Power Control in Multi-Hop Wireless Networks

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Technical Report

March 2002

Abstract— **This report presents a power control MAC protocol based on the IEEE 802.11 standard. Several researchers have proposed a simple modification 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 minimum required transmit power is used for DATA-ACK transmissions in order to save energy. However, we show that this scheme can severely degrade network throughput and can result in higher energy consumption than IEEE 802.11 with no power control. We propose an improved power control protocol, which does not degrade throughput and yields greater energy saving.**

I. INTRODUCTION

WIRELESS hosts are usually powered by batteries with limited amount of energy. Therefore, techniques to reduce energy consumption are of interest. One way to conserve energy is to use *power save* schemes [1] [2] [3] which turn off (or put in *doze* mode) the wireless network interface, when deemed reasonable. Another alternative is to use *power control* schemes which suitably vary transmit power to reduce energy consumption. In this report, we study *power control* for the purpose of energy saving.

Wireless network interface consists of several components such as a processor to execute MAC protocol, a baseband processor, RF/IF converter, RF power amplifier, etc. RF power amplifier consumes a significant fraction of energy. [4] reports that RF power amplifier may consume more than 50 % of the entire power consumption of wireless network interface during transmission. Therefore, reduction in the RF output power is desirable. Power control mechanisms try to reduce the RF output power in order to reduce the energy consumption.

In addition to providing energy saving, power control can potentially be used to improve spatial reuse of the wireless channel. However, in this report, we only focus on power control for the purpose of energy saving.

The rest of this report is organized as follows. Section II reviews the related work. Background on IEEE 802.11 is given in Section III. Section IV describes an often proposed power control scheme and its shortcoming. Section V presents our proposed power control MAC protocol. We will refer to the proposed scheme as PCM (Power Control MAC). Section VI discusses simulation results. Section VII concludes the report.

II. RELATED WORK

[5] [6] propose a power control mechanism that can be incorporated into the IEEE 802.11 RTS-CTS handshake. The scheme in [6] 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

This research is supported in part by National Science Foundation.

ratio. A similar protocol is utilized in [7], 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 refer to this scheme as *BASIC* power control MAC protocol. We found that the BASIC scheme has a shortcoming that seriously degrades the throughput. Furthermore, the BASIC scheme quite often consumes more energy compared to IEEE 802.11 without power control. We elaborate on this in section IV-B.

[7] presents PARO, a power-aware routing optimization, for determining routes with low energy consumption. PARO chooses a cost function based on transmit power level on each hop on a route, to determine a low energy consuming route between a pair of nodes. PARO also uses BASIC for its power control MAC protocol. Several other routing metrics are also proposed in [8] [9].

[10] proposes a power control protocol similar to the BASIC scheme. [10] maintains a table for the minimum transmit power necessary to communicate with neighbor nodes. It allows each node to increase or decrease its power level dynamically. However, different power levels among nodes result in asymmetric link, causing collisions (hidden terminal problem).

[11] [12] present an approach which controls transmit power based on packet size. Their scheme is based on the observation that reducing transmission power can result in energy saving, but can also result in more errors. A higher bit error rate can lead to increased retransmissions, consuming more energy. Thus, [11] [12] choose appropriate transmission power level based on the packet size. [13] also presents an adaptive scheme to choose MAC frame size based on channel conditions.

[14] shows that IEEE 802.11 results in unfairness (performance degradation) for nodes which have lower transmission power than their neighbor nodes. [14] proposes a protocol that extends the reach of the CTS transmitted by the intended receiver of a data packet, by propagating the CTS over multiple hops.

The COMPOW protocol proposed in [15] selects a common power level at all nodes in the network to ensure bi-directional links.

Power Controlled Multiple Access (PCMA) protocol proposed in [16] 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 channel 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 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. 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 tone with two separate channels are also used in [8] [17] [18] [19].

In [20] [21] [22] [23], power control was used for the purpose of topology control. Power control has been also used to establish energy efficient spanning trees for multicasting and broadcasting [24] [25].

III. IEEE 802.11 MAC PROTOCOL

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

We now define the terms *transmission range* and *carrier sensing range* which are used in the rest of the report.

- *Transmission range*: When a node is within transmission range of a sender node, it can receive and correctly decode packet sent by the sender node.

- *Carrier sensing range*: When a node is within carrier sensing range, it can sense the signal but cannot decode it correctly. Note that as per our definition here, carrier sensing range 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 carrier sensing range as per our definition. Carrier sensing range is often two times larger than transmission range. Note that the carrier sensing range and transmission range depend on the transmit power level.

Figure 1 shows the transmission and carrier sensing range 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 carrier sensing range.

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

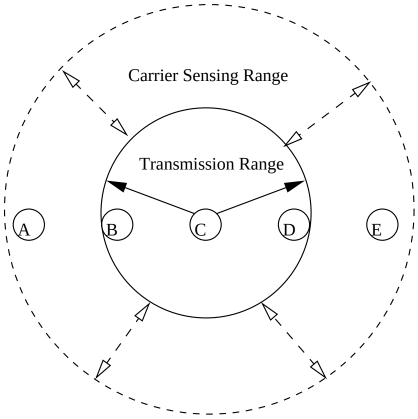

Fig. 1. Nodes in transmission range can receive and decode packet correctly, whereas nodes in carrier sensing range can detect signal, but cannot decode it correctly.

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 packet transmission, which is included in the header of RTS, CTS, and DATA frames. The duration included in each of these frames indicates the time when the source node would receive ACK frame from the destination node. For example, the duration field in RTS includes time for CTS, DATA, and ACK transmissions. Similarly, duration field for CTS includes time for DATA and ACK transmissions, and duration field for DATA only includes time for ACK transmission.

Each node in IEEE 802.11 maintains NAV (Network Allocation Vector) which indicates the remaining time of current transmission session. Using the duration information in RTS, CTS, and DATA packets, nodes update their NAVs whenever they receive a packet. The channel is consider 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 carrier sensing range adjust their NAVs during RTS-CTS-DATA-ACK transmission[2]. SIFS, DIFS, and EIFS are interframe spaces (IFSs) specified in IEEE 802.11.

IFS is 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 channel. SIFS is the shortest of the interframe spaces and 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, node waits for 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 carrier sensing range cannot decode packet, they do not know the duration of the packet transmission. To prevent collision with ACK reception at the source node, when nodes detect signal and cannot decode it, they set their NAVs for EIFS duration. The main purpose of EIFS is to provide enough time for source node to receive ACK frame, so the duration of EIFS is slightly longer than that of ACK transmission[3]. Note that it is not necessary for nodes in carrier sensing range to set NAV and defer transmission after detecting ACK transmission. However, as already mentioned, these nodes cannot distinguish between DATA and ACK, thus, in IEEE 802.11 nodes in carrier sensing range set NAVs for EIFS duration whenever they receive a packet incorrectly or cannot decode a packet correctly.

Note that IEEE 802.11 does not completely prevent collisions from hidden terminal – nodes in receiver's carrier sensing range, but not in sender's carrier sensing range or transmission range, can cause collision with reception of DATA packet at the receiver. For example, in Figure 3 suppose node C transmits packet to node D. When C and D transmit RTS and CTS respectively, A and F will set their NAVs for EIFS duration. During C's DATA transmission, A defers its transmission since 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 range, but not in C's.) When F starts a new transmission, it can cause 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 range, by symmetry, this implies that F can present sufficient interference at node D to cause a collision with DATA being received by D.

IV. BASIC POWER CONTROL SCHEME

This section describes the BASIC power control scheme [5] [6] [7] [10] and its limitation.

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[2] Note that in Figure 2 the lengths of RTS, CTS, DATA, and ACK do not exactly represent the actual sizes.

[3] As per IEEE 802.11, EIFS is defined to be equal to SIFS + DIFS + (8 * ACK size) + PreambleLength + PLCPHeaderLength [26]. For 2 Mbps bit rate, EIFS is equal to 212 μs.

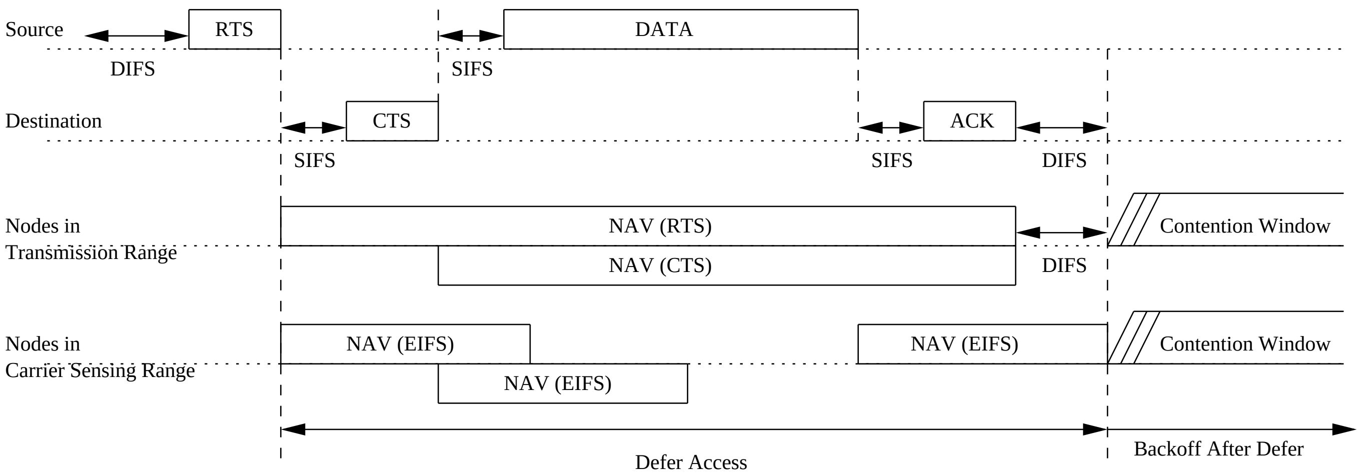

Fig. 2. When source and destination nodes transmit RTS and CTS, nodes in transmission range correctly receive these packets and set their NAVs for the duration of the whole packet transmission. However, nodes in carrier sensing range only detect signal and cannot decode it correctly, so these nodes set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

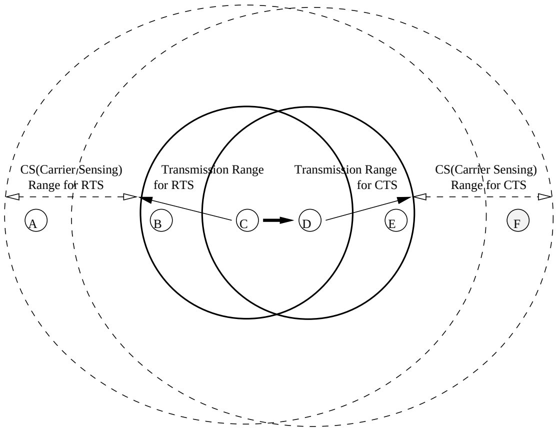

Fig. 3. IEEE 802.11 does not prevent collisions completely. After RTS-CTS handshake, when node C transmits DATA packet to node D, F cannot sense the DATA transmission since it is in D's carrier sensing range but not C's. Therefore, when F starts transmitting, this causes collision with DATA packet at node D.

A. BASIC Scheme

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 a node B, but B cannot reach A.

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 ongoing transmission at A and B.

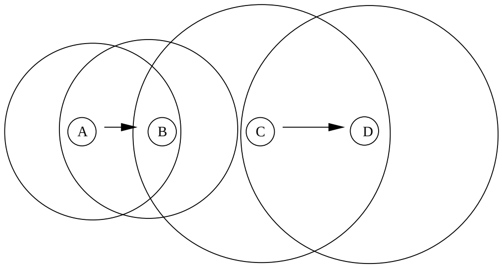

Fig. 4. Differences in transmit power can lead to increased collisions.

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 lower power levels, as suggested in [5] [6] [7] [10]. 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 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

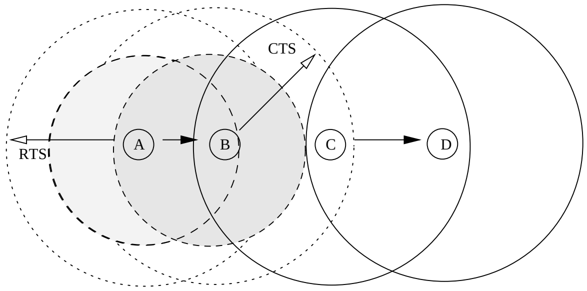

Fig. 5. RTS-CTS transmission at highest transmission power level

B receives RTS from A with signal level p_r, B can calculate the minimum necessary transmission power level $p_{desired}$ for DATA packet based on received power level p_r, the transmission power level p_{max}, and noise level at the receiver B. We can borrow the procedure for estimating $p_{desired}$ from [16]. 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. However, it is not compatible to IEEE 802.11, since it has to modify the format for the CTS in order to specify $p_{desired}$.

- To make the above procedure IEEE 802.11-compatible, the alternative below does not modify the format of CTS. We use this approach for our simulations of the BASIC scheme as well as the proposed scheme. When destination node receives RTS, it responds by sending CTS as usual. When source node receives CTS, it calculates $p_{desired}$ based on received power level p_r and transmitted power level (p_{max}), as

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

where Rx_{thresh} is the minimum necessary received signal strength and c is a constant (similar to [16]). We set c equal to 1 in our simulations. Then, the source transmits DATA using power level equal to $p_{desired}$. Similarly, the transmit power for ACK transmission is determined when the destination receives 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 reasonably high probability. An important benefit here is that the resulting protocol is IEEE 802.11-compatible.

As we now explain below, the BASIC scheme increases collisions as compared to IEEE 802.11, degrading throughput significantly.

B. 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 minimum necessary power to reach the destination. When the neighbor nodes receive RTS or CTS, they will 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 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 D-E transmission. Node A is in carrier sensing range of D (when D transmits at p_{max}) so it will only 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.

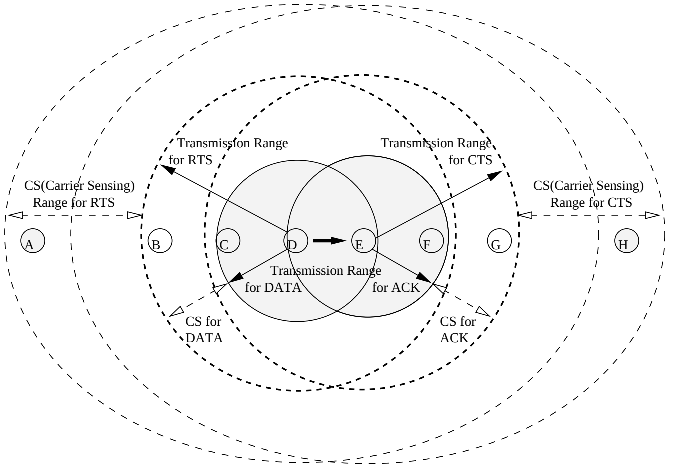

Fig. 6. BASIC scheme: Suppose node D transmits a packet to node E. Since DATA and ACK are transmitted using minimum necessary transmit power, nodes in carrier sensing range (such as A and H) during RTS-CTS transmission may not sense any signal during DATA-ACK. When these nodes initiate new transmission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

In the standard IEEE 802.11, carrier sensing range is the same for RTS-CTS and DATA-ACK since all packets are sent using the same power level. However, in BA-

SIC, when a source and destination pair decides to reduce the transmit power for DATA-ACK, transmission range for DATA-ACK is smaller than that for RTS-CTS; similarly, carrier sensing range for DATA-ACK is also smaller than that for 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 range are reduced. Thus, only C and F can correctly receive the DATA and ACK packets, respectively. Furthermore, since nodes A and H cannot sense any signal, 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 collision with ACK packet at D and DATA packet at E. This results in serious throughput degradation and energy consumption (because of retransmissions), as we will see in section VI-C.

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

The above discussion indicates that BASIC scheme is more prone to collisions than IEEE 802.11, degrading throughput (as shown in section VI-C). The BASIC scheme has been considered for saving energy [5] [6] [7] [10]. However, past work did not identify the above deficiency of the BASIC protocol. For instance, reference [7] considers 100x100 $meter^2$ area for the simulation. In this case, every node can correctly decode RTS or CTS and will know the duration of the remaining packet transmission. In such an environment, the negative impact of BASIC power control is not manifested.

V. 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 minimum necessary transmit power for DATA-ACK transmission. We now describe the procedure used in PCM.

1. Source and destination nodes transmit RTS and CTS using p_{max}. Nodes in carrier sensing range set their NAVs for EIFS duration. EIFS duration is 212 μs for 2 Mbps bit rate [26].

2. 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), source node transmits DATA at the power level p_{max} periodically for just enough time so that nodes in carrier sensing range can sense it.

4. Destination node transmits ACK using the minimum required power to reach the source node, similar to the BASIC scheme.

Figure 7 shows how transmit power level changes during the sequence of RTS-CTS-DATA-ACK transmission. After RTS-CTS handshake using p_{max}, suppose source and destination nodes decide to use 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 in PCM compared to 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 that the DATA is transmitted at p_{max} should be larger than the time required for physical carrier sensing.

According to [26], 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[4]. Thus, we believe 20 μs should be enough to power up (2 μs), sense the signal (15 μs), and power down (2 μs).

In PCM, a node transmits DATA at p_{max} every 190 μs for 20 μs duration. Thus, the interval between the transmissions at p_{max} is 210 μs, which is shorter than EIFS duration. 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 last 20 μs of the transmission.

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[4] [27] reports that power up/down time is typically 300ns, which is much quicker than 2 μs in [26].

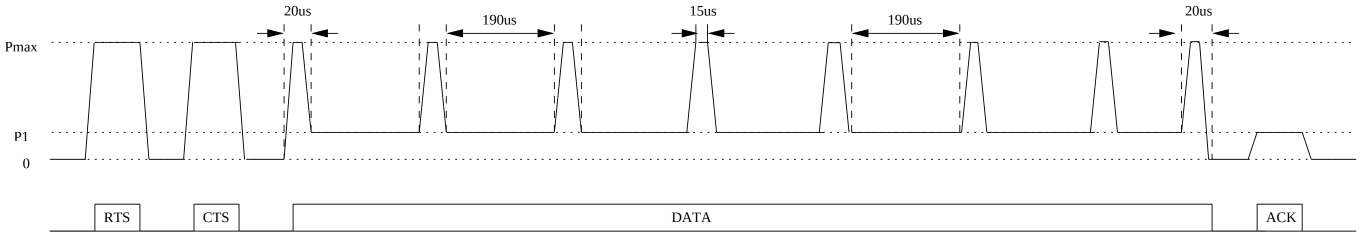


Fig. 7. PCM periodically increases the transmit power during DATA transmission in order to inform its transmission to nodes in carrier sensing range.

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

To be more conservative in estimating energy consumption of PCM, we also perform our simulations where we increase 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.

VI. PERFORMANCE EVALUATION

We have simulated BASIC, PCM, PCM40, as well as IEEE 802.11 MAC (which does not use power control). We use two metrics to evaluate the MAC protocols. The first metric is the aggregate throughput over all flows in the network. The second metric is the aggregate throughput per unit of transmit energy consumption (or, aggregate throughput per joule). This is calculated as aggregate throughput divided by the total amount of transmission energy consumption over all nodes (Mbps/joule).

A. Simulation Model

For simulations, we use ns-2 with the CMU wireless extension [28]. We use 2 Mbps for 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 simulation with various network loads. We assume carrier sensing range is two times larger than transmission range. We do not consider mobility in our simulations. All simulation results are the average of 30 runs, each run for 10 seconds of simulation time.

B. 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 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 flows. Nodes are shown as a circle, and the arrow between two nodes indicates traffic flows.

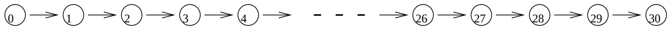


Fig. 8. Chain topology: 31 nodes with 30 flows.

Distance between adjacent node pairs in Figure 8 is constant. In our simulations, we vary the distance from 40 m to 250 m.

- *Random Topology*

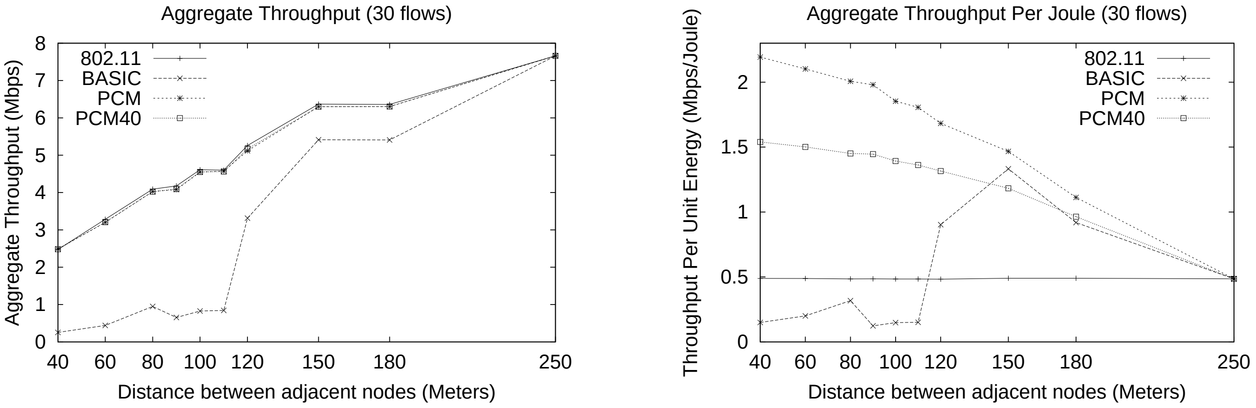
For random topology, we place 50 nodes randomly within 1000x1000 $meter^2$ area. Each node selects the nearest node as its destination, so total of 50 flows are generated.

TABLE I

NUMBER OF FLOWS AT VARIOUS POWER LEVELS

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) Aggregate Throughput per Joule

Fig. 9. Chain Topology: Each flow generates traffic at the rate of 1 Mbps.

(We only consider one hop flows.) We simulated 50 random scenarios. Table I shows the number of flows using each power level for each scenario. In Table I, 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.

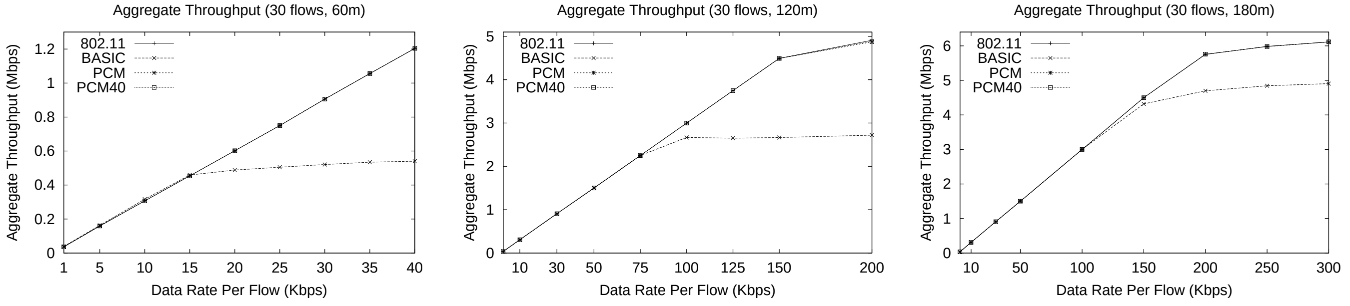
C. Simulation Results

We first look at the simulation results for the chain topology.

C.1 Chain Topology: Varying node distance

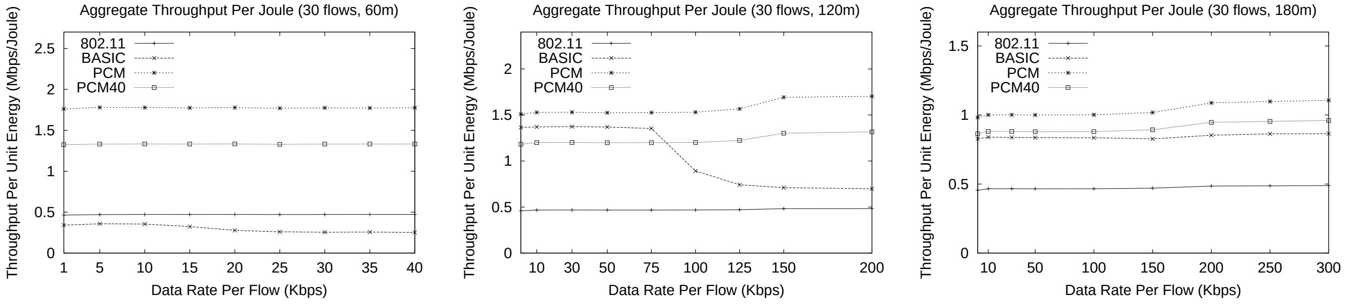
Figure 9 shows the simulation results for 31 nodes with 30 flows in a chain topology. Each flow generates traffic at the rate of 1 Mbps.

While PCM, PCM40 and IEEE 802.11 achieve comparable aggregate throughput as seen from the overlapping curves in Figure 9(a), the BASIC scheme performs poorly in most cases. To understand the graph, we use Table II, which shows the number of nodes which can interfere with a transmission between two neighbors at the center of the chain, that is, 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 the receiver node 15 or ACK reception at the sender node 14 in Figure 8. The trend of the number of interfering nodes shown in Table II is similar for other transmissions in the chain topology as well. Specifically, the trend of the number of nodes that can interfere with a transmission is decreasing (except at 90 m) 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 II. As the number of poten-



(a) Aggregate Throughput (60 m Distance) (b) Aggregate Throughput (120 m Distance) (c) Aggregate Throughput (180 m Distance)

Fig. 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) Aggregate Throughput per Joule (60 m Distance) (b) Aggregate Throughput per Joule (120 m Distance) (c) Aggregate Throughput per Joule (180 m Distance)

Fig. 11. Chain Topology: Large number of retransmissions in BASIC results in more energy consumption.

tial collisions becomes smaller, the aggregate throughput increases in Figure 9(a). The aggregate throughput of the BASIC scheme jumps at 120 m and 150 m distance in Figure 9(a) mainly because of less collisions.

TABLE II

BASIC: THE NUMBER OF INTERFERING NODES

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

Energy saving in terms of throughput per unit energy of the BASIC scheme is worse than IEEE 802.11 for many cases in Figure 9(b) 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 throughput per unit energy, but it still performs better than IEEE 802.11, or BASIC (except for 150 m distance).

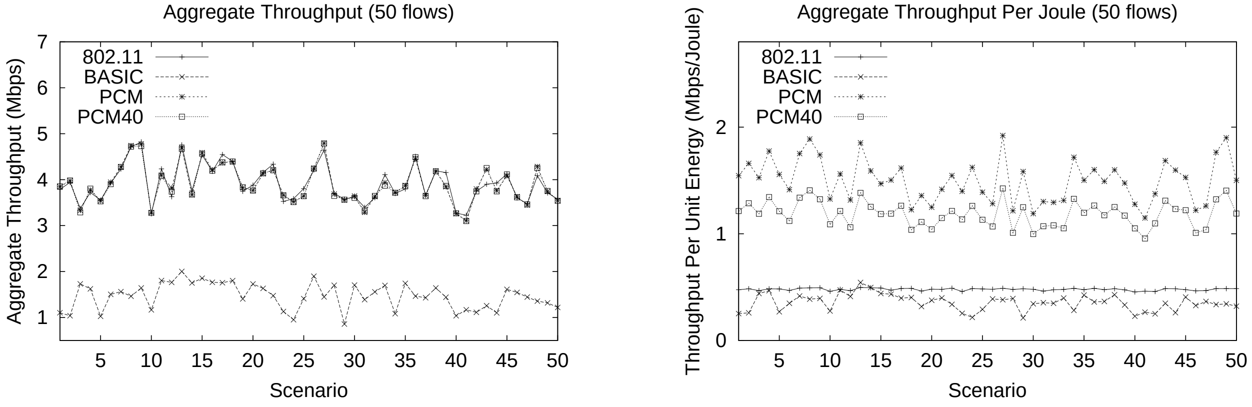
When the adjacent nodes are 250 meters apart, BASIC and PCM cannot reduce the transmit power for DATA-ACK. (Recall that the transmission range at p_{max} is 250 m.) Therefore, in Figure 9, all four schemes (IEEE 802.11, BASIC, PCM and PCM40) perform the same when nodes are at 250 m distance.

C.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, varying data rate (load) per flow.

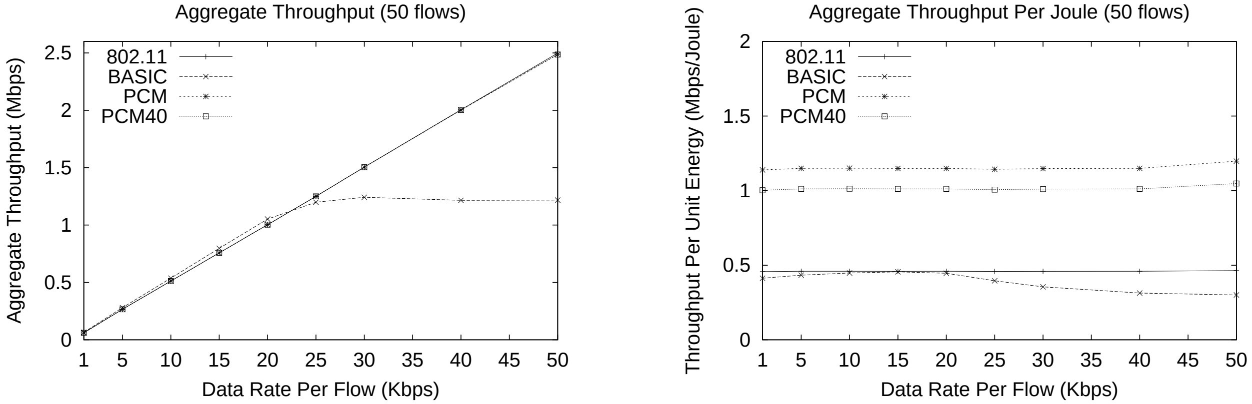
When the network is lightly loaded in Figure 10(a), the aggregate throughput of all the schemes is identical. Figure 10(a) also shows that the aggregate throughput of BASIC is much less than that of PCM and IEEE 802.11 at moderate to high load. Simulation results for 120 m and 180 m distances in Figure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

Figure 11 shows the aggregate throughput per joule for 60 m, 120 m, and 180 m distance. It is interesting to see



(a) Aggregate Throughput (b) Aggregate Throughput per Joule

Fig. 12. Random topology with 50 different scenarios: 1 Mbps data rate per flow



(a) Aggregate Throughput (b) Aggregate Throughput per Joule

Fig. 13. Random topology with different network load

that throughput per joule for PCM in Figure 11 is higher than that for BASIC even when the aggregate throughputs for both schemes are the same in Figure 10. In PCM, nodes periodically increase transmit power to 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, net result is that BASIC consumes more energy compared to PCM.

Figure 11 also indicates that as node distance increases, the aggregate throughput per unit energy for BASIC gets better. This is because as node distance increases, the number of collisions decreases (see Table II), hence the number of retransmissions decreases.

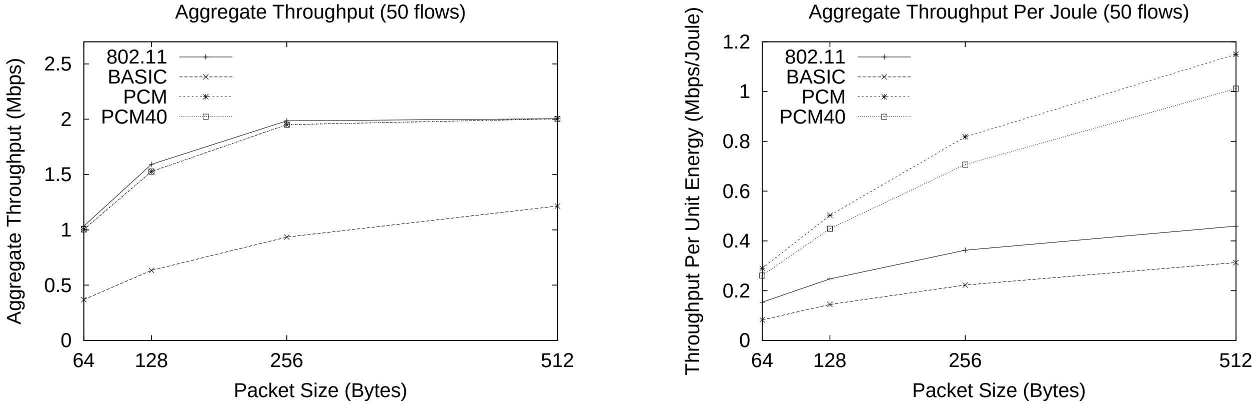
C.3 Random Topology: 50 different scenarios

Figure 12 shows the simulation results for random topology with 50 flows. Each flow generates traffic at the rate of 1 Mbps. The numbers on the horizontal axis indicate 50 different scenarios (or topologies). In Figure 12(a), PCM and PCM40 achieve throughput very close to IEEE 802.11 in every scenario, while BASIC performs poorly.

The poor aggregate throughput of the BASIC scheme results in poor aggregate throughput per unit of energy consumption. As we see in Figure 12(b), when aggregate throughput per joule is compared, the BASIC scheme performs worse than IEEE 802.11 due to additional collisions and retransmissions. However, in Figure 12(b), PCM always performs better than IEEE 802.11 or BASIC in terms of aggregate throughput per unit energy. Similar to the simulation results for chain topology, PCM40 gives less aggregate throughput per unit energy compared to PCM, but it still performs better than IEEE 802.11 or BASIC in Figure 12(b).

C.4 Random Topology: Varying network load

Figure 13 shows the simulation results for one particular scenario in random topology, varying data rate per



(a) Aggregate Throughput

(b) Aggregate Throughput per Joule

Fig. 14. Random topology with different packet sizes

flow. As expected, simulation results are similar to those for the chain topology (see Figures 10 and 11). That is, in Figure 13(a), the aggregate throughput for BASIC becomes relatively low, once the load becomes moderately high. PCM, PCM40, and IEEE 802.11 curves overlap in Figure 13(a).

Simulation results for aggregate throughput per unit energy in Figure 13(b) show that PCM performs better than IEEE 802.11 or BASIC. As explained in Figure 12(b), PCM40 gives less aggregate throughput per unit energy compared to PCM, but it still performs better than IEEE 802.11 or BASIC in Figure 13(b).

C.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 the rate of 40 Kbps.

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

For the aggregate throughput per unit energy in Figure 14(b), PCM performs better than all other schemes. Also, the gap between PCM and BASIC (or IEEE 802.11) becomes bigger, as the packet size increases. This is because using 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 IEEE 802.11 in terms of aggregate throughput per unit energy.

VII. CONCLUSIONS

It is a common belief that using the maximum transmit power for RTS-CTS and the minimum necessary transmit power for DATA-ACK improves energy saving. We refer to this as the BASIC scheme. However, we have shown that this BASIC scheme has a defect, which increases collisions and degrades throughput.

In IEEE 802.11, carrier sensing range for RTS-CTS is the same as that for DATA-ACK since transmit power does not change. However, in BASIC, carrier sensing range for RTS-CTS and that for DATA-ACK may be different because transmit power can be different for those packets. Thus, when using BASIC, nodes in carrier sensing range 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 the aggregate throughput as well as aggregate throughput per unit energy 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 throughput comparable to IEEE 802.11, but conserves significant amount of energy compared to IEEE 802.11 or BASIC.

One possible concern with PCM is that increasing and decreasing transmit power periodically during short duration is not feasible with current devices, although it is possible in principle. We expect future device to be able to perform such frequent power level changes. An alternative is to replace this higher power level for data by a busy tone at p_{max} in a separate channel – one channel for busy tone and the other channel for RTS-CTS-DATA-ACK. Future work includes development of a power control MAC protocol that conserves energy as well as increasing spatial reuse.

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