Transmission Power Control for Ad Hoc Wireless Networks: Throughput, Energy and Fairness

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Abstract—We introduce a new power control scheme, for IEEE 802.11-like MAC protocols. Our scheme carefully combines collision avoidance and spatial reuse. Although many power control schemes were proposed for IEEE 802.11, to the best of our knowledge, our scheme is the first to achieve significant improvements for network throughput and energy efficiency simultaneously (up to 40% throughput increase and 3 times more data delivery with the same amount of energy), while adhering to the single-channel, single-transceiver design rule. Furthermore, our scheme solves the fairness problem identified in [11], i.e., IEEE 802.11 and some power control schemes deliver more packets for short distance source-destination pairs than for long distance pairs. Thus, our scheme also improves the bit-meter/sec metric (by up to 70%). Our proposed scheme belongs to a more general class of power control schemes, that we extensively simulate. We also provide a theoretical analysis to justify our approach and simulation results.

I. INTRODUCTION

Improving the channel efficiency in wireless ad hoc networks is challenging and of significant importance to keep up with the increasing need for higher capacity. Furthermore, ad hoc wireless node operates on limited and often non-replenishable battery power. Therefore, energy efficiency is another critical issue in the design of ad hoc wireless networks.

The IEEE 802.11 standard [1] is currently the dominant medium access control protocol for MANETs (mobile ad-hoc networks). In IEEE 802.11 DCF (distributed coordination function), the RTS/CTS handshake is used to reserve the transmission floor for subsequent DATA and ACK transmissions. Nodes transmit at a fixed and maximum power $P_{\text{max}}$ for all control and data packets. Several drawbacks of IEEE 802.11 have been identified in the past several years. First, IEEE 802.11 uses maximum transmission power $P_{\text{max}}$ regardless of the distance between the transmitter and the receiver. This leads to its energy inefficiency since a short traffic pair (i.e., transmitter-receiver pairs with short distance) need much less power than $P_{\text{max}}$ for the communication to be successful. Second, spatial channel reuse in IEEE 802.11 is not optimized. One on-going transmission can unnecessarily block multiple nearby sessions by transmitting at $P_{\text{max}}$ [11], [12]. The third drawback of IEEE 802.11, identified in [11], is the fairness problem: IEEE 802.11 delivers more packets for short distance traffic pairs than for long-distance traffic pairs. When the network load increases, the ratio of delivered short distance traffic to long-distance traffic increases.

Many power control schemes have been proposed to improve the performance of MAC protocols for MANETs. However, as described in [13], these schemes suffer from one or more of the following: (1) the scheme improves energy-efficiency but not network throughput, or increase the throughput at the expense of energy consumption; (2) extra hardware and spectrum availability are required, i.e., multiple wireless channels and transceivers; (3) strong assumptions on MAC or physical layers are imposed, which are often difficult to implement. Also, some power control schemes reveal stronger preference for short distance traffic pairs than IEEE 802.11 [11]. To the best of our knowledge, a protocol that improves network throughput, energy-efficiency, and fair to different length traffic pairs at the same time has not been identified yet. In this paper, we propose such a scheme.

A. Related work

Power control has been studied primarily as a way to improve energy efficiency of MAC protocols for MANETs [2], [4], [8], [9], [15]. In [2], [4], [9], [15], nodes transmit RTS/CTS at maximum power, $P_{\text{max}}$, but send DATA/ACK at minimum necessary power $P_{\text{min}}$. The minimum necessary power $P_{\text{min}}$ varies for traffic pairs with different lengths, and different interference levels at the receiver side. We refer to this scheme as the basic power control scheme. It was shown in [8] that basic power control scheme has a deficiency which leads to network throughput degradation. Since the DATA/ACK packet is transmitted at a lower power than RTS/CTS, nodes in the carrier sensing zone of RTS/CTS cannot sense the DATA/ACK transmission. Therefore, these nodes consider the channel idle and might start their own transmission sessions, which leads to a collision with the DATA/ACK transmission of the original session and results in throughput degradation. In [8], the authors propose PCM (power control MAC) that operates similarly to the basic power control scheme, except that the power level is periodically raised to $P_{\text{max}}$ from $P_{\text{min}}$ for a very short time during the transmission of the DATA packet. PCM achieves a comparable network throughput with IEEE 802.11, because nodes that sense RTS/CTS can now sense DATA too and will not interrupt DATA of on-going transmissions. While these protocols achieve significant energy saving over IEEE 802.11, they at best achieve a throughput comparable to that of IEEE 802.11. The main reason is that RTS and CTS are transmitted at $P_{\text{max}}$, which prevent potential concurrent

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sessions from proceeding in the vicinity of the transmitter and receiver.

The schemes in [11], [12], [19] improve spatial channel reuse, and demonstrate significant throughput increase over that of IEEE 802.11 in simulations. However, these schemes introduce additional hardware cost and implementation complexity by requiring two transceivers and two channels. Furthermore, their assumptions about the physical and MAC layers raise practicality questions (see [13] for details). In [13], the authors propose a throughput-oriented protocol, POWMAC (power control MAC protocol), which follows the single-channel and single-transceiver design principle of IEEE 802.11. In POWMAC, an access window is used to allow for a series of RTS/CTS exchanges to take place before multiple concurrent data packet transmissions start. Collision avoidance information attached in CTS is used to bound the transmission power of potential interfering nodes, rather than silencing those nodes. Therefore, spatial channel reuse is improved. POWMAC yields significant increase in network throughput over IEEE 802.11, and some reduction in energy dissipation.

Other related work can be found in [3], [7], [14], [16].

B. Our contributions

To increase network throughput we use a novel transmission power function \( P(t) \) to compute an appropriate transmission power, so that a better spatial channel reuse is achieved. Unlike POWMAC no collision avoidance information is explicitly advertised in our scheme. Instead, nodes choose a transmission power level based on its traffic distance \( d \), and an estimate of the interference level it experiences. Our power function, \( \delta \)-PCS, is the following:

\[
\delta(t) = P_{\text{max}}(d/d_{\text{max}})^{\delta}, \quad \text{where } d_{\text{max}} \text{ is the transmission range of } P_{\text{max}}, \delta \text{ is a constant between 0 and } \alpha, \text{ and } \alpha \text{ is the power attenuation factor (see Section II for details). Each } \delta \text{ value corresponds to a different power control scheme, and in one scheme the value } \delta \text{ is uniform to each node in the network. It can be seen that all nodes in our scheme transmit at a power level below } P_{\text{max}} \text{ and above the minimum necessary power } P_{\text{min}}, \text{ for constant } \delta \text{ between 0 and } \alpha. \]

Our main contributions in this paper are:

- We introduce a new class of power control scheme, \( \delta \)-PCS. We identify a single scheme from this class that shows significant improvement in network throughput, energy efficiency and fairness over 802.11 at the same time, and adheres to the same single-channel and single-transceiver design principle. To the best of knowledge, our scheme is the first that achieves simultaneous improvement in all three metrics.

- Through extensive simulations, our identified power control scheme increases the network throughput up to 40%, reduces the energy consumption per delivered information bit by a factor of 3, and shows better fairness toward both long and short traffic pairs. We also show how our proposed scheme can be implemented on current wireless cards.

Table I compares existing power control schemes discussed in Section I-A and \( \delta \)-PCS under our three considered performance metrics [8], [11], [13]. The figures in columns 3 and 4 are as reported in corresponding citations, and are normalized to 802.11.\(^1\)

<table>
<thead>
<tr>
<th>Power Control Schemes</th>
<th># of Chann.</th>
<th>Throughput</th>
<th>Mb/Joule</th>
<th>Fairness</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE 802.11 [11]</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>prefers short</td>
</tr>
<tr>
<td>PCM [8]</td>
<td>1</td>
<td>( \approx 1 )</td>
<td>( \approx 3 )</td>
<td>-</td>
</tr>
<tr>
<td>PCMA [11]</td>
<td>2</td>
<td>( \approx 2 )</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>POWMAC [13]</td>
<td>1</td>
<td>( \approx 1.45 )</td>
<td>( \approx 1 )</td>
<td>-</td>
</tr>
<tr>
<td>( \delta )-PCS</td>
<td>1</td>
<td>( \approx 1.4 )</td>
<td>( \approx 3 )</td>
<td>fair to both</td>
</tr>
</tbody>
</table>

II. NETWORK MODELS AND ASSUMPTIONS

Radio frequency signals are subject to propagation attenuation. The attenuation is usually denoted by path loss and estimated by a power of the traveled distance \([17]\). Let \( p^{(r)}_i \) be the received signal power and \( p^{(t)}_i \) be the transmitted power, we have \( p^{(r)}_i = c \cdot p^{(t)}_i / d^\alpha \), where \( c \) is a constant that depends on the antenna gains and heights, and carrier frequency, \( d \) is the distance that the signal travels, and \( \alpha \) is the power attenuation factor. The typical value of \( \alpha \) ranges from 2 to 4. For our simulation study, we adopt the standard two-ray ground model that sets \( \alpha \) to be 4 for long-range distances and 2 for short-range distances.

In addition to path loss, the bit-error rate of a transmission depends on the noise power and the interference level at the receiver. Let \( \{X_k, k \in T\} \) be the set of nodes simultaneously transmitting at any time instant. Let \( X_j \) be the receiver of a transmitter \( X_i \in T \). For the transmission by \( X_i \) to be successfully received by \( X_j \); (1) the received power \( p^{(r)}_{ij} \) at node \( X_j \) must exceed the receiving threshold, \( RX_{th} \); (2) the SINR (signal to interference noise ratio) at \( X_j \) must exceed the SINR threshold, \( SINR_{th} \). For the latter, we adopt the so called physical model in [5], [10]

\[
SINR_j = \frac{p^{(r)}_{ij}}{N + \sum_{k \in T, k \neq i} p^{(r)}_{kj}} \geq SINR_{th}, \quad (1)
\]

where \( SINR_{th} \) specifies a threshold for successful packet receptions, \( N \) is the noise level (noise is usually modeled as a white Gaussian signal), and \( p^{(r)}_{ij} \) is the received signal strength of the transmission from \( X_i \) to node \( X_j \).

In the rest of our paper, we use traffic distance or traffic length to denote the distance between the transmitter and the receiver. The transmission range of a certain power level \( p^{(t)} \) denotes the maximum distance at which the received signal is right above \( RX_{th} \). Beyond the transmission range, the signal can still be detected (but not decoded) if its strength is above the carrier sensing threshold, \( CS_{th} \). Typically, \( CS_{th} \) is several dBs lower than \( RX_{th} \). Thus, the sensing range defined by \( CS_{th} \) is larger than the transmission range. In our simulation setting, the maximum transmission power \( P_{max} \) (25dBm) has a transmission range of 250m, and its corresponding

\(^1\)These schemes are evaluated under similar network settings of random network topologies and the presence of both long and short traffic pairs. However, the simulation settings can be different to some extent.
sensing range is about 550m (see Section IV for the detailed parameter settings).

III. δ-PCS: A CLASS OF POWER CONTROL SCHEMES

In this section, we introduce δ-PCS, a continuous space of power control schemes parametrized by δ and compatible with IEEE 802.11. We analyze the fairness of δ-PCS with respect to traffic distance, and discuss the implications of fairness on the aggregate network throughput.

A. Overview of δ-PCS

As discussed in Section II, \( P^{(r)} \geq RX_{th} \) is required for a transmission to be successfully received. In IEEE 802.11, every packet is transmitted at maximum power level. In order to make the protocol more energy-efficient, various simple power control schemes have been proposed for IEEE 802.11. The most basic of these is to set the transmission powers to be the minimum necessary power. The class δ-PCS represents a spectrum of protocols between two extremes: IEEE 802.11 with no power control, and the basic power control scheme.

Given the maximum transmission power level, \( P_{\text{max}} \), the corresponding maximum transmission range \( d_{\text{max}} \) satisfies \( c \cdot P_{\text{max}} / d_{\text{max}}^\alpha = RX_{th} \). Similarly, given the distance \( d \) between the transmitter and receiver, the minimum necessary transmission power, \( P_{\text{min}}(d) \), for a transmission to be successful satisfies \( c \cdot P_{\text{min}}(d) / d^\alpha = RX_{th} \). Thus we have,

\[
P_{\text{max}} = d_{\text{max}}^\alpha \frac{RX_{th}}{c}, \quad P_{\text{min}}(d) = d^\alpha \frac{RX_{th}}{c}.
\]

Now we are ready to establish our power function \( P^{(t)} \). Let parameter \( \delta \) be any constant between 0 and \( \alpha \), our power function is the following:

\[
P^{(t)} = d^\delta d_{\text{max}}^{-\delta} \frac{RX_{th}}{c}.
\]

Let \( d_T \) be the transmission range of \( P^{(t)} \). By the definition of transmission range, the received signal power at \( d_T \) is equal to the receiving threshold, i.e., \( P^{(r)} = c \cdot P^{(t)}/(d_T)^\alpha = RX_{th} \). We then have that the transmission range of \( P^{(t)} \) is \( d_T = d^\delta / d_{\text{max}}^{-\delta} / \alpha \). Note that \( d \leq d_T \leq d_{\text{max}} \), for any \( \delta \) between 0 and \( \alpha \). Figure 1(a) depicts the transmission range δ-PCS that lies between \( d \) and \( d_{\text{max}} \). Figure 1(b) shows how the transmission power changes as a function of the traffic distance \( d \), under different δ-PCS schemes. Note that δ-PCS provides a continuous space of power functions for \( \delta \) between 0 and \( \alpha \).

Our power function is expressed in terms of \( d \) and \( d_{\text{max}} \) only to facilitate the analysis in Section III-B. When we discuss implementation issues in Section V, we derive another form of our power function that replaces \( d \) and \( d_{\text{max}} \) with channel gain information, a common and essential component of many power control schemes [8], [11–13]. Our main goal is to identify a “good” \( \delta \) value such that the corresponding power control scheme yields performance improvement in network throughput, energy efficiency and fairness simultaneously. As we show in Section IV, there exists a substantial and continuous range of “good” \( \delta \) values on \( [0, \alpha] \) that outperforms all proposed power control schemes for IEEE 802.11.

B. Analysis of δ-PCS

We analyze the fairness behavior of δ-PCS, and show that in an environment with both long and short traffic pairs, adjusting the parameter \( \delta \) changes the channel capacity allocation for different traffic pairs. This provides us a way to address the fairness problem that arises in IEEE 802.11 and some other power control schemes. As we discuss in Section IV, the fairness for different traffic distance is closely related to the aggregate throughput.

By definition, \( P^{(t)} \) under δ-PCS is always above the minimum necessary power \( P_{\text{min}}(d) \). This implies that the received signal power at the designated receiver is above \( RX_{th} \) - the first condition for successful reception. We now examine Equation 1, the second condition for successful packet reception. In order to facilitate our analysis and make the derivation tractable, we assume the following (i) each source node is located independently and uniformly in the Euclidean plane; (ii) for each source, its destination is located at a distance chosen independently and uniformly at random from \( [0, d_{\text{max}}] \). We assume \( N = 0 \) in our following derivation for simplicity; our analysis applies to the cases where \( N > 0 \), and similar
results can be obtained. Consider an on-going transmission from a node \( X_i \) to node \( X_j \). For any other transmitting node \( X_k, k \neq i \), let \( X_k' \) be the receiver. Applying Equation 3 to Equation 1, we obtain

\[
\frac{1}{\text{SINR}_j} = \sum_{k \neq i} \left( \frac{d_{k'}}{d_{ij}} \right)^\alpha \left( \frac{d_{ij}}{d_{kj}} \right)^\alpha.
\]

In order for the transmission from \( X_i \) to \( X_j \) to be successful, we need \( \text{SINR}_j \) to exceed \( \text{SINR}_{th} \). In the following, we determine the value \( \delta \) that minimizes \( E[1/\text{SINR}_j] \). We note that minimizing \( E[1/\text{SINR}_j] \) is only an approximation for maximizing the aggregate throughput. However, as shown in Section IV, our approximation matches the simulation result closely. Due to space constraints, we defer the proof of the following lemma to the full paper [6].

**Lemma 3.1:**

\[
E[1/\text{SINR}_j] = \sum_{k \neq i} E \left[ \left( \frac{d_{ij}}{d_{kj}} \right)^\alpha \left( \frac{d_{ij}}{d_{ij}} \right)^\delta \frac{1}{\delta + 1} \right].
\]  

The minimum of Equation 4 is achieved at \( \delta_{\text{opt}}(d_{ij}) = 1/(\ln d_{max} - \ln d_{ij} - 1) \). We can thus infer the following: (1) Equation 4 is a decreasing function of \( \delta \) on \( [\delta_{\text{opt}}, \infty] \), and an increasing function of \( \delta \) on \( [0, \delta_{\text{opt}}] \); (2) \( \delta_{\text{opt}} \) is an increasing function of \( d_{ij} \); (3) there exist threshold distances \( d' \), \( d'' \) with \( \delta_{\text{opt}}(d') = 0 \) and \( \delta_{\text{opt}}(d'') = \alpha \). These lead to three key observations:

**Observation 1:** For \( 0 < d_{ij} \leq d' \), \( \delta_{\text{opt}}(d_{ij}) < 0 \), which implies that \( E[1/\text{SINR}_j] \) increases as \( \delta \) increases from 0 to \( \alpha \). Thus, the throughput of the traffic pairs with \( 0 < d_{ij} \leq d' \) decreases when \( \delta \) increases from 0 to \( \alpha \).

**Observation 2:** For \( d' < d_{ij} \leq d'' \), \( 0 \leq \delta_{\text{opt}}(d_{ij}) \leq \alpha \), which implies that \( E[1/\text{SINR}_j] \) first decreases then increases when \( \delta \) increases from 0 to \( \alpha \). This indicates that the throughput of the traffic pairs with \( d' \leq d_{ij} \leq d'' \) first decreases then increase when \( \delta \) increases from 0 to \( \alpha \).

**Observation 3:** For \( d'' < d_{ij} \), \( \delta_{\text{opt}}(d_{ij}) \geq \alpha \), which implies that \( E[1/\text{SINR}_j] \) decreases when \( \delta \) decreases from 0 to \( \alpha \). This indicates that the throughput of the traffic pairs with \( d_{ij} > d'' \) increases when \( \delta \) decreases from 0 to \( \alpha \).

Plugging our simulation setting of \( d_{max} = 250m \) into \( \delta_{\text{opt}} \), we obtain \( d' = 92m \) and \( d'' = 204m \). From our analysis, the throughput of the traffic pairs with distance smaller than 92\( m \) is expected to decrease on \( \delta \in [0, \alpha] \); for traffic pairs with distances between 92\( m \) and 204\( m \), the throughput is expected to first increase then decrease on \( \delta \in [0, \alpha] \); for traffic pairs with distances larger than 204\( m \), the throughput is expected to increase on \( \delta \in [0, \alpha] \). Our simulation results support our analysis (Figures III-A(a) and III-A(b)), and we elaborate on this in Section IV-B.2.

IV. Simulation results

In this section, we evaluate \( \delta \)-PCS through extensive simulations. We concentrate on the comparison between \( \delta \)-PCS and IEEE 802.11, and identify a \( \delta \) value that leads to performance improvement in network throughput, energy efficiency and fairness at the same time. In brief, our identified \( \delta \) value achieves the following:

1. It achieves up to 40% increase in throughput over IEEE 802.11.
2. It delivers three times the amount of data that IEEE 802.11 delivers with the same amount of energy.
3. It achieves a fair allocation of delivered traffic for long and short traffic pairs.

A. Simulation model

We use GloMoSim-2.03 [18] with these settings:

**Physical Layer.** The channel carrier frequency is 914Mhz and the bandwidth is 2Mbps. The receiving threshold is -64dBm, and the carrier sensing threshold is -71dBm. Two-ray path loss is used as the radio propagation model, where signal attenuates as \( 1/d^2 \) at near distance and \( 1/d^4 \) at far distance. Therefore, we simulate the feasible range of \( \delta \) from 0 to 4. The transmission range at maximum power 25dBm is 250m, and the corresponding sensing range is 550m. When transmitting at reduced power, the transmission range and carrier sensing range also reduce according to the receiving and sensing thresholds.

**Application layer.** We adopt a constant bit rate (CBR) traffic model. The default packet size is 512 bytes.

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Since energy-oriented schemes [2], [4], [8], [9], [15] achieve throughput at best comparable to IEEE 802.11 and throughput-oriented schemes are limited in their energy savings [11], [13], [19] (see Section I-A for details), we present out results with IEEE 802.11 as a base reference.
Topology and traffic. We generate random topologies with 200 stationary nodes distributed on a $2000 \times 2000 m^2$ area. As typical to many MAC protocol evaluations [8], [11], [13], we select randomly located single-hop transmitter-receiver pairs (also referred to as traffic pairs). We select random traffic pairs from 0 to 250m. We give detailed description of our traffic setting in each subsequent sections.

In this section, we compare $\delta$-PCS with IEEE 802.11 under a 914Mhz/2Mbps setting. The motivation of using this setting is to achieve a fair comparison of our scheme with the proposed schemes in [8], [11], [13], as listed in Table I. Investigating the performance of our scheme under a more recent network setting is part of our future research direction. We study the following performance metrics:

Aggregate and normalized throughput. Aggregate throughput refers to the total throughput achieved over all flows in the network. Normalized throughput refers to the ratio of the aggregate throughput of a defined scheme over that of IEEE 802.11. We also measure the bit-meter/sec performance, which is considered another suitable indicator of network capacity [5].

Energy efficiency. We measure Mb/Joule for delivered data, where the energy expenditure is taken over all attempted transmissions (i.e., including retransmissions).

Throughput achieved in different destination ranges. We measure the fairness of a power control scheme by the fraction of data delivered for five destination ranges: 0-50, 50-100, 100-150, 150-200, and 200-250 meters.

B. Random topologies with varying number of traffic pairs

We first compare the performance of IEEE 802.11 and $\delta$-PCS when varying the number of traffic pairs, each with fixed data rate. We consider 5 sets of experiments on random topologies: 10, 20, 30, 40 and 50 traffic pairs. Since the topology size is fixed, more traffic pairs implies higher traffic density. In each experiment, we select traffic pairs such that there are equal number of pairs within destination ranges 0-50, 50-100, 100-150, 150-200 and 200-250 meters. For example, in our experiment with 30 total traffic pairs, we select 6 pairs in each destination range. The data rate is 1.0Mbps for each pair. Our simulation results are the average of 30 simulation runs.

1) Aggregate throughput: Figure 2 plots the aggregate throughput with $\delta$ being the X-axis. We observe common behaviors for all experiments: the throughput first increases then decreases when $\delta$ increases from 0 to 4, and the maximum throughput is achieved when $\delta$ is in the range of 2 to 3. Figure 3 presents the normalized throughput (with respect to IEEE 802.11) of $\delta$-PCS. We see that 1-PCS, 2-PCS, 2.5-PCS, and 3-PCS all achieve throughput increase over IEEE 802.11. In particular, 2.5-PCS (as well as 2-PCS and 3-PCS) achieves up to 40% throughput increase. In fact, all of our simulated schemes with $\delta \in [2, 3]$ achieve close to $30 - 40\%$ throughput increase over IEEE 802.11.

The plots in Figure 2 and 3 can be explained as follows. IEEE 802.11 uses $P_{max}$ to transmit, regardless of traffic lengths. Thus, in the presence of short pairs, the spatial channel reuse is inefficient. As illustrated in Figure 1(b), the transmission range keeps decreasing when $\delta$ increases from 0 to $\alpha$. Thus, power control schemes with larger $\delta$ are able to accommodate more simultaneous transmissions. Consequently, the aggregate throughput increases due to improved spatial channel reuse. However, when $\delta$ is close to $\alpha$, the transmission power is close to the minimum power needed for successful reception. Therefore, the reception is sensitive to interference from other transmissions. At the same time, the potential for improving spatial channel reuse by reducing transmission ranges is limited, since the transmission range $\frac{\delta^\alpha p_{max}^{1-\delta/\alpha}}{\alpha}$ is a convex decreasing function of $\delta$ (Figure 1(b)). This leads to the throughput decrease when $\delta$ is close to 4.

2) Fairness: We now study the achieved throughput in each destination range, in addition to the aggregate throughput over all pairs. Figure III-A(b) presents the results of our experiment with 30 traffic pairs as a histogram. Each group of bars corresponds to a $\delta$-scheme. Within each group, the heights of the 5 bars from left to right represent the achieved throughput for destination ranges 0-50, 50-100, 100-150, 150-200 and 200-250 meters respectively. We see that IEEE 802.11 delivers more data for short traffic pairs than for long traffic pairs (as also observed in [11]). The preference is slowly inverted when $\delta$ increases from 0 to 4, with 4-PCS showing a strong preference for long traffic pairs; this matches our Observation 1 in Section III-B. for destination range 100-150m, the achieved throughput first increases then decreases, which matches our
Observation 2; for destination range 200-250m, the achieved throughput increases, which matches Observation 3. When $\delta$ is equal to 2 or 2.5, the achieved throughputs on each range are close to the average, thus a fair allocation of the channel capacity is observed. We also observe that only relative short traffic pairs (e.g., 0-50 meters) suffer when $\delta$ increases from 0 to 2.5, and traffic pairs in all other destination ranges benefit simultaneously. This justifies the plots in Figure 2.

Figure 5 plots the normalized bit-meter/sec performance of $\delta$-PCS over IEEE 802.11. For $\delta$ equal to 2.5 or 3, the improvement over IEEE 802.11 is about 50-70%. This significant increase is directly acquired from the throughput increase and the fair allocation of throughput in each destination range (since IEEE 802.11 delivers less data for long range pairs.). Under the bit-meter/sec metric, 4-PCS also shows significant improvement over IEEE 802.11. However, its performance is not the best. This is because its throughput is lower than 3-PCS, even though it delivers more packets for long distance pairs as shown in Figure III-A(b).

3) Energy efficiency: Figure 6 depicts the energy efficiency of $\delta$-PCS by measuring delivered data per Joule. The consumed energy is taken over all transmission attempts, both successful and failed. IEEE 802.11 delivers 0.9Mb with 1 unit energy consumption, while 2.5-PCS delivers 2.74Mb data with the same amount of energy. The performance of 3-PCS is slightly better than 2.5-PCS, since the transmission power in 3-PCS is smaller than in 2.5-PCS. Although 4-PCS uses the minimum necessary power to transmit among all schemes, its Mb/Joule performance is not the best due to its less competitive throughput. From Figure 6, we also observe a slight decrease in the Mb/Joule measurement when the total number of traffic pairs increases. This is because when load increases, collision also increases, which leads to increased retransmissions. This leads to a slight decrease in delivered bits per Joule.

C. Random topologies with varying data rate

In this study, we select 30 flows in each experiment, and generate CBR data at rates in the 100Kbps-1Mbps range. Similar to Section IV-B, each value in our plots is the average of 30 simulation runs.

Figure 7 plots the aggregate throughput of $\delta$-PCS. When the data rate is 100Kbps, all power control schemes, except for 3.5-PCS and 4-PCS, deliver all the packets. As the data rate increases, we observe the same behavior as in Figure 2: the maximum throughput in each data rate is achieved when $\delta$ is in the range of 2 to 3. In this $\delta$ range, the throughput improvement over IEEE 802.11 is about 40% when the data rate is above 800Kbps.

Figure 8 shows the achieved throughput in each destination range (30 traffic pairs each at data rate 600Kbps). The result is similar to that of Figure III-A(b). We see that IEEE 802.11 delivers more data for short traffic pairs than for long traffic pairs, while 2-PCS and 2.5-PCS show fair allocation of channel capacity for both long and short pairs. Figure 9 plots the bit-meter/sec performance of $\delta$. When data rate increases, the bit-meter/sec performance improvement of $\delta$-PCS over IEEE 802.11 increases.

The energy efficiency of $\delta$-PCS for varying data rates is depicted in Figure 10. The schemes 2.5-PCS and 3-PCS exhibit a stable 3 factor energy saving over IEEE 802.11. In the experiment with data rate 100Kbps, 4-PCS outperforms 2.5-PCS; when the data rate increases, 2.5-PCS outperforms 4-PCS. This is because 4-PCS uses minimum necessary power to transmit, whose reception is more sensitive to interference. When the data rate increases, 4-PCS experiences more collisions, thus more retransmissions. This explains its lower energy efficiency.

V. IMPLEMENTATION ISSUES

In order to implement the near optimal scheme, two main issues have to be resolved. Firstly, the power level as a function of distance has to be transformed into a function of a parameter that can be easily estimated by the communicating nodes. Secondly, in a mobile environment the transmission power level for the RTS/CTS has to be regularly updated.

Power function implementation: Within the RTS/CTS handshake protocol, the communicating nodes can estimate the channel gain. We propose to convert the distance variable of the power function into a gain variable. The proposed power function is as follows: $p(t) = P_{\text{max}}(\frac{RX_{ij}G_{ij}}{P_{\text{max}}})^{\delta/\alpha}$ where $G_{ij}$ is the channel gain from node $i$ to node $j$. If the gain is taken

$\delta$ The hidden constant $C$ is included in the gain.

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**Fig. 8.** Achieved throughput on different destination ranges (30 traffic pairs at data rate 600Kbps).

**Fig. 9.** Normalized bit-meter/sec under varying data rate, where the total number of pairs is 30.

**Fig. 10.** Data delivered per energy unit under varying data rate. The total number of pairs is 30.
as a power of the distance, the chosen power function results in the one we have used in our simulations.

**RTS/CTS power level update:** In a mobile network the channel characteristics change as the nodes move, therefore the transmission power levels have to be updated. We propose to use a technique similar to the closed-loop power control used in CDMA cellular systems. It is reasonable to assume that each packet transmission is part of a session. Therefore for each data packet sent the power level used is cached and used for the subsequent RTS/CTS. The RTS/CTS allows improving the estimation of the channel gain and determining the power level to be used for the current data packet transmission.

**VI. Conclusions and Future Work**

In this paper we propose $\delta$-PCS, a class of power control schemes for ad hoc wireless networks, based on a novel transmission power function. Compared with IEEE 802.11, our proposed scheme achieves up to 40% throughput increase, improves energy efficiency by a factor of 3, and shows better fairness with respect to the traffic length distribution. Although several power control schemes have been proposed in the past, this is the first one to achieve significant improvement on energy, capacity, and fairness, while adhering to the simple single-channel, single-transceiver design principle. Among the feasible values of $\delta$, we show that the schemes with $\delta$ between 2 and 3 all achieve significant improvements over IEEE 802.11. As future research, we plan to integrate our power control scheme within a resource efficient multi-hop routing protocols we are currently developing. As indicated in Section IV, investigating our scheme under a more recent network setting is also part of future research research direction.

**References**


