). Carrier sensing is performed using physical carrier sensing (by air interface) as well as virtual carrier sensing. Virtual carrier sensing uses the duration of the packet transmission, which is included in the header of RTS, CTS, and DATA frames. The duration included in each of these frames can be used to infer the time when the source node would receive an ACK frame from the destination node. For example, the duration field in RTS includes time for CTS, DATA, and ACK transmissions. Similarly, the duration field for CTS includes time for DATA and ACK transmissions, and the duration field for DATA only includes time for the ACK transmission.

Each node in IEEE 802.11 maintains a NAV (Network Allocation Vector) which indicates the remaining time of the on-going transmission sessions. Using the duration information in RTS, CTS, and DATA packets, nodes update their NAVs whenever they receive a packet. The channel is considered to be busy if either physical or virtual carrier sensing indicates that the channel is busy.

Figure 2 shows how nodes in transmission range and the carrier sensing zone adjust their NAVs during RTS-CTS-DATA-ACK transmission. SIFS, DIFS, and EIFS are interframe spaces (IFSs) specified in IEEE 802.11. Note that in Figure 2 the lengths of RTS, CTS, DATA, and ACK do not exactly represent the actual sizes.

IFS is the time interval between frames. IEEE 802.11 defines four IFSs – SIFS (short interframe space), PIFS (PCF interframe space), DIFS (DCF interframe space), and EIFS (extended interframe space). The IFSs provide priority levels for accessing the channel. The SIFS is the shortest of the interframe spaces and is used after RTS, CTS, and DATA frames to give the highest priority to CTS, DATA and ACK, respectively. In DCF, when the channel is idle, a node waits for the DIFS duration before transmitting any packet.

In Figure 2, nodes in transmission range correctly set their NAVs when receiving RTS or CTS. However, since nodes in the carrier sensing zone cannot decode the packet, they do not know the duration of the packet transmission. To prevent a collision with the ACK reception at the source node, when nodes detect a transmission and cannot decode it, they set their NAVs for the EIFS duration. The main purpose of the EIFS is to provide enough time for a source node to receive the ACK frame, so the duration of EIFS is longer than that of an ACK transmission. As per IEEE 802.11, the EIFS is obtained using the SIFS, the DIFS, and

[1]Transmission range and carrier sensing range may not be circular in reality.

the length of time to transmit an ACK frame at the physical layer's lowest mandatory rate, as the following equation [22]: $EIFS = SIFS + DIFS + [(8 \times ACKsize) + PreambleLength + PLCPHeaderLength]/BitRate$, where ACK size is the length (in bytes) of an ACK frame, and BitRate is the physical layer's lowest mandatory rate. PreambleLength is 144 bits and PLCPHeaderLength is 48 bits [22]. Using a 1 Mbps channel bit rate, EIFS is equal to 364 μs.

In IEEE 802.11 [22], the EIFS is used whenever the physical layer has indicated to the MAC that a frame transmission was begun but that frame transmission did not result in the correct reception of a complete MAC frame with a correct FCS (Frame Check Sequence) value. (In this context, a frame transmission is considered to have begun when its PLCP header is received correctly.) The EIFS interval begins following indication by the physical layer that the channel is idle after sensing of the erroneous frame. In our simulations, we use a somewhat conservative variation on the above 802.11 specification. In our simulation model of the 802.11 protocol, whenever a node senses a transmission (whether or not PLCP header is received) but cannot receive the transmission correctly, EIFS is used. Thus, nodes in the carrier sensing zone use EIFS whenever they can sense the signal but cannot decode it. In the rest of this paper (and Figure 2), unless otherwise mentioned, when we say 802.11, we refer to the above conservative variation. This variation may reduce collisions as compared to the IEEE 802.11 standard in multi-hop wireless networks.

Note that IEEE 802.11 does not completely prevent collisions due to a hidden terminal – nodes in the receiver's carrier sensing zone, but not in the sender's carrier sensing zone or transmission range, can cause a collision with the reception of a DATA packet at the receiver. For example, in Figure 3, suppose node C transmits a packet to node D. When C and D transmit an RTS and CTS respectively, A and F will set their NAVs for EIFS duration. During C's DATA transmission, A defers its transmission because it senses C's DATA transmission. However, node F does not sense any signal during C's DATA transmission, so it considers the channel to be idle. (F is in D's carrier sensing zone, but not in C's.) When F starts a new transmission, it can cause a collision with the reception of DATA at D. As F is outside D's transmission range, by symmetry, D may be outside F's transmission range. However, since F is in D's carrier sensing zone, by symmetry, this implies that F can present sufficient interference at node D to cause a collision with DATA being received by D.

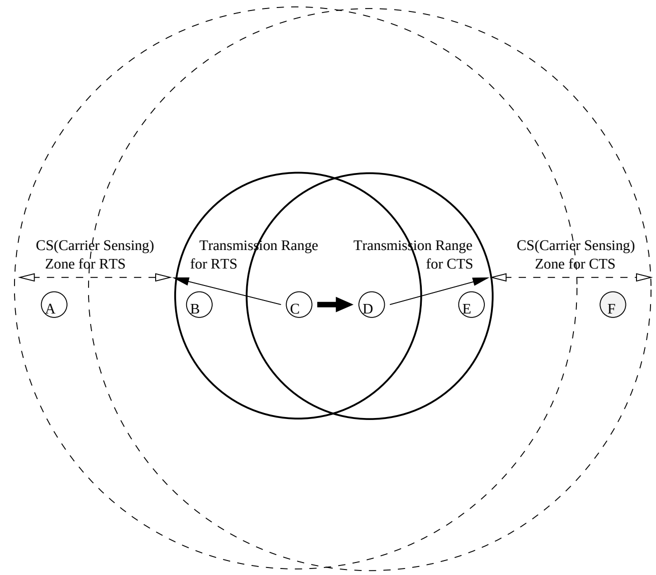


Figure 3: IEEE 802.11 does not prevent collisions completely. After the RTS-CTS handshake, when node C transmits a DATA packet to node D, F cannot sense the DATA transmission since it is in D's carrier sensing zone but not C's. Therefore, when F starts transmitting, it can cause a collision with the reception of the DATA packet at node D.

Different transmit powers used at different nodes may also result in increased collisions, unless some precautions are taken. Suppose nodes A and B in Figure 4 use lower power than nodes C and D. When A is transmitting a packet to B, this transmission may not be sensed by C and D. So, when C and D transmit to each other using a higher power, their transmissions will collide with the on-going transmission from A to B.

One simple solution (as a modification to IEEE 802.11) is to transmit RTS and CTS at the highest possible power level but transmit DATA and ACK at the minimum power level necessary to communicate, as suggested in [1, 6, 10, 15]. We refer to this as the BASIC scheme. Figure 5 illustrates the BASIC scheme. In Figure 5, nodes A and B send RTS and CTS, respectively, with the highest power level so that node C receives the CTS and defers its transmission. By using a lower power for DATA and ACK packets, nodes can conserve energy.

In the BASIC scheme, the RTS-CTS handshake is used to decide the transmission power for subsequent DATA and ACK packets. This can be done in two different ways as described below. Let p_{max} denote the maximum possible transmit power level.

- Suppose that node A wants to send a packet to node B. Node A transmits the RTS at power level p_{max}. When B receives the RTS from A with signal level p_r, B can calculate the minimum necessary transmission power level, $p_{desired}$, for the DATA packet based on received power level p_r, the transmitted power level,

4. *BASIC* POWER CONTROL PROTOCOL

This section describes the BASIC power control scheme [1, 6, 10, 15] and its limitation.

4.1 Protocol Description

As mentioned earlier, power control can reduce energy consumption. However, power control may introduce different transmit power levels at different hosts, creating an asymmetric situation where a node A can reach node B, but B cannot reach A.

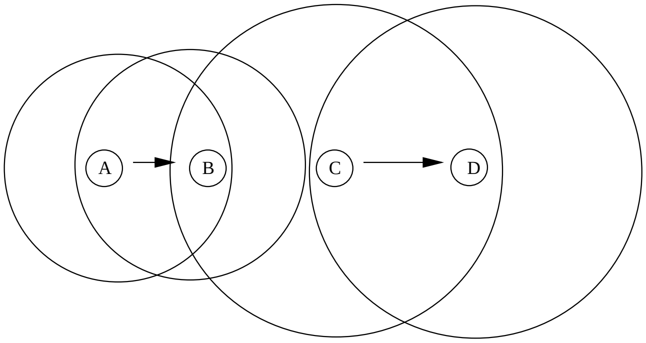


Figure 4: Differences in transmit power can lead to increased collisions.

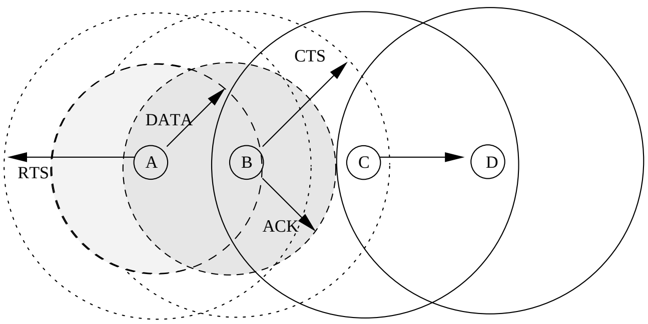


Figure 5: BASIC scheme: RTS and CTS are transmitted at the highest transmission power level.

p_{max}, and noise level at the receiver B. We can borrow the procedure for estimating $p_{desired}$ from [12]. This procedure determines $p_{desired}$ taking into account the current noise level at node B. Node B then specifies $p_{desired}$ in its CTS to node A. After receiving CTS, node A sends DATA using power level $p_{desired}$. Since the signal-to-noise ratio at the receiver B is taken into consideration, this method can be accurate in estimating the appropriate transmit power level for DATA.

- In the second alternative, when a destination node receives an RTS, it responds by sending a CTS as usual (at power level p_{max}). When the source node receives the CTS, it calculates $p_{desired}$ based on received power level, p_r, and transmitted power level (p_{max}), as

$$p_{desired} = \frac{p_{max}}{p_r} \times Rx_{thresh} \times c$$

where Rx_{thresh} is the minimum necessary received signal strength and c is a constant (similar to [12]). We set c equal to 1 in our simulations. Then, the source transmits DATA using a power level equal to $p_{desired}$. Similarly, the transmit power for the ACK transmission is determined when the destination receives the RTS.

This method makes two assumptions. First, signal attenuation between source and destination nodes is assumed to be the same in both directions. Second, noise level at the receiver is assumed to be below some predefined threshold. This approach may result in unreliable communication when the assumptions are wrong. However, it is likely to be reliable with a fairly high probability. This alternative does not require any modification to the CTS format. We use this alternative in our simulation of BASIC and the proposed scheme.

As we now explain below, the BASIC scheme can lead to increased collisions, degrading throughput.

4.2 Deficiency of the BASIC Protocol

In the BASIC scheme, RTS and CTS are sent using p_{max}, and DATA and ACK packets are sent using the minimum necessary power to reach the destination. When the neighbor nodes receive an RTS or CTS, they set their NAVs for the duration of the DATA-ACK transmission. For example, in Figure 6, suppose node D wants to transmit a packet to node E. When D and E transmit the RTS and CTS respectively, B and C receive the RTS, and F and G receive the CTS, so these nodes will defer their transmissions for the duration of the D-E transmission. Node A is in the carrier sensing zone of D (when D transmits at p_{max}) so it will only

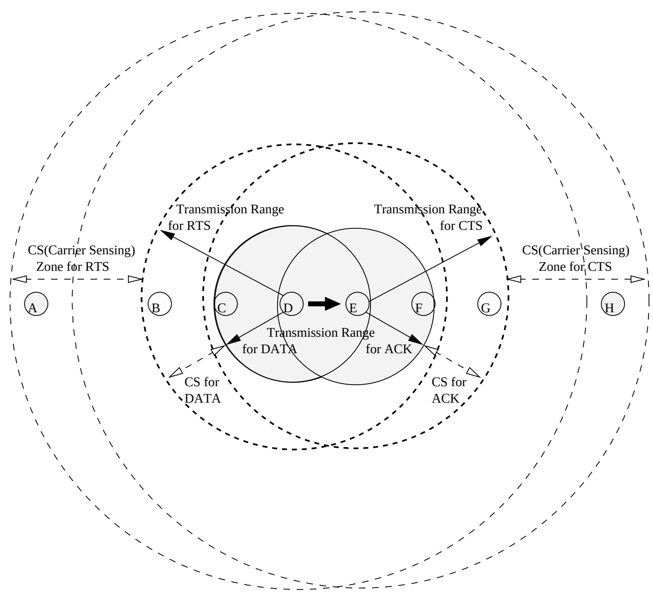


Figure 6: BASIC scheme: Suppose node D transmits a packet to node E. Since DATA and ACK are transmitted using the minimum necessary transmit power, nodes in carrier sensing zone (such as A and H) during the RTS-CTS transmission may not sense any signal during DATA-ACK. When these nodes initiate a new transmission by sending RTS at the power level p_{max}, a collision may occur at D and E. The collisions trigger retransmissions, resulting in more energy consumption.

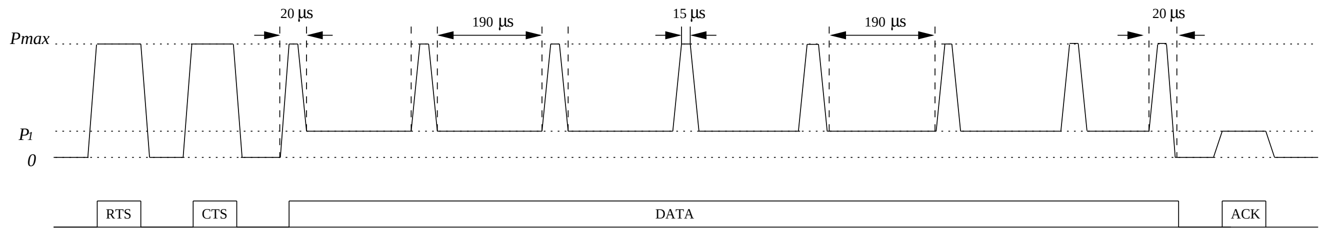


Figure 7: PCM periodically increases the transmit power during DATA transmission in order to inform nodes in the carrier sensing zone of its transmission.

sense the signals and cannot decode the packets correctly. Node A will set its NAV for EIFS duration when it senses the RTS transmission from D. Similarly, node H will set its NAV for EIFS duration following CTS transmission from E.

When transmit power control is not used, the carrier sensing zone is the same for RTS-CTS and DATA-ACK since all packets are sent using the same power level. However, in BASIC, when a source and destination pair decides to reduce the transmit power for DATA-ACK, the transmission range for DATA-ACK is smaller than that of RTS-CTS; similarly, the carrier sensing zone for DATA-ACK is also smaller than that of RTS-CTS.

When D and E in Figure 6 reduce their transmit power for DATA and ACK transmissions respectively, both transmission range and carrier sensing zone are reduced. Thus, only C and F can correctly receive the DATA and ACK packets, respectively. Furthermore, since nodes A and H cannot sense the transmissions, they consider the channel to be idle. When any of these nodes (A or H) starts transmitting at the power level p_{max}, this transmission causes a collision with the ACK packet at D and DATA packet at E. This results in throughput degradation and higher energy consumption (because of retransmissions), as we will see in Section 6.3.

As discussed in Section 3, IEEE 802.11 also does not prevent nodes in the carrier sensing zone (node H in Figure 6) from causing collisions with the DATA packet at the destination node (node E in Figure 6). However, BASIC makes the situation worse by introducing interference with the reception of an ACK at the source node. Using BASIC, node A in Figure 6 cannot sense D's DATA transmission at the lower power level, so a transmission from A can interfere with the reception of the ACK at D.

The above discussion indicates that the BASIC scheme is more prone to collisions, degrading throughput (as shown in Section 6.3). The BASIC scheme has been considered for saving energy [1, 6, 10, 15]. However, past work did not identify the above deficiency of the BASIC protocol.

5. PROPOSED POWER CONTROL MAC PROTOCOL

Proposed Power Control MAC (PCM) is similar to the BASIC scheme in that it uses power level p_{max} for RTS-CTS and the minimum necessary transmit power for DATA-ACK transmissions. We now describe the procedure used in PCM.

1. Source and destination nodes transmit the RTS and CTS using p_{max}. Nodes in the carrier sensing zone set their NAVs for EIFS duration when they sense the signal and cannot decode it correctly (similar to the variation on IEEE 802.11 described earlier).
2. The source node may transmit DATA using a lower power level, similar to the BASIC scheme.
3. To avoid a potential collision with the ACK (as discussed earlier), the source node transmits DATA at the power level p_{max}, periodically, for just enough time so that nodes in the carrier sensing zone can sense it.
4. The destination node transmits an ACK using the minimum required power to reach the source node, similar to the BASIC scheme.

Figure 7 shows how the transmit power level changes during the sequence of an RTS-CTS-DATA-ACK transmission. After the RTS-CTS handshake using p_{max}, suppose the source and destination nodes decide to use power level p_1 for DATA and ACK. Then, the source will transmit DATA using p_1 and periodically use p_{max}. The destination uses p_1 for ACK transmission.

As we described, the key difference between PCM and the BASIC scheme is that PCM periodically increases the transmit power to p_{max} during the DATA packet transmission. With this change, nodes that can potentially interfere with the reception of ACK at the sender will periodically sense the channel as busy, and defer their own transmission. Since nodes that can sense a transmission but not decode it correctly only defer for EIFS duration, the transmit power for DATA is increased once every EIFS duration. Also, the interval which the DATA is transmitted at p_{max} should be larger than the time required for physical carrier sensing.

According to [22], 15 μs should be adequate for carrier sensing, and time required to increase output power (power-on) from 10% to 90% of maximum power (or power-down from 90% to 10% of maximum power) should be less than 2 μs. Thus, we believe 20 μs should be enough to power up (2 μs), sense the signal (15 μs), and power down (2 μs).

In our simulation, EIFS duration is set to 212 μs using a 2 Mbps bit rate[2]. In PCM, a node transmits DATA at p_{max}

[2] According to the 802.11 standard [22], EIFS is equal to 364 μs when the lowest data rate is 1 Mbps. In our simulation, we use 2 Mbps bit rate as the lowest data rate, so EIFS is equal to 212 μs. Note that the performance of PCM will improve if we use 364 μs for EIFS because PCM will increase the transmit power level less frequently.

every 190 μs for a 20 μs duration. Thus, the interval between the transmissions at p_{max} is 210 μs, which is shorter than EIFS duration. A source node starts transmitting DATA at p_{max} for 20 μs and reduces the transmit power to a power level adequate for the given transmission for 190 μs. Then, it repeats this process during DATA transmission, (see Figure 7). The node also transmits DATA at p_{max} for the last 20 μs of the transmission.

With the above simple modification, PCM overcomes the problem of the BASIC scheme and can achieve throughput comparable to 802.11, but uses less energy. However, note that PCM, just like 802.11, does not prevent collisions completely. Specifically, collisions with DATA being received by the destination can occur, as discussed earlier. Our goal in this paper is to match the performance of 802.11 while reducing energy consumption.

To be more conservative in estimating the energy consumption of PCM, we also perform our simulations where we increase the transmit power every 170 μs for 40 μs during DATA transmission. We refer to this variation as PCM40. This variation will consume more energy as compared to the above version of PCM.

Recall that, as discussed earlier, this paper evaluates a variation of IEEE 802.11 wherein EIFS is used differently from the standard. However, the proposed approach of transmitting part of a packet at a higher power level and rest at (potentially) lower power level can be applied to the IEEE 802.11 specification as well. For instance, when the rate at which the data is transmitted is greater than the rate used for PLCP header, the range over which PLCP header is received can be greater than the range over which data is received. We can exploit this by transmitting the PLCP header at p_{max} and the rest of the packet at the lower power level. This is expected to eliminate some collisions, but perhaps not all the collisions introduced by the BASIC scheme. This paper, however, only evaluates the variation of 802.11, and the PCM scheme.

6. PERFORMANCE EVALUATION

We have simulated BASIC, PCM, PCM40, as well as 802.11. We use the following two metrics to evaluate the MAC protocols.

- Aggregate throughput over all flows in the network.
- Total data delivered per unit of transmit energy consumption (or, Mbits delivered per joule). This is calculated as the total data delivered by all the flows divided by the total amount of *transmit* energy consumption over all nodes (Mbits/joule). The energy consumed in packet reception is not counted in the above metric.

6.1 Simulation Model

For simulations, we use ns-2 (ns-2.1b8a) with the CMU wireless extension [21]. We use 2 Mbps for the channel bit rate. Packet size is 512 bytes unless otherwise specified. (We performed some simulations varying packet sizes as well.) Each flow in the network transmits CBR (Constant Bit Rate) traffic. We performed the simulation with various network loads. We do not consider mobility in our simulations.

For the radio propagation model, a two-ray path loss model is used [21]. We do not consider fading in our simulations.

We assume that carrier sensing range is about two times larger than the transmission range. In particular, in our simulation, the transmission range is 250 m, and the carrier sensing range is 550 m, at the highest transmit power level. All simulation results are the average of 30 runs. Each simulation runs for 20 seconds of simulation time.

6.2 Simulation Topology

For network topologies, we use both a simple chain and random topologies.

For the chain topology, we consider 10 transmit power levels, 1 mW, 2 mW, 3.45 mW, 4.8 mW, 7.25 mW, 10.6 mW, 15 mW, 36.6 mW, 75.8 mW, and 281.8 mW, which roughly correspond to the transmission ranges of 40 m, 60 m, 80 m, 90 m, 100 m, 110 m, 120 m, 150 m, 180 m, and 250 m, respectively. For the random topology, we consider four transmit power levels, 2 mW, 15 mW, 75.8 mW, and 281.8 mW, roughly corresponding to the transmission ranges of 60 m, 120 m, 180 m, and 250 m, respectively. Since the simulation results for the BASIC scheme showed dramatic changes as the node distances varies, we included more transmit power levels for the chain topology in order to understand the behavior of the BASIC scheme. The transmission range at power level p_{max} is 250 m in our simulations for both topologies.

- *Chain topology*

  Figure 8 shows our chain topology, which consists of 31 nodes with 30 single hop flows. Nodes are shown as a circle, and the arrow between two nodes indicates traffic flows. The distance between adjacent node pairs in Figure 8 is uniform. In our simulations, we vary the distance from 40 m to 250 m.

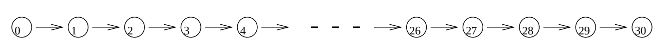


Figure 8: Chain topology: 31 nodes with 30 flows.

- *Random topology*

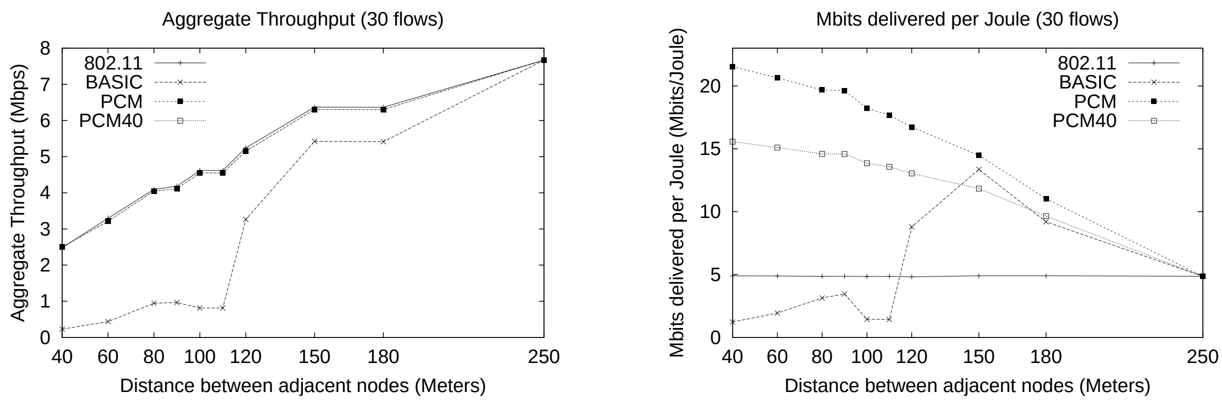
  For the random topology, we place 50 nodes randomly within a 1000x1000 m^2 flat area. One flow originates at each node with the nearest node as its destination. Thus, a total of 50 flows are generated.

  We simulated 50 different random topologies (scenarios). Table 1 shows the number of flows using each power level for each scenario. In Table 1, p_1, p_2, p_3, and p_4 indicate transmit power levels, corresponding to the transmission ranges of 60 m, 120 m, 180 m, and 250 m, respectively.

Table 1: Number of Flows at Various Power Levels for the Random Topology

Scenario	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
p1 flows	15	14	10	18	11	16	16	15	17	17	18	5	14	12	10	19	8	11	7	13	12	13	6	12	12
p2 flows	18	23	28	23	26	17	24	24	22	24	18	27	27	24	23	16	27	27	27	25	27	21	27	26	19
p3 flows	14	10	9	8	9	14	10	10	8	8	11	13	8	12	15	13	13	9	13	6	8	14	15	9	16
p4 flows	3	3	3	1	4	3	0	1	3	1	3	5	1	2	2	2	2	3	3	6	3	2	2	3	3
Total	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50

Scenario	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
p1 flows	18	18	13	15	16	8	14	13	20	16	15	11	15	15	11	16	17	12	12	7	7	15	14	17	11
p2 flows	16	19	20	26	18	25	22	20	17	17	20	25	17	18	22	18	17	24	22	31	25	17	21	24	25
p3 flows	11	10	13	8	11	12	8	13	12	15	12	12	16	12	14	13	11	12	15	10	15	16	15	6	12
p4 flows	5	3	4	1	5	5	6	4	1	2	3	2	2	5	3	3	5	2	1	2	3	2	0	3	2
Total	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50



(a) Aggregate throughput (b) Total data delivered per joule

Figure 9: Chain topology: Each flow generates traffic at a rate of 1 Mbps: the curves for PCM, PCM40, and 802.11 overlap in (a).

6.3 Simulation Results

We first discuss the simulation results for the chain topology. We consider the random topology later.

6.3.1 Chain topology: varying node distance

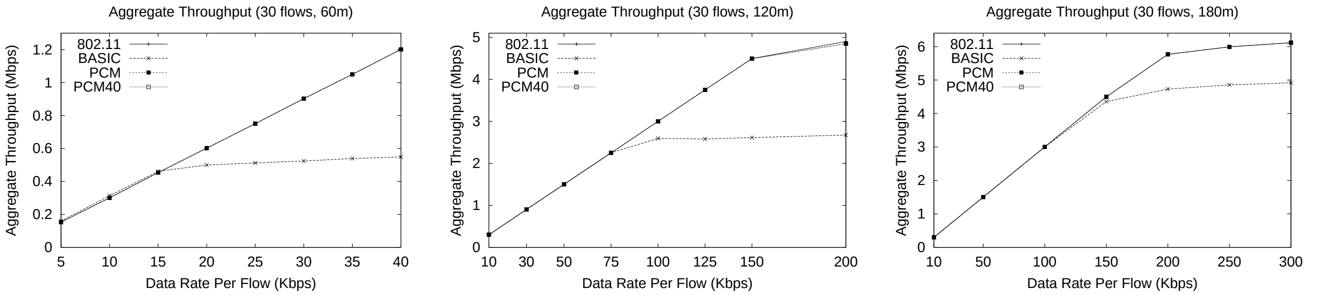
Figure 9 shows the simulation results for 31 nodes with 30 flows in a chain topology. Each flow generates traffic at the rate of 1 Mbps. Recall that PCM is our proposed scheme where transmit power is increased to p_{max} every 190 μs for 20 μs, and PCM40 is a variation of PCM where the transmit power is increased to p_{max} every 170 μs for 40 μs during DATA transmission.

As the distance between two neighbors increases in Figure 9(a), the aggregate throughput of all schemes increases. This is because when nodes are far apart, a larger number of nodes can transmit simultaneously.

PCM, PCM40 and 802.11 achieve comparable aggregate throughput as seen from the overlapping curves in Figure 9(a), but the BASIC scheme performs poorly in most cases. To understand the graph, we use Table 2, which shows the number of nodes in the carrier sensing zone. Table 2 shows the number of nodes that can interfere with a transmission between two neighbors at the center of the chain, that is, the transmission from node 14 to node 15 in Figure 8. Thus the table shows the number of nodes which can interfere with DATA reception at receiver node 15 or ACK reception at sender node 14 in Figure 8. The trend of the number of nodes in the carrier sensing zone shown in Table 2 is similar for other transmissions in the chain topology as well. Specif-

Table 2: BASIC – The Number of Nodes in the Carrier Sensing Zone

Distance (m)	40	60	80	90	100	110	120	150	180	250
Number of Interfering nodes	14	10	6	8	6	6	4	2	2	1

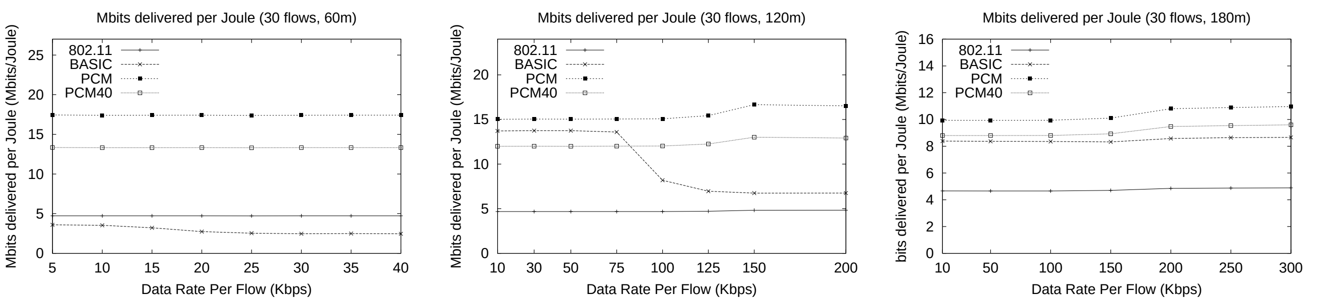


(a) Aggregate throughput (60 m Distance)

(b) Aggregate throughput (120 m Distance)

(c) Aggregate throughput (180 m Distance)

Figure 10: Chain topology: As the network load increases, aggregate throughput for all four schemes also increases. However, the aggregate throughput of BASIC saturates sooner.



(a) Total data delivered per joule (60 m Distance)

(b) Total data delivered per joule (120 m Distance)

(c) Total data delivered per joule (180 m Distance)

Figure 11: Chain topology: A large number of retransmissions in BASIC results in more energy consumption.

ically, the number of nodes in the carrier sensing zone is decreasing (except at 90 m[3]) as the distance between nodes increases. This explains the graph in Figure 9(a); the aggregate throughput curve for the BASIC scheme in Figure 9(a) follows the same trend as that in Table 2. As the number of potential collisions becomes smaller, the aggregate throughput increases in Figure 9(a). The aggregate throughput of the BASIC scheme jumps at the 120 m and 150 m points in Figure 9(a) mainly because of less collisions.

The total data delivered per joule with the BASIC scheme is worse than 802.11 for many cases in Figure 9(b). This is due to poor aggregate throughput with BASIC and extra energy consumption from collisions and retransmissions. Since PCM40 consumes more energy compared to PCM, it gives less data delivered per joule, but it still performs better than 802.11, or BASIC (except for the 150 m distance).

When the adjacent nodes are 250 meters apart, BASIC and PCM cannot reduce the transmit power for DATA-ACK. (Recall that the transmission range at p_{max} is 250 m.) Therefore, in Figure 9, all four schemes (802.11, BASIC, PCM and PCM40) perform the same when nodes are 250 m apart.

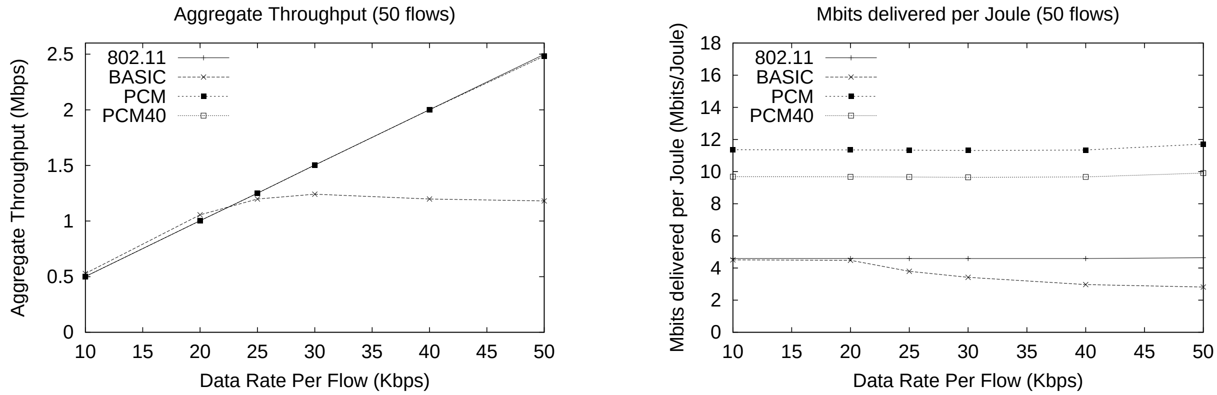
6.3.2 *Chain topology: varying network load*

Figures 10 and 11 show the simulation results for 3 different node distances (60 m, 120 m, and 180 m) in the chain topology, with a varying data rate (load) per flow.

When the network is lightly loaded in Figure 10(a), the aggregate throughput of all the schemes is identical. Figure 10(a) also shows that the aggregate throughput of BASIC is much less than that of PCM and 802.11 at a moderate to high load. Simulation results for 120 m and 180 m distances in Figure 10(b) and (c) are similar to the 60 m distance in Figure 10(a). PCM, PCM40, and 802.11 curves overlap in Figure 10.

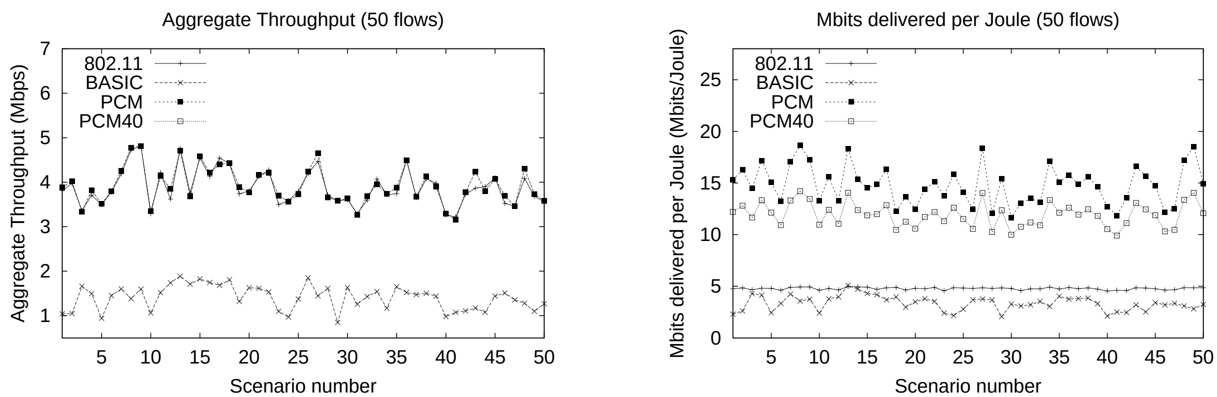
Figure 11 shows the total data delivered per joule for distances of 60 m, 120 m, and 180 m. It is interesting to see that the total data delivered per joule for PCM in Figure 11 is higher than that of BASIC even when the aggregate throughput for both schemes is the same in Figure 10. In PCM, nodes periodically increase the transmit power to

[3]The number of nodes in the carrier sensing range at p_{max} (550 m) is 12 for both 80 and 90 m distance networks. However, the number of nodes in the transmission range at p_{max} (250 m) for 80 and 90 m distance networks is 6 and 4, respectively. Therefore, the number of nodes in the carrier sensing zone for 80 and 90 m distance networks in Table 2 is 6 ($12 - 6 = 6$) and 8 ($12 - 4 = 8$), respectively.



(a) Aggregate throughput (b) Total data delivered per joule

Figure 12: Random topology with different network loads: the curves for PCM, PCM40, and 802.11 overlap in (a).



(a) Aggregate throughput (b) Total data delivered per joule

Figure 13: Random topology for 50 different scenarios with a 1 Mbps data rate per flow. The curves for PCM, PCM40, and 802.11 overlap in (a).

p_{max}, which should cause higher energy consumption compared to BASIC. However, with BASIC more collisions occur, and when nodes retransmit packets, additional energy is consumed. Therefore, the net result is that BASIC consumes more energy than PCM.

Figure 11 also indicates that as node distance increases, the total data delivered per joule for BASIC gets better. This is because as node distance increases, the number of collisions decreases (see Table 2), hence the number of retransmissions decreases.

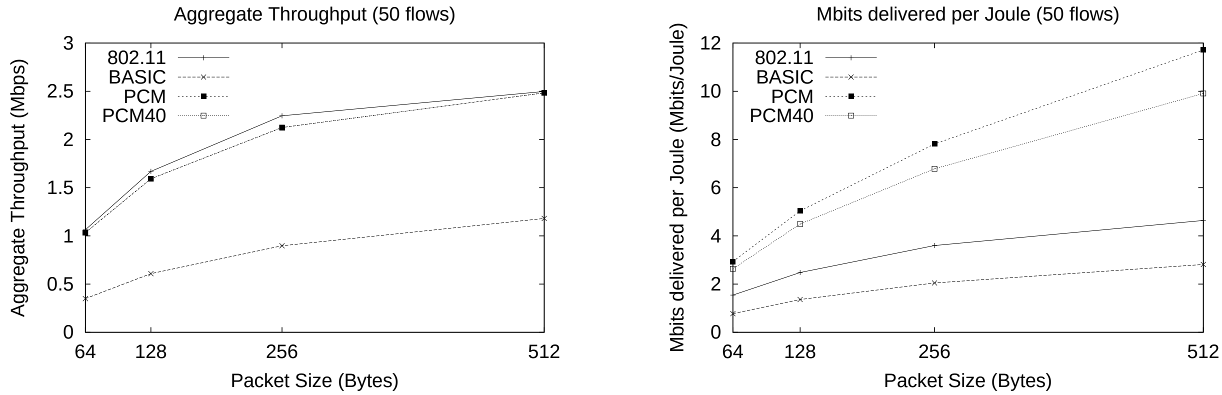
6.3.3 Random topology: varying network load

Figure 12 shows the simulation results for one particular scenario in the random topology, with a varying data rate per flow. Simulation results for a highly loaded network are shown in the following section. As expected, simulation results are similar to those for the chain topology (see Figures 10 and 11). That is, in Figure 12(a), the aggregate throughput for BASIC becomes relatively low, once the load becomes moderately high. PCM, PCM40, and 802.11 curves overlap in Figure 12(a).

Figure 12(b) shows the simulation results for the total data delivered per joule for the random topology with different data rates. When the data rate per flow is more than 20 Kbps, the BASIC scheme performs worse than 802.11 due to additional collisions and retransmissions. However, in Figure 12(b), PCM always performs better than 802.11 or BASIC. Similar to the simulation results for the chain topology, PCM40 results in a smaller amount of data delivered per joule compared to PCM, but it still performs better than 802.11 or BASIC in Figure 12(b).

6.3.4 Random topology: 50 different topologies

Figure 13 shows the simulation results for a random topology with 50 flows. Each flow generates traffic at a rate of 1 Mbps; the network is overloaded. The numbers on the horizontal axis indicate 50 different scenarios (or topologies). In Figure 13(a), PCM and PCM40 achieve throughput



(a) Aggregate throughput (b) Total data delivered per joule

Figure 14: A random topology with different packet sizes and a 50 Kbps data rate per flow. PCM and PCM40 curves are overlapped in (a).

very close to 802.11 in every scenario, while BASIC performs poorly.

The poor aggregate throughput of the BASIC scheme results in poor data delivered per unit of energy consumption. Simulation results for the total data delivered per joule in Figure 13(b) show that PCM performs better than 802.11 or BASIC. As explained in Figure 12(b), PCM40 results in a smaller amount of data delivered per joule compared to PCM, but it still performs better than 802.11 or BASIC in Figure 13(b).

6.3.5 Random topology: varying packet size

Figure 14 shows the simulation results for a random topology with 50 flows varying the packet size. Simulated packet sizes are 64, 128, 256, and 512 bytes. Each flow generates traffic at a rate of 50 Kbps.

The RTS/CTS overhead per packet is independent of the packet size. Therefore, as expected, when the packet size increases in Figure 14(a), the aggregate throughput of all schemes also increases. The curves for PCM and PCM40 overlap in Figure 14(a). PCM and PCM40 perform similar to 802.11 but BASIC performs poorly.

For the total data delivered per joule in Figure 14(b), PCM performs better than all other schemes. Also, the gap between PCM and BASIC (or 802.11) becomes bigger, as the packet size increases. This is because using a large packet size PCM has more time to use lower power during DATA transmission, thus conserving more energy. PCM40 also performs better than BASIC and 802.11 in terms of the total data delivered per joule.

7. CONCLUSIONS

In the past, MAC protocols that use the maximum transmit power for RTS-CTS and the minimum necessary transmit power for DATA-ACK have been proposed with the goal of achieving energy saving. We refer to this as the BASIC scheme. However, we have shown that the BASIC scheme increases collisions and retransmissions, which can result in more energy consumption, and throughput degradation.

In IEEE 802.11, carrier sensing range for RTS-CTS is the same as that of DATA-ACK since transmit power does not change. However, in BASIC, carrier sensing range for RTS-CTS and DATA-ACK may vary because the transmit power can be different for those packets. Thus, when using BASIC, nodes in the carrier sensing zone of RTS-CTS can cause collisions with on-going DATA-ACK transmissions because these nodes may not sense DATA transmission which may use a lower transmit power. Such collisions trigger retransmissions, consuming more energy. Due to this, the BASIC scheme often yields an aggregate throughput and total data delivered per joule worse than IEEE 802.11 without power control.

We propose PCM, a Power Control MAC protocol, which periodically increases the transmit power during DATA transmission. Simulation results show that PCM achieves energy savings without causing throughput degradation.

One possible concern with PCM is that it requires a frequent increase and decrease in the transmit power which may make the implementation difficult. An alternative approach is to replace this higher power level for data by a busy tone at p_{max} in a separate channel, with one channel being used for the busy tone and the another channel for RTS-CTS-DATA-ACK. Another concern is that fading may adversely affect the PCM performance. As a variation of PCM, a different time interval can also be used between the transmissions at p_{max} during a packet transmission. In this variation, there is a trade-off between performance and energy savings.

Although PCM provides energy saving it does not yield improved spatial reuse as compared to IEEE 802.11. Future work includes the development of a power control MAC protocol that conserves energy while increasing spatial reuse, preferably, without using a separate control channel.

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9. REFERENCES

[1] S. Agarwal, S. Krishnamurthy, R. H. Katz, and S. K. Dao. Distributed Power Control in Ad-hoc Wireless Networks. In *PIMRC01*, 2001.

[2] B. Chen, K. Jamieson, H. Balakrishnan, and R. Morris. Span: An Energy-Efficient Coordination Algorithm for Topology Maintenance in Ad Hoc Wireless Networks. In *MOBICOM 2001*, July 2001.

[3] J. Deng and Z. J. Haas. Dual Busy Tone Multiple Access (DBTMA): A New Medium Access Control for Packet Radio Networks. In *IEEE International Conference on Universal Personal Communications (ICUPC '98)*, volume 2, pages 973–977, 1998.

[4] J.-P. Ebert, B. Stremmel, E. Wiederhold, and A. Wolisz. An Energy-efficient Power Control Approach for WLANs. *Journal of Communications and Networks (JCN)*, 2(3):197–206, September 2000.

[5] J.-P. Ebert and A. Wolisz. Combined Tuning of RF Power and Medium Access Control for WLANs. In *IEEE International Workshop on Mobile Multimedia Communications (MoMuC'99)*, November 1999.

[6] J. Gomez, A. T. Campbell, M. Naghshineh, and C. Bisdikian. Conserving Transmission Power in Wireless Ad Hoc Networks. In *ICNP'01*, November 2001.

[7] Z. J. Haas and J. Deng. Dual Busy Tone Multiple Access (DBTMA)–Performance Evaluation. In *VTC'99*, volume 1, pages 314–319, 1999.

[8] E.-S. Jung and N. H. Vaidya. An Energy Efficient MAC Protocol for Wireless LANs. In *INFOCOM 2002*, June 2002.

[9] A. Kamerman and L. Monteban. WaveLAN-II: A High-Performance Wireless LAN for the Unilicensed Band. *Bell Labs Technical Journal*, 2(3), summer 1997.

[10] P. Karn. MACA - A New Channel Access Method for Packet Radio. In *Proc. 9th ARRL Computer Networking Conference*, 1990.

[11] P. Lettieri and M. B. Srivastava. Adaptive Frame Length Control for Improving Wireless Link Throughput, Range, and Energy Efficiency. In *INFOCOM '98*, volume 2, pages 564–571, March 1998.

[12] J. P. Monks, V. Bharghavan, and W. mei W. Hwu. A Power Controlled Multiple Access Protocol for Wireless Packet Networks. In *INFOCOM 2001*, April 2001.

[13] S. Narayanaswamy, V. Kawadia, R. S. Sreenivas, and P. R. Kumar. Power Control in Ad-Hoc Networks: Theory, Architecture, Algorithm and Implementation of the COMPOW protocol. In *European Wireless 2002*, February 2002.

[14] N. Poojary, S. V. Krishnamurthy, and S. Dao. Medium Access Control in a Network of Ad Hoc Mobile Nodes with Heterogeneous Power Capabilities. In *IEEE International Conference on Communications (ICC 2001)*, volume 3, pages 872–877, 2001.

[15] M. B. Pursley, H. B. Russell, and J. S. Wysocarski. Energy-Efficient Transmission and Routing Protocols for Wireless Multiple-hop Networks and Spread-Spectrum Radios. In *EUROCOMM 2000*, pages 1–5, 2000.

[16] R. Ramanathan and R. Rosales-Hain. Topology Control of Multihop Wireless Networks using Transmit Power Adjustment. In *INFOCOM 2000*, volume 2, pages 404–413, March 2000.

[17] V. Rodoplu and T. H. Meng. Minimum Energy Mobile Wireless Networks. *IEEE Journal on selected areas in communications*, 17(8), August 1999.

[18] M. Sanchez, P. Manzoni, and Z. J. Haas. Determination of Critical Transmission Range in Ad-Hoc Networks. In *Workshop on Multiaccess, Mobility and Teletraffic for Wireless Communications*, October 1999.

[19] S. Singh and C. S. Raghavendra. PAMAS - Power Aware Multi-Access Protocol with Signalling for Ad Hoc Networks. In *Computer Communications Review*, July 1998.

[20] S. Singh, M. Woo, and C. S. Raghavendra. Power-aware Routing in Mobile Ad Hoc Networks. In *MOBICOM '98*, October 1998.

[21] The CMU Monarch Project. The CMU Monarch Project's Wireless and Mobility Extensions to NS.

[22] The editors of IEEE 802.11. *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification*, 1997.

[23] C.-K. Toh. Maximum Battery Life Routing to Support Ubiquitous Mobile Computing in Wireless Ad Hoc Networks. *IEEE Communications Magazine*, 39(6):138–147, June 2001.

[24] R. Wattenhofer, L. Li, P. Bahl, and Y.-M. Wang. Distributed Topology Control for Power Efficient Operation in Multihop Wireless Ad Hoc Networks. In *INFOCOM 2001*, volume 3, pages 1388–1397, April 2001.

[25] J. E. Wieselthier, G. D. Nguyen, and A. Ephremides. On the Construction of Energy-Efficient Broadcast and Multicast Trees in Wireless Networks. In *INFOCOM 2000*, pages 585–594, March 2000.

[26] J. E. Wieselthier, G. D. Nguyen, and A. Ephremides. Resource-Limited Energy-Efficient Wireless Multicast of Session Traffic. In *Hawaii International Conference on System Sciences HICSS 2001*, January 2001.

[27] H. Woesner, J.-P. Ebert, M. Schlager, and A. Wolisz. Power-Saving Mechanisms in Emerging Standards for Wireless LANs: The MAC Level Perspective. *IEEE Personal Communications*, June 1998.

[28] S.-L. Wu, Y.-C. Tseng, C.-Y. Lin, and J.-P. Sheu. A Multi-Channel MAC Protocol with Power Control for Multi-Hop Mobile Ad Hoc Networks. *The Computer Journal (SCI)*, 45(1):101–110, 2002.

[29] S.-L. Wu, Y.-C. Tseng, and J.-P. Sheu. Intelligent Medium Access for Mobile Ad Hoc Networks with Busy Tones and Power Control. *IEEE Journal on Selected Areas in Communications*, 18(9):1647–1657, September 2000.