Power Control MAC Protocol Analysis and Improvement for Ad Hoc Networks

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Abstract: Several MAC layer power control protocols have been proposed to address the limited power supplies in ad hoc networks. Recent protocols suggest varying the transmission power such that the RTS/CTS handshake is done at the maximum, and the Data-ACK are transmitted at the minimum necessary transmission power level. It has also been suggested to periodically use maximum transmission power during Data transmission. However, using the maximum transmission power level in RTS/CTS handshake does not solve the hidden node problem and in fact causes throughput degradation. Also, IEEE 802.11 does not allow the power levels to change in the same transmission. In this paper, we review different power control MAC protocols, and analyze the effect of transmission power levels on the hidden node problem and the throughput. We then propose an efficient low-power MAC protocol that reduces power consumption and improves throughput. We validate our protocol via detailed simulations.

1 Introduction and Related Work

In general, a wireless node in an ad-hoc network has limited battery power. One technique proposes using a power control scheme at the MAC layer by varying the power at which the control and the data packets are sent. Since control packets are much shorter, the authors in [1,2,3] suggest sending these at the maximum power possible, and once the channel is established, using much lower energy to send the longer data packet. We refer to this scheme as the BASIC scheme in the rest of the paper.

However, BASIC results in lower thoughput [4] because it causes more packets losses due to interference from hidden nodes. To solve this problem, Eun-Sun et al.[4] proposed Power Control MAC (PCM) that uses the BASIC scheme but periodically increases the power level while transmiting a DATA packet. The protocol successfully solves the hidden node problem on the sender side. However, collisions may still occur on the receiver side. In addition to this, IEEE 802.11[5] does not allow the power levels to change in the same transmission.

In this paper, we show that the interference from the hidden nodes degrades the network throughput when the handshake is performed at the maximum energy level. In fact, we show that using the maximum energy increases the likelihood of having more hidden nodes since the interference range also increases. We propose the Efficient Low Power Control MAC Protocol (ELPCM) to establish the lowest power necessary to communicate. The contributions of this paper are two-fold: 1) we analyze the effect of the transmission power level on the hidden node problem and show that using high energy reduces the network throughput by causing more nodes to become hidden, and 2) we propose a new power control MAC protocol that increases the throughput while conserving energy, and validate it via simulations.

2 Background

We define three terms related to a wireless radio. There are: **Transmission Range** (A_{tx}): The A_{tx} of a sender is the area within which a receiver can receive and correctly decode the packet from the sender. It is determined by transmission power level and radio propagation properties (i.e., attenuation). R_{tx} represents it's radius. **Carrier Sensing Range** (A_{cs}): A receiver inside a sender's A_{cs} can detect the transmission but can not correctly decode it. R_{cs} represents it's radius. $R_{cs} = 2 R_{tx}$. **Interference Range** (A_i): Nodes within the A_i of a receiver that do not defer will interfere with the reception. R_i represents its radius, $R_i < R_{cs}$. R_i is not fixed and is determined by transmission power levels of both the sender and interfering node.

3 Power Level and Interference Range

In this section, we analyze the effectiveness of RTS/CTS handshake by explaining the relationship between A_{tx}, A_i, and A_{cs}. Furthermore, we show how these affect the energy consumption of an ad hoc network.

A_{tx} , A_{cx} , A_i: Whether a packet is successfully received is based on the receiving power at the receiver. Given the transmission power (P_t), the receiving power of the signal (P_r) is calculated using two-way ground model . If The signal (P_r) to the noise ratio (*SNR*) is above a certain threshold , then the packet can be successfully received. Let us assume that a transmission is going from a transmitter to a receiver at a distance d, and simultaneously, a hidden node inside the interference range transmits to the receiver at a distance R_i. Let P_t and P_i represent the transmission power of the transmitter and interfering node respectively and $P_i = nP_t$. Since RTS/CTS handshake covers the area where, interference occurs when $R_i > R_x$. Replacing Ri with Rtx, we get the boundary beyond which interference will occur. Solving for R_i:

$$R_i = 1.78n^{1/4}d \qquad R_{tx} \ge d > 0.56R_{tx}n^{-1/4} \tag{1}$$

Effectiveness of RTS/CTS Handshake in 802.11: Based on equation (1), we illustrate the relationship of the interference, transmission and carrier sensing ranges in Figure 1. Here, $n = 1$, and $d = R_{tx}$. The *Total Interference Area* in the figure is the area inside A and B's interference ranges denoted as $A_i(A) \cup A_i(B)$. This is a rather large area, but the RTS/CTS handshake reduces this area since a node either in the transmission range or in the carrier sensing range of a transmitting node will detect the transmission and will defer, avoiding collisions. Yet, the RTS/CTS handshake cannot cover (i.e., avoids collisions) the entire interference area. The nodes inside interference area are called *hidden nodes*. Since the interference range of a node is not fixed, the area where hidden nodes exist varies. The area of the interference in which the RTS/CTS handshake can avoid collisions is called the *Effective Area* of RTS/CTS. The area around a node where interference occurs is called the *Actual Interference Area*. ACT_A_i(A) and ACT_A_i(B) denote this area for nodes A and B, respectively. In Figure 1, the area is shaded with solid lines. We use the metric “Effectiveness” to denote the percentage of the interference area that a handshake protocol covers. Therefore, $E_{RTS/CTS}$ = *Effective Area/Total Interference Area*. The following define the approximate $E_{RTS/CTS}$ based on figure 2.

$$E_{RTS/CTS} = \frac{(A_i(A) - \text{ACT\_}\ A_i(A)) \cup (A_i(B) - \text{ACT\_}A_i(B))}{A_i(A) \cup A_i(B)} \qquad (2)$$

Since α is based on the distance between A and B, $\cos\alpha = \frac{d}{2R_{tx}}$:

$$E_{RTS/CTS} = \begin{cases} 1 & \text{if } 0 \le d \le 0.56R_{tx} \\ \left(\frac{1}{2} - \frac{\alpha}{\pi}\right) + \frac{R_{tx}^2}{R_i^2}\left(\frac{1}{2} + \frac{4\alpha}{\pi}\right) & \text{if } 0.56R_{tx} < d \le R_{tx} \end{cases} \qquad (3)$$

Let $d = xR_{tx}$, then,

$$\frac{\partial E}{\partial x} = \begin{cases} 0 & \text{if } 0 \le x \le 0.56 \\ \frac{2}{\pi\sqrt{4-x^2}} - \frac{1}{3.17x^3} - \frac{4}{3.17\pi}\left(\frac{2}{x^2\sqrt{4-x^2}} + \frac{2\operatorname{acos}\frac{x}{2}}{x^3}\right) & \text{if } 0.56 < x \le 1 \end{cases} \qquad (4)$$

$\frac{\partial E}{\partial x} < 0$, when $0.56 < x \le 1$. Equation (4) shows that $E_{RTS/CTS}$ will decrease when x increases and achieves the maximum when $0 \le x \le 0.56$. So, if $P_t = P_i$, the $E_{RTS/CTS}$ is a fixed value. Therefore, if two nodes are closer to each other, then RTS/CTS covers more of the interference area, thus will avoid more collisions.

Effect of Transmission Power on Throughput: Transmission power determines physical carrier sensing, which determines the size of transmission and carrier sensing ranges. However, when a transmission power higher than the minimum necessary power level between two nodes causes more nodes defer. This is why some power control MAC protocols have lower throughput than IEEE 802.11. Furthermore, it consumes more energy and will be limited by hardware. Also, from the previous analysis, we know the larger transmission power level will not help to improve the $E_{RTS/CTS}$

IEEE 802.11: In 802.11, all packets are sent with the max (P_{max}) transmission power level. This suppresses the transmissions from the hidden nodes on the transmitter side. However, the hidden nodes in receiver side may not detect the RTS or DATA transmissions .Thus, collisions caused by hidden nodes still occur and will consume more energy. Furthermore, the throughput is degraded because all nodes inside max transmission range must defer. **BASIC**: The protocol assumes that signal attenuations and environment conditions are the same in both sides. This may be wrong in an ad hoc network. A more important disadvantage is that the RTS/CTS and DATA-ACK are transmitted with different power levels. Both interference ranges of the transmitter and receiver sides exist and increase. So, collision probability increases. As for the effect on throughput, since RTS/CTS are transmitted at $P_{max,}$ all nodes that detect them will defer and the throughput is degraded. As a result, instead of saving energy, more energy may be consumed. **PCM**: It consumes less energy but realizes the same results as in IEEE 802.11. However, it inherits all the disadvantages of IEEE 802.11. It does not solve the hidden nodes problem in receiver side and causes the degradation of throughput.

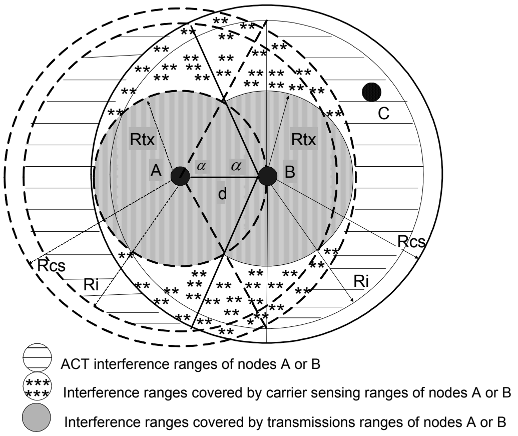


Figure 1 A_{tx}, A_i, A_{cs} when d=R_{tx}

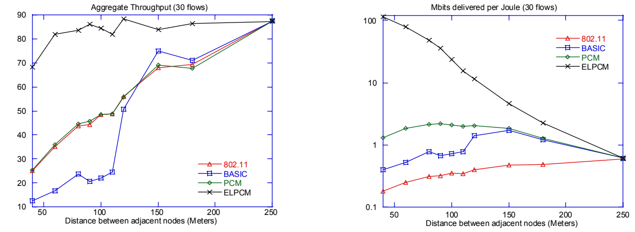
4 Efficient Low Power Control MAC Protocol

From the previous analysis, we conclude that in an efficient power control MAC protocol: 1) the difference between the RTS/CTS transmission power and DATA-ACK transmission power should be as small as possible (the best n in equation (1) is 1), and 2) the minimum necessary transmission power level should be used to reduce energy consumption and improve throughput. In the light of these findings, we propose the Efficient Low Power Control MAC (ELPCM) Protocol as follows:

ELPCM

1. A transmitter transmits RTS at the minimum transmission power level. If the transmitter receives the CTS from the receiver, then the transmission power level will be the initial transmission power. If the transmitter does not get a response from the receiver, it tries to transmit the RTS with the same power level three times to avoid collision with other transmissions. After failing three times, the transmitter transmits the RTS at the least larger transmission power level than the one it

Figure 2 Chain Topology (30 flows)



a) Aggregate Throughput b) Data delivered per joule

uses. The process continues until it finds the minimum necessary transmission power level.

2. After a receiver receives the RTS, it can determine the needed transmission power level based on its received power level P_r. Since it knows the transmitter always uses the minimum necessary transmission power, the receiver first assumes he used the minimum power level and solves equation (1) for d. If value of d is a reasonable range for that power level, that becomes the transmission power level. If d is beyond the transmission range of that power level, the receiver tries the next higher level and solves equation (1) again. The results of the equation with different distance and power level pairs can be stored in a look up table for quick reference. Here, we assume all the nodes have the same system parameters in equation (1).

3. This deduced power level is used for the remainder of the transmission (for DATA and ACK packets as well). In fact, this power level can be stored in the routing table for future transmissions to the same node if the network is static.

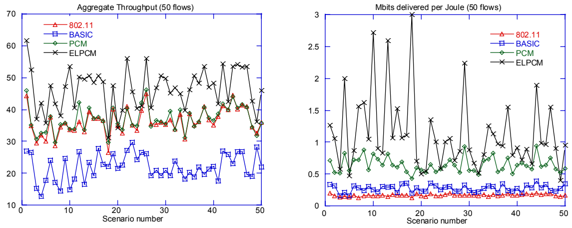
The goals of our protocol are:1) *Reducing energy consumption:* When a node uses the minimum necessary transmission power level for all packets, it creates the minimum interference range, thus, it has the smallest number of hidden nodes. Therefore, fewer collisions will occur and energy will be saved.2) *Improving throughput*: Using the minimum necessary transmission power level, the transmission power level of the transmission node causes the minimum nodes to defer. Thus, more nodes can transmit simultaneously.

5 Performance Evaluation

We use ns-2 (ns2.27) with the CMU wireless extension [6] to perform the simulations. Channel bit rate is 2 Mbps, packet size is 512 bytes. CBR is used as the traffic generator and traffic rate is 1Mbps. We use two metrics to evaluate 802.11, BASIC, PCM and our ELPCM. They are: aggregate throughput over all flows in the networks and efficient data delivered per joule. We simulate in: 1) A chain topology, which is composed of 31 nodes with the same distance between them. 2) 50 different random topologies, each of which is composed of 50 nodes. In both cases, each node transmits to the nearest node.

Chain topology: Figure 2 (a) shows the aggregate throughput of the chain topology using 802.11, BASIC, PCM and ELPCM. The x-axis shows the distance between two nodes, 40m, 60m, 80m, 90m, 100m, 110m, 120m, 150m, 180m, and 250m. The y-axis shows the aggregate throughput. ELPCM always achieves the max throughput. This is because ELPCM transmits all packets at the same transmission power level, which reduces the interference range to the minimum. Also, every transmitting node only has two hidden nodes. 802.11 and PCM overlap as we expect. The throughput of BASIC shows the worst performance. The y-axis of Figure 2 (b) shows the Mbits delivered per joule. It was necessary to make the y-axis logarithmic because the performance of ELPCM is so much better than the others. PCM performs better than BASIC and 802.11. 802.11 deliveres the least data per joule. .

Figure 3 Random Topology (50 topologies)



a) Aggregate Throughput b) Data delivered per joule

Random Topologies: In Figure 3, each point shows a random topology, total is 50. The x-axis is the scenario number. The y-axis of a) is the aggregate throughput and the y-axis of b) is the data delivered per joule. As in the chain topology. ELPCM achieves the max aggregate throughput and much better than the others. 802.11 and PCM overlap. BASIC is the poorest one. ELPCM delivers the max data in a joule. PCM is better than 802.11 and BASIC. BASIC is pretty close to 802.11. BASIC overlap with 802.11 in some topologies.

6 Conclusions

In this paper, we have proposed ELPCM, which transmits all packets at the same transmission power after finding the minimum needed power level. It saves energy by reducing collisions caused by hidden nodes. It improves aggregate throughput by minimizing interference ranges. Simulation results also validate ELPCM.

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