Power Control in Multihop CSMA

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***Abstract*—This paper aims at improving the power efficiency of the CSMA/CA protocol for transmission of multimedia information over multihop wireless channels. Using a distance dependent propagation model, we present a power control scheme, which is based on the receiver sensitivity adjustment mechanism. The receiver sensitivity approach aims at exploiting a tradeoff between the interference and the contention in accessing the shared medium. For real-time traffic, we show that by controlling the receiver sensitivity threshold we can significantly improve the multihop link performance.**

Keywords-power-control, CSMA/CA, WLAN, multihop , MANET.

I. INTRODUCTION

With advances in Wi-Fi technology (typically based on IEEE 802.11) and ad-hoc routing protocols, there is a growing demand for delivery of voice and video services over multihop ad-hoc channels. The major drawback with WLAN is its packet-oriented CSMA/CA MAC layer inefficiency for handling real-time signals. For instance, in contrast to a single hop, in a multihop communication, packets are continually competing to access the media in their shared collision domains. This can significantly limit the end-to-end throughput performance [1]. Under these conditions the problem is not only the contention between neighboring hopping nodes, but also the co-channel interference from those nodes that are more than one hop away from each other. In order to reduce interference it would be essential to study the effect of the transmit power with respect to receiver sensitivity threshold in a CSMA multihop link.

The issue of power control for ad-hoc networks has been extensively studied in the past. For instance, Kawadia and Kumar [2] describe a power controlled routing system wherein the total power consumed can be minimized at the network layer without involving the physical layer. Muqattash and Krunz [3] proposed a power controlled MAC protocol called POWMAC, which inserts the collision avoidance information into the CTS packet to limit the transmission power of potentially interfering terminals. Nevertheless, these power control schemes are not specifically concerned with inefficiencies of the CSMA/CA multihop network for voice and video communications. Bear in mind that in a situation where nodes along a multihop path are continually involved in receiving or forwarding packets to their next hop, energy efficiency would be a crucial factor in maintaining service over a longer period of time. Therefore, in this paper our main objective has been to develop a power control scheme, aimed at reducing the total consumed power and/or improving the throughput performance for transmission of voice and video packets over multihop channels. The proposed scheme is based on controling the receiver's sensitivity in order to achieve the best compromise between the CSMA/CA contention access and co-channel interference.

The paper is organized as follows. In the following section we derive a set of requirements for achieving minimum power in an active route. We then evaluate the effect of the receiver sensitivity adjustment control on the multihop link.

II. PROPOSED METHOD

Let's assume that there is an active route consisting of N nodes where a stream of packets is transmitted from node 1 to node N. Defining $\gamma_{i,i+1}$ as the Signal to Interference plus Noise Ratio (SINR) for the link ($i,i+1$), we can show,

$$\gamma_{i,i+1} = \frac{P_i / D_{i,i+1}^{\alpha}}{P_{Noise} + \sum_{k=1(k\neq i,i+1)}^{N} X_k P_k / D_{k,i+1}^{\alpha}}, \quad 1 \le i \le N-1 \tag{1}$$

where P_{Noise} is the background noise at node $i+1$, P_i is the transmitting power at node i, $D_{i,i+1}$ is the distance between node i and node $i+1$, α is a constant that depends on the propagation medium (free-space) and antenna characteristics (e.g., $2 \le \alpha \le 4$), and X_k is a binary variable where

$$X_k = \begin{cases} 1 & \text{if node } k \text{ transmits,} \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

In order to receive a signal reliably, SINR should satisfy

$$\gamma_{i,i+1} \ge \gamma_0, \quad 1 \le i \le N-1 \tag{3}$$

where γ_0 is the minimum SINR at which the bit error rate can remain below a certain threshold. On the other hand, the receiving power $P_{R,i+1}$ from node i to node $i+1$ should satisfy:

$$P_{R,i+1} \ge S_0, \quad 1 \le i \le N-1 \tag{4}$$

where S_0 is the receiver sensitivity threshold, which indicates the ability of the receiving radio to "hear" the signal and it is defined as the minimum power level at which a signal can be reliably received in the absence of any interference (i.e., SNR). Note that in our proposed power control scheme, we assume that each node has the same receiving power, P_0, where

$$P_0 = P_{R,i+1} = P_i / D_{i,i+1}^{\alpha}, \quad 1 \le i \le N-1 \tag{5}$$

Thus, the transmitting power P_i for node i is

$$P_i = P_0 D_{i,i+1}^{\alpha}, \quad 1 \le i \le N-1 \tag{6}$$

From (1), (5), and (6) $\gamma_{i,i+1}$ can be shown as:

$$\gamma_{i,i+1} = \frac{1}{P_{Noise}/P_0 + \sum_{k=1(k\neq i,i+1)}^{N} X_k \left(D_{k,k+1}/D_{k,i+1}\right)^{\alpha}}, \quad 1 \le i \le N-1 \tag{7}$$

As can be observed from (7), $\gamma_{i,i+1}$ increases while increasing P_0. From (7), we can also obtain the upper limit for $\gamma_{i,i+1}$ as

$$\gamma_{i,i+1} < \lim_{P_0 \to +\infty} \gamma_{i,i+1} = \frac{1}{\sum_{k=1(k \neq i,i+1)}^{N} X_k \left(D_{k,k+1} / D_{k,i+1}\right)^{\alpha}}, \quad 1 \le i \le N-1 \qquad (8)$$

The above equation indicates that the upper limit for $\gamma_{i,i+1}$ depends entirely on the location of active nodes. For instance, $\gamma_{i,i+1}$ could become very small if there are interferences from other nodes (i.e., $X_k = 1$). Such interferences could be more severe in video communications in which a higher transmission rate would be needed. Under these conditions and despite increased received power, a successful packet reception cannot be guaranteed unless $\gamma_{i,i+1} > \gamma_0$. However, in the absence of any interferences (i.e., $X_k = 0$), (7), which represents the SNR, can be shown as

$$\gamma_0 \le \gamma_{i,i+1} = \frac{P_0}{P_{Noise}}, \quad 1 \le i \le N-1 \qquad (9)$$

In this case, P_0 should satisfy the following condition

$$P_0 \ge \gamma_0 P_{Noise} \qquad (10)$$

On the other hand, in a multihop link it is important that nodes more than one-hop away do not sense each other (i.e., the received power should be below the receiver sensitivity threshold, S_0) in order to avoid unnecessary contention backoff. Therefore, for node k we can write

$$\begin{cases} P_k / D_{k,i}^{\alpha} \ge S_0, & k = i-1 \\ P_k / D_{k,i}^{\alpha} < S_0, & k = i-2 \end{cases}, \quad 3 \le i \le N \qquad (11)$$

Using $P_k = P_0 D_{k,k+1}^{\alpha}$, (11) can be shown as:

$$\begin{cases} P_0 \ge S_0 \left(\frac{D_{k,i}}{D_{k,k+1}}\right)^{\alpha}, & k = i-1 \quad (a) \\ P_0 < S_0 \left(\frac{D_{k,i}}{D_{k,k+1}}\right)^{\alpha}, & k = i-2 \quad (b) \end{cases}, \quad 3 \le i \le N \qquad (12)$$

The above shows the lower limit (12a) and upper limit (12b) for P_0. Since for a given S_0, every node should have the same receiving power, we define L_{max} and H_{min} as the maximum and minimum values for lower and upper limits, where

$$\begin{cases} L_{max} = \max \{ (\frac{D_{k,i}}{D_{k,k+1}})^{\alpha} \} & k = i-1 \quad (a) \\ H_{min} = \min \{ (\frac{D_{k,i}}{D_{k,k+1}})^{\alpha} \} & k = i-2 \quad (b) \end{cases}, \quad 3 \le i \le N \qquad (13)$$

and

$$\begin{cases} P_0 \ge S_0 L_{max} \\ P_0 < S_0 H_{min} \end{cases} \qquad (14)$$

From (12a) we can easily deduce that $L_{max} = 1$. Finally, from (10) and (14), the following set of requirements is obtained,

$$\begin{cases} P_0 \ge \gamma_0 P_{Noise} & (a) \\ P_0 \ge S_0 & (b) \\ P_0 < S_0 H_{min} & (c) \end{cases} \qquad (15)$$

In order for P_0 to satisfy all the above conditions, we can show: $\gamma_0 P_{Noise} < S_0 H_{min}$, which means that S_0 should satisfy:

$$S_0 > \frac{\gamma_0 P_{Noise}}{H_{min}} \qquad (16)$$

Therefore there will be two cases in which P_0 can be selected.

- Case 1: if $S_0 > \frac{\gamma_0 P_{Noise}}{H_{min}}$, we can then obtain the following set of conditions for P_0,

  $$\{P | P \ge \gamma_0 P_{Noise}, P \ge S_0, P < S_0 H_{min}\} \qquad (17)$$

  As discussed earlier (see (7)), $\gamma_{i,i+1}$ will be increased while increasing P_0. We can clearly observe that conditions (15.b) and (15.c) would guarantee that the existing route will not be altered by the higher transmit power (i.e., consequence of increasing P_0). Obviously, for the best performance we should select the maximal power for P_0 as long as (16) is satisfied. Thus, for case 1 we can write

  $$P_0 = \max\{P | P \ge \gamma_0 P_{Noise}, P \ge S_0, P < S_0 H_{min}\} \qquad (18)$$

- Case 2: if $S_0 \le \frac{\gamma_0 P_{Noise}}{H_{min}}$, all three conditions in (15) cannot be satisfied at the same time. Therefore, we should increase the value of S_0, i.e.,

  $$S_0' = \frac{\gamma_0 P_{Noise}}{H_{min}} + \delta_P, \quad \delta_p > 0 \qquad (19)$$

  where δ_p should satisfy,

  $$S_0' H_{min} = \gamma_0 P_{Noise} + \delta_P H_{min} > \gamma_0 P_{Noise} \qquad (20)$$

  Then, P_0 can be obtained as follows,

  $$P_0 = \max\{P | P \ge \gamma_0 P_{Noise}, P \ge S_0', P < S_0' H_{min}\} \qquad (21)$$

Upon calculating P_0, the Data transmitting power P_i and ACK transmitting power $P_{i, ACK}$ for node i can be derived from (6):

$$\begin{cases} P_i = P_0 D_{i,i+1}^{\alpha}, & 1 \le i \le N-1 \\ P_{i,ACK} = P_0 D_{i-1,i}^{\alpha}, & 2 \le i \le N \end{cases} \qquad (22)$$

III. PERFORMANCE EVALUATION

In order to evaluate the performance of the proposed method, we used our real-time QualNet-based simulation testbed. We considered the IEEE 802.11b technology with a data-rate option of 2 Mb/s. In our simulations the input data at constant bitrates was first encapsulated into 500 bytes UDP packets. They were then transmitted to the destination via a multihop route consisting of seven nodes, according to the scenario depicted in Fig 1.

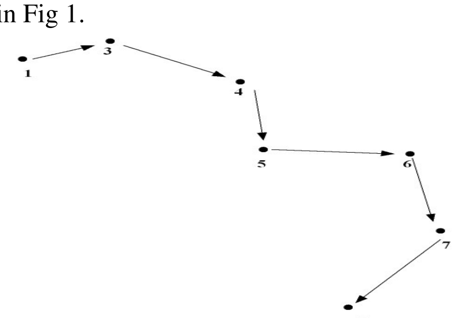


Figure 1. Multihop scenario with six hop-count.

In the physical layer, the initial transmission power was 10.5 dBm, the initial receiver sensitivity was –93.0 dBm, and the noise factor was 10.0. We assumed that the distances between one-hop away and two-hop away nodes (i.e., $D_{i-2, i-1}$ and $D_{i-2, i}$) were known by means of Global Positioning System (GPS). The smallest distance ratio (DR) of $D_{i-2, i}$ over $D_{i-2, i-1}$, which corresponds to H_{min}, was then used to calculate the receiver Sensitivity, S'_0 and the receiving power P_0.

Note that the process begins from a node located at least two hops away from the destination node. This node first calculates its DR before sending it to the next node in the reverse direction. The receiving node then compares the received DR with its own DR and then sends the smaller of the two to the next neighboring node along the reverse path. This continues until the smallest DR, which represents H_{min}, reaches the source node.

Although in our experiments all the nodes are fixed (no mobility) we used the AODV protocol [4] in order to establish a link from source to the destination according to Fig 1. We use the reserved bits of the RREP (Route Reply) packet to transfer the DR towards the source node. A 128-level uniform quantizer is used to carry the DR value via the RREP packet.

Next the source node calculates the new sensitivity threshold (i.e., S'_0), the receiving power P_0, and its new transmitting power. The source node then forwards P_0 and S'_0 (one-byte each) to the next hop as a part of the first data packet. As soon as the next node receives this information, it will update both its receiver sensitivity and its transmitting power before relaying P_0 and S'_0 to the next hops. In this way each node can update its transmitting power and receiver sensitivity as soon as a route is formed.

For the sake of comparison we present our results under the following schemes: scheme 1, uses IEEE 802.11b standard with no power control (NPC), scheme 2 uses power control with fixed receiver sensitivity (PCFS), and finally, scheme 3 uses the full proposed power control scheme that uses the adaptive receiver sensitivity (PCAS). As mentioned before, both scheme 1 and scheme 2 use the minimum receiver sensitivity of –93.0 dBm. Scheme 3, however, uses this sensitivity threshold initially. In the simulations, we use throughput and average transmission power per signal in the physical layer to evaluate the performance. Fig.2 shows the comparisons results between NPC, PCFS, and PCAS using different bitrates with no retransmission. For PCAS, two different SNR values: $\gamma_0 = 35$ and $\gamma_0 = 50$ have been used. From Fig. 2(a), we can observe that in terms of throughputs PCAS performs better than the NPC, even when $\gamma_0 = 35$. With respect to the energy saving aspect, as shown in Fig. 2(b), PCAS shows a significant gain over NPC. We note that when γ_0 is too large (i.e., $\gamma_0 = 50$), the advantage of PCAS over NPC in terms of power consumption will almost vanish. As far as the PCFS scheme is concerned, its throughput is much lower than the other two schemes and almost near zero (see Fig. 2 (a)). This is mainly because when nodes are randomly spaced, H_{min} (see 13.b) and P_0 (see15.c) will become very small. In this situation, it may not be possible to satisfy condition (16) (case 1). Consequently this necessitates increasing the receiver sensitivity threshold in order to meet condition (21) (case 2). However, because of a fixed sensitivity threshold in PCFS, the condition (21) cannot be met either. Under these conditions packets with a smaller P_0 will get through before dropping at the MAC layer (i.e., erroneous packets). This clearly demonstrates that the main trust of the proposed scheme is in its ability to achieve an excellent tradeoff between the transmission power and the interference power through a combination of power control and receiver sensitivity adjustment. For instance, Fig. 2(c) compares the throughput performance of PCAS and NPC under the same average energy per signal. From this Figure we can clearly observe that a significant gain in throughput can be achieved using the proposed power control scheme. Finally, we should point out that for mobile ad-hoc network applications, this approach can be extended using more complex multipath and shadow fading models where receiver sensitivity can be controlled adaptively each time a new route is established.

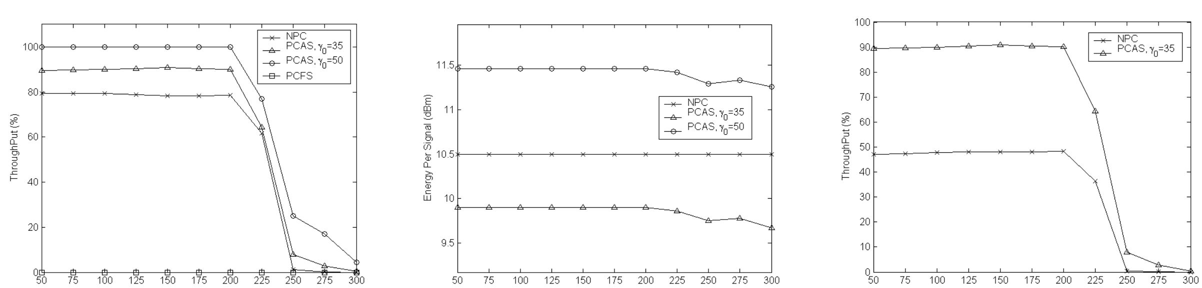
References

[1]. H. Gharavi and K. Ban, "Dynamic Packet Control for Video Communications over Ad-hoc Networks," 2004 IEEE International Conference on Communications (ICC 2004), Paris, France, June 2004.

[2]. V. Kawadia and P.R. Kumar, "Principles and protocols for power control in wireless ad hoc networks", IEEE Journal on Selected Areas in Communications, v 23, n 1, January, 2005, p 76-88.

[3]. A. Muqattash and M. Krunz, "POWMAC: A single-channel power-control protocol for throughput enhancement in wireless ad hoc networks", IEEE Journal on Selected Areas in Communications, v 23, n 5, May, 2005, p 1067-1084.

[4]. C. E. Perkins, E.M. Royer, S.R. Das, "Ad Hoc On Demand Distance Vector (AODV) Routing, " Internet Engineering Task Force, RFC 3561, July 2003.



(a) Throughput comparison

b) Average energy comparison per signal in physical layer

(c) Throughput comparison when NPC and PCAS consume the same energy.

Figure 2. Performance comparisons of scenario shown in Figure 1.