A Distributed Power and Rate Control Scheme for Mobile Ad hoc Networks

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***Abstract*—The IEEE 802.11 Distributed Coordination Function (DCF) is the medium access protocol widely used for wireless local networks (LAN). Unfortunately, IEEE 802.11 DCF described in the standard faces some challenges when adopted for multi hop networks, which arise from the presence of the so-called hidden stations. This can cause degradation of the network throughput performance and energy consumption. Solving the hidden terminal problem will increase the possibility of the so-called exposed terminal and vice versa. In this paper, we present a novel scheme, called PRAS-CP (transmission power and rate adaptive scheme with collision prevention), which enhances network performance through balancing the tradeoff between the hidden terminals and the exposed terminals. To accomplish this, PRAS-CP integrates the Physical/MAC attributes (the carrier sensing range and the interference range) and carrier sensing mechanisms (PCS,VCS) to assign the appropriate data rate and transmission power values to successfully exchange the RTS/CTS DATA/ACK packets. Simulation results under different scenarios are used to demonstrate the significant throughput, energy gains, and fairness that can be obtained by PRAS-CP.**

I. Introduction

In wireless ad hoc networks, the medium access control (MAC) protocol plays a key role in coordinating the access to the shared medium among wireless nodes. Currently, the distributed coordination function (DCF) of the IEEE 802.11 [1] is the dominant MAC protocol for both wireless LANs and wireless multihop ad hoc environment due to its simple implementation and distributed nature. A station running the DCF protocol uses carrier sensing to determine the status of the medium (e.g., assess its current interference level) before initiating any transmission to avoid collisions. Two types of carrier sensing are used, a mandatory physical carrier sensing (PCS) and an optional virtual carrier sensing (VCS). In the former, a node monitors the radio frequency (RF) energy level on the channel and initiates channel access for transmission only if the power of the detected signal is below a certain carrier sense threshold (CS_{th}) [1]. In the latter, each node regards the channel busy for a period indicated in the MAC frames defined in the protocol. Namely, nodes hearing the RTS/CTS (request-to-send and clear-to-send) exchange (typically nodes in the transmission range of these frames) will adjust their network allocation vector (NAV) to the duration of the complete four-way handshake. Hence, a node contends for a channel only if the conditions for both carrier sense mechanisms are satisfied. However, it has been shown that the DCF access method does not make efficient use of the shared channel due to its inherent conservative approach in assessing the level of interference. For example, when a station senses a busy medium (either through the PCS or VCS functions of the IEEE 802.11), it simply blocks its own transmission [1] to yield for other ongoing communication. However, if the transmission of this station does not cause enough interference to corrupt the frame reception of the ongoing transmission, then blocking that transmission would be unnecessary. This problem has been referred to as the *exposed terminal problem* and has been shown to severely affect the spatial reuse of the spectral resource and thus limit the network capacity. Now, after a node senses an idle medium, it can initiate a transmission; the signal to interference and noise ratio (SINR) perceived at the receiver determines whether this transmission is successful or not. Namely, if the SINR is smaller than a minimum threshold (ζ), the transmission cannot be correctly decoded. However, the interference contributed by concurrent transmissions outside the carrier sense range of the sender may corrupt the ongoing communication. Those potential interferes that are outside the carrier sense range of the sender are commonly known as the *hidden terminals*.

To date, various methods have been proposed to improve the capacity of IEEE 802.11-based multihop wireless networks; for example, one can increase the level of spatial reuse by either reducing the transmission power or increasing the CS_{th}. However, in either method, the SINR may decrease as a result of the smaller received signal or the increased interference level respectively; this in turn leads to a decrease in the data rate sustained by each transmission. Temporal mechanisms, on the other hand, such as contention window adaptation for collision resolution exist and methods to maximize the network performance through optimizing the backoff interval selection have been proposed [2], [3].

In this paper, we present a localized, distributed power and rate control scheme through which nodes, in a multihop wireless network, dynamically adjust their transmission power and data rates to eliminate collisions from hidden terminals and enhance the spatial reuse by diminishing the effect of exposed terminals. We assume a four-way handshake access method in our work. We start from the premise that high

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system throughout could be achieved when the area silenced by a sender (e.g., through physical carrier sense) is reduced as much as possible while covering the interference area if its intended receiver [4]. The area silenced by the sender depends on the transmission power and the carrier sense threshold, while the interference range depends on the distance between the sender and the receiver and the SINR threshold. It was however shown in [4] that better spatial reuse may be obtained with smaller silence area and accordingly better system throughput.

In our work, the area silenced by the sender does not need to cover the interference area around the receiver of that frame (as opposed to [4]); rather, the receiver of a frame (e.g., RTS or CTS) would adjust its transmission power (and data rate for the DATA transmission) so that the interference area of its transmission would coincide with the area silenced by the prior transmission of the sender. We adopt both physical and virtual carrier sense in our method; the former to protect the transmission of CTS and ACK frames while both mechanisms are used to protect the transmission of DATA.

The rest of the paper is organized as follows. In Section II, we present an overview of the related work. The background on the communication model adopted is presented in Section III and in section IV we present the concepts for our proposed power and rate control scheme and present different heuristics supported by sound analysis. Section V present the performance evaluation and comparisons of our methods and finally we conclude the work in section VI.

II. Background and Related Work

A number of proposals on transmission power control for optimizing the network capacity exist in the literature. For example, the authors of [5], [6], [7], [8] and [9] studied the problem of topology maintenance, where the objective is to preserve network connectivity, reduce power consumption, and mitigate MAC-level interference. A simple power control MAC protocol that allows nodes to vary transmission power on a per packet basis is presented in [10]; the main idea is to allow nodes to use different power levels for RTS/CTS and DATA/ACK frames. More specifically, a maximum transmission power is used for sending RTS/CTS frames and a lower power level, necessary to communicate, is used for DATA/ACK packets. This protocol is referred to as the *BASIC* protocol and the authors of [10] have pointed out its deficiencies and suggested simple improvements, to resolve some potential collisions, through allowing the DATA packet to be transmitted periodically at maximum power. Nonetheless, as the control packets are always sent at maximum power, the protocol suffers from low spatial reuse.

A power controlled multiple access protocol (*PCMA*) has been proposed in [11]; in *PCMA*, the receiver advertises its tolerable interference margin on an out-of-band channel and the transmitter selects the transmission power that does not disrupt any ongoing transmissions. Similarly, a power controlled dual channel (*PCDC*) MAC that constructs the network topology by overhearing RTS and CTS packets was proposed in [12] and the computed interference was announced on an out of band channel. In [13], the authors proposed a power control method (*POWMAC*) which uses a single channel to exchange the interference margin information. Moreover, in [14], the authors investigated the correlations that exist between the required transmission power of RTS, CTS, DATA and ACK frames to guarantee a successful 4-way handshake. Based on these correlations, they proposed *Core-PC*: a class of correlative power control schemes, and after further simulation performance verifications with other power control schemes from literature, one of schemes was shown to achieve the best performance. The scheme argues that all the packets should be transmitted at the same power value.

The authors of [15] introduced a collision avoidance power control (*CAPC*) MAC protocol to protect the transmission of DATA and ACK packets by appropriately selecting their power values; for example, a DATA packet may be protected if the interference range at its receiver is set equal to the transmission range of the ensued CTS packet. To achieve this, the authors assumed that an interfering node always sends at maximum power to derive the interference range. Similar to *BASIC*, RTS and CTS frames are sent at maximum power and that may impact the spatial reuse in the network. In [16], the authors proposed an energy efficient scheme (MiSer) by jointly controlling both transmit power and PHY transmission rate. They compute offline an optimal rate-power combination table, and then at runtime, a wireless station determines the most energy efficient transmission strategy for each data frame. More recently, the authors of [17] extended the work in [15] and proposed an adaptive range-based power control (*ARPC*) MAC protocol for avoiding collisions and conserving energy consumption. They derived four mechanisms and studied their performances. However in their methods, the RTS (and most of the time CTS) frame is always transmitted at maximum power, which, as mentioned earlier, affects the channel spatial reuse.

Alternatively, one can improve the level of spatial reuse through tuning the CS_{th} and several efforts have been made to either analytically or experimentally evaluate its effect on the system throughput performance. For example, the authors of [18] investigated first the spatial reuse in dense wireless networks and identified the minimum separation distance between two concurrent transmitters so that the best achievable spatial reuse can be obtained. They however did not consider MAC layer overhead in their model. Similarly, the authors of [19] presented an analytical model to derive the optimal sensing threshold given reception power, data rate, and network topology.

The authors of [20] studied the impact of spatial reuse on network capacity and derived the network capacity as a function of both transmission power and CS_{th}. They showed that in the case where discrete data rates are available, tuning the transmission power offers several advantages that tuning CS_{th} cannot, provided there is a sufficient number of power levels available. They also pointed out that in the case the achievable channel rate follows the Shannon capacity, spatial reuse depends only on the ratio of transmission power and CS_{th}. This is contrary to the work of [21] where they showed that transmitters should keep the product of transmission power and CS_{th} fixed at a constant.

III. Communication Model Background

A. Basic framework and definitions

In wireless networks, a receiver is able to receive and correctly decode a packet with received power P_r if and only if two conditions are satisfied:

- The signal to interference noise ratio (SINR) at the receiver side is larger than a predetermined threshold denoted by ζ ; hence, we have the following constraint:

$$P_r \geq \zeta \times (P_n) \tag{1}$$

  where P_n is the total allowed interference power which consists of interference power from interfering nodes and background thermal noise. Here, the value of ζ is determined according to the rate at which a packet is received at the receiver.
- The received power P_r of a frame from a transmitter node with transmission power P_t in its transmission zone should be higher than or equal to κ (the receiver sensitivity). Accordingly, and adopting the two-ray model with antenna heights and gains equal to one, the the transmission range (r_t) is:

$$r_t = (\frac{P_t}{\kappa})^{\frac{1}{4}} \tag{2}$$

  where κ is dependent on the rate the packet is received at the receiver and the higher the rate, the smaller κ is [1]. If the distance between the sender and receiver is equal to r, and according to equation (2) the minimum transmission power P_{min} is equal to $\kappa \cdot r^4$.

Furthermore, a transmitter cannot initiate any communication if it senses a signal with a power level larger than a predefined CS_{th}. Hence, the CS_{th} specifies the signal strength above which a node determines the medium is busy and will not attempt for transmission. Let the Carrier Sense set of a transmitter A (denoted as CS_A) be defined as the set of nodes, if any of them transmits, node A will sense the medium busy [4]. Formally,

$$CS_A = \{A' \mid \frac{P_{A'}}{d^4} \geq CS_{th}\}$$

where d is the distance between the sender A and node A' and $P_{A'}$ is the transmission power of A'. If all nodes use the same transmission power, P_t, then the carrier sense range d_{cs}, defined as the maximum value of d such that the above constraints hold, can be expressed as:

$$d_{cs} = (\frac{P_t}{CS_{th}})^{\frac{1}{4}} \tag{3}$$

Note that, however, if nodes use different power, the carrier sense region (CS_A) will have an arbitrary shape. We further define the Silence set of a transmitter A (denoted as SL_A), assuming fixed CS_{th} for all nodes, as the set of nodes that will detect the channel to be busy if A transmits [4]. Formally:

$$SL_A = \{A' \mid \frac{P_A}{d^4} \geq CS_{th}\}$$

Clearly, $SL_A \equiv CS_A$ if all nodes use the same transmission power. Without loss of generality, we denote r_c as the range of the silence set SL_A.

B. Interference Range

We now define the interference range, r_i, of a node receiving a packet. Consider an ongoing communication between nodes A and B that are r distant apart. If node A transmits with power P_t, node B receives this signal with received power $P_r = \frac{P_t}{r^4}$. Moreover, if we neglect the thermal noise, P_n in equation (1) can be expressed as $P_n = P_{cn} + P_{tn}$. Here, P_{cn} is the current measured interference at node B and P_{tn} is the maximum remaining interference that node B can tolerate while it is still able to decode correctly the packet it receives from node A. Accordingly, and making use of equation (1), we can express P_{tn} as follows:

$$P_{tn} \leq \frac{P_t}{r^4 \cdot \zeta} - P_{cn} \tag{4}$$

Now assume an interfering node F which is d_i meters away from node B initiates a communication with a power P_i while node B is receiving a packet from node A. The received power $P_{ri} = \frac{P_i}{d_i^4}$ at node B from node F should satisfy the condition that $P_{ri} \leq P_{tn}$ such that node B is still able to receive and correctly decode the packet from node A. Accordingly, we define the interference set of a receiver B (denoted as IN_B) as the set of nodes whose transmission, if overlapping with the transmission of A, will cause collision at the receiver. Specifically, if node F transmits,

$$IN_B = \{F \mid \frac{P_i}{d_i^4} \geq \frac{P_t}{r^4 \cdot \zeta} - P_{cn}\} \tag{5}$$

With the condition of the interference set from equation (5), we define the interference range r_i as the maximum value of d_i such that the inequality in equation (5) holds:

$$r_i = \left(\frac{P_i}{\frac{P_t}{r^4 \cdot \zeta} - P_{cn}} \right)^{\frac{1}{4}} \tag{6}$$

Based on the above equation, we can see that both the ζ (whose value depends on rate) and the power value (P_t) of an ensued packet determines the interference range at the receiver.

IV. Distributed Power and Rate Control Scheme

A. Preliminaries

Clearly, the level of spatial reuse plays a key role in determining the capacity of a multihop wireless network [22]. As mentioned earlier, one can increase the level of spatial reuse either through reducing the sender transmission power or increasing the carrier sense threshold. We focus in this work on the former approach and assume a fixed carrier sense threshold. While decreasing the transmit power allows multiple concurrent transmissions to co-exist, a reduced transmission power, however, yields a lower SINR which results from either a weaker received signal or increased interference level [20]. This consequently yields to a lower data rate that is sustained by each transmission, ultimately affecting the system performance. Additionally, a lower transmit power would result in a higher interference range and hence more hidden nodes that may corrupt the transmission between a sender and a receiver. Alternatively, increasing the transmit power enhances the capture effect (SINR) and thus decrease the possibility of collision from hidden terminals. Additionally, with enhanced SINR, a node can use higher rates for transmitting its packets and this would yield to a better throughput. However, larger sender transmission power adversely impacts the spatial reuse by unnecessarily suppressing concurrent communications. Hence, in order to achieve higher level of spatial reuse and thus network throughput, one needs to find a balance between the transmission power and the transmission rate. To achieve this, one can derive analytically the network capacity as a function of both the transmit power and the SINR threshold (hence the transmission rate) [4], [23] and study the interplay among these parameters so that a maximum capacity can be achieved. Instead, in this work, we propose a localized heuristic method for power control from the perspective of collision avoidance. We note first that in [4] the authors observed that a high system throughput can be achieved when the area silenced by a sender is reduced as much as possible under the premise that the interference area of its intended receiver is covered by the silence area. Next, we derive an alternative method for protecting the sender transmissions by appropriately selecting the transmission power and rate while minimizing the exposed terminals. We assume the four-way handshake mode operation of the DCF.

B. Methodologies

Consider a data frame transmission between two nodes A and B. We assume an RTS frame, whose silence range is $r_{c,RTS}$, has been successfully transmitted and we consider first the protection of the CTS packet reception. Here, if the receiver (B) selects a transmission power for its CTS frame such that the interference range at the receiver of the CTS packet (A), $r_{i,CTS}$, coincides with or falls inside the silence range of the RTS, then the CTS frame will be received without corruption. We call this the physical carrier sense (PCS) approach and is shown in Figure 1(a). Here, although nodes C and D lie in the interference range of a CTS packet, they cannot initiate any communication while the CTS is being received because they already lie in the silence range of the RTS packet. Both nodes (C and D) are silenced upon hearing the RTS for an extended inter-frame space (EIFS) [1]. Since EIFS is a sufficient duration for a CTS packet to be received at the transmitter (A), the reception of CTS packet will not be corrupted. A similar approach, as shown in Figure 1(c), is adopted for protecting the ACK packet reception by setting $r_{c,DATA} = r_{i,ACK}$.

On the other hand, the EIFS duration is not sufficient to protect larger DATA frames since the transmission duration (or vulnerable period) may be much longer than EIFS period; accordingly, a different approach is used to protect the transmission of the DATA packet. Namely, we use virtual carrier sense (VCS) in order to protect DATA transmission from hidden nodes; this can effectively be achieved by selecting a transmission power for DATA such that the resulting interference range at the receiver (B) is completely covered by the transmission range, $r_{t,CTS}$, of the ensued CTS frame. Thus, all potential interfering nodes including hidden terminals, lying within the interference range of the DATA packet (say nodes C and D in Figure 1(b)) will be silenced by the CTS packet for the whole duration of the DATA packet transmission.

First, we analyze the minimum power requirements for delivering the CTS packet; let P_{RTS} and P_{CTS} be the transmission power of RTS and CTS packets respectively. The selection of P_{RTS} is presented later in the section. Using equation (6), we can obtain the interference range at the receiver of the CTS packet, $r_{i,CTS} = \left(\frac{P_i}{\frac{P_{CTS}}{r^4 \cdot \zeta_{R,CTS}} - P_{cn}} \right)^{\frac{1}{4}}$. Here, $\zeta_{R,CTS}$ is the SINR threshold when receiving a CTS packet at rate R and P_i is the estimated transmission power of an interfering node. We will explain how to estimate P_i later in the section. Furthermore, from equation (3), we can obtain $r_{c,RTS} = (\frac{P_{RTS}}{\eta})^{\frac{1}{4}}$. Since PCS is applied to control the power of the CTS packet as discussed earlier and shown in Figure 1(a), we choose $r_{i,CTS} \leq r_{c,RTS}$ in order to prevent collisions from hidden nodes (those in the interference range of the receiver of the CTS but outside the transmission range of the RTS frame). Thus, for equality, the lower bound on P_{CTS} can be expressed as:

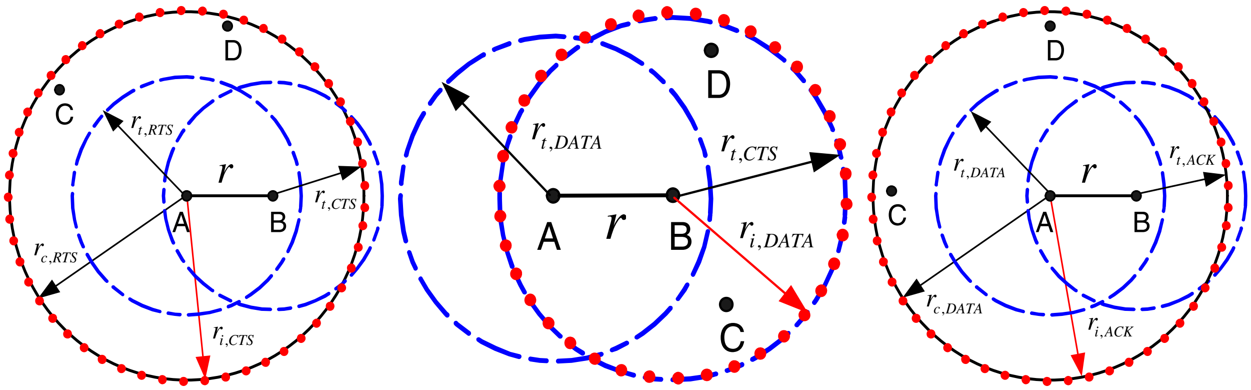
$$P_{CTS,low} = max(P_{min}, (\frac{\eta \cdot P_i}{P_{RTS}} + P_{cn}) \cdot \zeta_{R,CTS} \cdot r^4) \quad (7)$$

where P_{cn} is the current noise measured at the sender node and is encapsulated in the RTS packet.

Now, in order to protect the DATA packet against interference from hidden nodes, we set the interference range of DATA equal to the transmission range of CTS (note, if the vulnerable period is smaller than EIFS, e.g., case of shorter data frames, then PCS may be used). Here, the transmission range of CTS packet can be expressed using equation (2) as $r_{t,CTS} = (\frac{P_{CTS}}{\kappa_{R,CTS}})^{\frac{1}{4}}$, where $\kappa_{R,CTS}$ is the receiver sensitivity of a transmitted CTS at rate R. Moreover, the interference range of the DATA packet is expressed as $r_{i,DATA} = (\frac{P_i}{\frac{P_{DATA}}{r^4 \cdot \zeta_{R,DATA}} - P_{cn}})^{\frac{1}{4}}$. P_{DATA} is the transmission power of the DATA packet and $\zeta_{R,DATA}$ is the SINR threshold requirement when receiving a DATA packet transmitted at rate R_{DATA}. Accordingly, by making $r_{t,CTS} = r_{i,DATA}$, we obtain the following system:

$$P_{DATA} = max(P_{min}, (\frac{\kappa_{R,CTS} \cdot P_i}{P_{CTS}} + P_{cn}) \cdot \zeta_{R,DATA} \cdot r^4) \quad (8a)$$

$$P_{max} \geq P_{CTS} \geq P_{CTS,low} \quad (8b)$$



(a) PCS to protect CTS (b) VCS to protect DATA (c) PCS to protect ACK

Fig. 1. Power Scheme Analysis

where P_{cn} is the current noise measured measured at the receiver upon receiving the CTS packet and $P_{DATA} \leq P_{max}$. Note that, P_{DATA} is a function of P_{CTS} whose value is still unknown. In addition P_{DATA} is dependent on the SINR threshold, $\zeta_{R,DATA}$, whose value depends on the packet transmission rate.

The solution of the above system is a tuple (P_{CTS}, $\zeta_{R,DATA}$,P_{DATA}), and there may exist more than one feasible solution among which we need to select one that yields better performance. Recall that the values of P_{CTS}, $\zeta_{R,DATA}$, and P_{DATA} are selected from a set of discrete power and transmission rate levels available for the node.

In this paper, we consider three alternative approaches for determining P_{DATA}, P_{CTS} and $\zeta_{R,DATA}$:

1) $PRAS-CP_1$: Here, we select $P_{CTS} = P_{CTS,low}$. This selection stems from our understanding that a large P_{CTS} may unnecessarily silence more nodes and hence could severely affect the channel spatial reuse. Accordingly, a set of (P_{DATA}, $\zeta_{R,DATA}$) can be selected to satisfy condition 8(a). In our work, we select the highest possible rate such that $P_{DATA} \leq P_{max}$.
2) $PRAS-CP_2$: We set P_{CTS} = P_{DATA} in equation 8(a), then we solve for P_{DATA}:

$$P_{DATA} = \frac{1}{2}[P_{cn} \cdot \zeta_{R,DATA} \cdot r^4 + ((P_{cn} \cdot \zeta_{R,DATA} \cdot r^4)^2 + 4(\kappa_{R,CTS} \cdot \zeta_{R,DATA} \cdot P_i \cdot r^4))^{\frac{1}{2}}] \quad (9)$$

after which we select the highest data rate such that the constraint $P_{CTS,low} \leq P_{DATA} = P_{CTS} \leq P_{max}$ is satisfied. In this scheme, the data rate that can be supported to transmit the DATA frame is larger than the previous scheme whereas the transmit power for DATA is lower (i.e., better spatial reuse).
3) $PRAS-CP_3$: Here, we set $P_{CTS} = P_{max}$; although a larger P_{CTS} may prevent more nodes from concurrently transmitting (hence impacting the spatial reuse), a larger P_{CTS} implies a smaller P_{DATA} or larger supported transmission data rates. Again, we select the highest possible transmission rate such that $P_{DATA} \leq P_{max}$.

Finally, given that the DATA packet is successfully received, the ACK power value can be derived similar to the way we derived the lower bound for the power of CTS by making $r_{c,DATA} = r_{i,ACK}$ and as shown in Figure 1(c). The power of ACK is expressed as:

$$P_{ACK} = max(P_{min}, (\frac{\eta \cdot P_i}{P_{DATA}} + P_{cn}) \cdot \zeta_{R,ACK} \cdot r^4) \quad (10)$$

where $\zeta_{R,ACK}$ is the SIR threshold for an ACK frame received at rate R. P_{cn} is the measured noise when receiving the CTS packet and it is encapsulated in the DATA packet.

C. P_{RTS} tuning and P_i Estimation

1) RTS Power Tuning: In PRAS, the tuning of the transmission power of an RTS frame is a key design aspect for enhancing the spatial reuse (as the analysis showed earlier). Note that all the power values of other packets should be correlated with the power of RTS packet. Initially, the RTS frame is sent at a maximum power to a destination node. If N_S consecutive RTS packets were sent successfully to the same destination, then the node decreases its RTS power value to the next lower possible power level which is higher or equal to P_{min} when sending to the same destination. Similarly, after N_F consecutive packets reception failures, the power of RTS will be increased by one level ($P_{min} \leq P_{RTS} \leq P_{max}$). Here N_S and N_F are simulation parameters.

2) P_i Estimation: As stated earlier, P_i represents the transmission power of an interfering node F (F is a neighbor, say, to a receiver B); according to Eq. 6, determining P_i is critical for determining the interference range around B. Furthermore, according to PRAS (equations (7)-(10)), P_i is also needed to determine the power assignment of CTS/DATA/ACK frames. Therefore, a heuristic to locally determine the transmission power of a neighboring (interfering) node is needed. We note here that the value of P_i differs from one node to another. For a sender(A)-receiver(B) pair, the receiver maintains an estimate of $P_{i,A}$ ($P_{i,B}$) where $P_{i,A}$ ($P_{i,B}$) represents the transmission power of an interfering node neighbor to A (B). Initially, these values are assigned a value of P_{max} and both values are lower bounded by P_{min}. When B responds to an RTS received from A, it will use the value of $P_{i,A}$ to compute P_{CTS} (Eq.7). Node B will also use the value of $P_{i,B}$ to compute P_{DATA} and the data transmission rate. For every N_{CTS} CTS packets, that a node transmits, and are consecutively received successfully at the sender, $P_{i,A}$ is decreased by a factor of $\alpha \times P_{i,A}$; otherwise, if one frame is lost, $P_{i,A}$ is increased by a factor of $\alpha \times P_{i,A}$ (e.g $\alpha = 0.1$). Note, too, that $P_{i,A}$ is also updated upon the success (loss) of N_{ACK} (one) ACK packets (similar procedure as before). The same methodology applies as well for updating $P_{i,B}$ with N_{DATA} being the consecutive number of successful DATA packets received. Here, N_{CTS}, N_{DATA} and N_{ACK} are all simulation parameters. Note that, whether a CTS or an ACK packet was successfully received at the sender or not is indicated to the receiver through a previously transmitted RTS frame.

D. Network Allocation Vector Adaptation

According to the IEEE 802.11[1], the NAV contained in RTS is equal to $T_{CTS} + SIFS + T_{DATA} + SIFS + T_{ACK} + SIFS$. Here T_{CTS}, T_{DATA} and T_{ACK} are time durations for transmitting CTS, DATA and ACK packets respectively and SIFS is a short inter-frame space. Recall that in our scheme, the transmission rate of DATA packet is decided at the receiver side, and accordingly the transmitter is unable to calculate T_{DATA} since it does not know the transmission rate for the DATA frame when it transmits the RTS packet. To rectify this issue, in PRAS, the NAV contained in RTS is set to $T_{CTS} + 2SIFS$. This is reasonable due to the collision prevention property in PRAS. We elaborate more on this through the example shown in Figure 1(a). Upon transmitting the RTS frame from node A to node B, nodes in A's RTS transmission range will refrain from transmission for a $T_{CTS} + 2SIFS$ period. When node B replies with a CTS, nodes within B's CTS transmission range will update their NAV value to $T_{DATA} + SIFS + T_{ACK} + SIFS$ period. Nodes in A's RTS transmission range but outside node B's CTS transmission range will update their NAV through the information contained in node A's DATA packet.

V. Performance Evaluation

A. Simulation Setup

We use Qualnet [24] to evaluate by simulation the performance of PRAS-CP. Here, PRAS-CP is compared with IEEE 802.11, BASIC, and correlative (case ii,B)[14] and Adaptive [17]. In our simulation, the control channel rate is 2 Mbps and the DATA channel rate varies from 1 Mbps to 11 Mbps. The carrier sensing threshold η is set to -78 dBm. The simulation time is 300 seconds. We use the transmission rate levels of the IEEE 802.11b, which are 11, 5.5, 2 and 1Mbits/s, and the receiver sensitivity (κ) for each rate is -74.37, -70.37, -68.37 and -64.37 dBm respectively. Moreover, the SINR threshold (ζ) for each rate is 15, 11, 9 and 7dB respectively. The set of discrete power values used in this simulation are 1, 5, 10, 14, 18, 22, 24 dbm. Ad hoc on Demand Vector Routing (AODV) is selected as the routing protocol. $N_s = 10$, $N_F = 1$, $N_{DATA} = N_{CTS} = N_{ACK} = 10$. Other parameters such as antenna gains and heights are assumed to be fixed and equals to one, and known to all nodes. In our simulations, we take the following measurements:

- Aggregate Throughput: This counts the total number of the data bytes correctly received by the receivers per time unit
- Effective Data Delivered per Joule: This counts the total number of received data bytes divided by the entire energy consumption
- Collision rate: This counts the total number of observed collisions that involve RTS, CTS, DATA, and ACK packets by all attempted deliveries per second.
- Fairness Index: We adopted Jain's Fairness index in order to measure the bandwidth sharing of the connections. The fairness index is given as $F = \frac{(\sum_{i=1}^{N} \gamma_i)^2}{N \cdot \sum_{i=1}^{N} (\gamma_i)^2}$ where N is the total number of connections and γ_i is the number of received packets for connection i.

Five simulation seeds are used to calculate the average of each metric measurement.

TABLE I
Performance for Chain Topology

Algorithms	Throughput	Energy Efficiency	Collision Rate	Fairness
PRAS-CP1	320.76	11.51	0.24	0.81
PRAS-CP2	436.28	15.69	0.18	0.87
PRAS-CP3	179.70	5.91	0.32	0.75
IEEE 802.11	168.59	4.76	0.24	0.73
Correlative	398.56	13.63	0.22	0.82
BASIC	138.76	2.76	0.4312	0.64
Adaptive	310.24	12.72	0.21	0.79

B. Chain Topology

We first consider a chain topology network consisting of eight nodes. Through this topology, we can address delicately the tradeoff between spatial reuse (exposed terminal problem) and collision probability (Hidden node problem). Here, each node has a single one-hop receiver at distance 50 m for its packets throughout the simulation time, to which a CBR traffic flow with packet size 512 bytes is sent to. The distance between the non-connected nodes is set to 350 m (the transmission range of RTS/CTS is $\simeq$ 353 m). Each node generates a traffic at a rate of 400 packets/second.

Table 1 shows the network throughput in the chain topology for all protocols. As can be viewed from Table 1, the throughput achieved by PRAS-CP2 outperforms slightly the correlative scheme while outperforming by far the other protocols. Recall, in all proposed protocols (also PRAS-CP3) except Correlative, the RTS frames are sent at maximum power, and in most often the CTS frame. Transmitting RTS or CTS at maximum power, although provides a good chance of eliminating the possibility of DATA collisions, nevertheless it increases the possibility of control packet collisions and highly affects the spatial reuse which directly decreases the network throughput as can be seen from Table 1. In PRAS-CP1, transmitting CTS at the minimum required power leaves some hidden nodes uncovered and may corrupt the transmission of the DATA packet during the vulnerable period. Recall that P_{DATA} is bounded by P_{max}); hence, the interference area (at the receiver of the DATA frame) resulting for the minimum selected rate may not be completely covered by the transmission range of the CTS packet. The traffic load of 400 packets/sec is considered high and thus the IEEE 802.11 starts to show its limitations in sharing the channel in the time domain. On the other hand, as stated previously, BASIC suffers from collisions from hidden nodes and low spatial reuse which has a high effect on its final throughput. This can be verified by the overall collision probability shown in Table 1. Tuning the power of the RTS packet has definitely enhanced spatial reuse for PRAS-CP2 and Correlative. Furthermore, assigning the CTS power value to be equal to that of DATA and tuning the DATA rate to oblige the power constraint of the CTS and DATA packets to be less than RTS packet has caused interference suppression. This is why PRAS-CP2 achieved better throughput than Correlative.

By evaluating the energy efficiency achieved by all protocols, we an see that PRAS-CP2 achieved the best results among all protocols (this is shown in Table 1). In IEEE 802.11, all packets are transmitted at maximum power which results in unnecessary wate of energy. For BASIC scheme, the collision probability dominates the network energy consumption; in another words, the higher the collision probability is, the more energy is consumed in retransmission of packets. For Adaptive, RTS and most of the times CTS is transmitted at maximum power, thus energy consumption in these schemes is due to control packets transmissions and retransmissions.

Finally, the best Fairness Index in this scenario is achieved by nodes implementing PRAS-CP2 as shown in Table 1. An explanation for this is that PRAS-CP mechanism enhances spatial reuse by decreasing the number of exposed terminals. Here the exposed terminal problem is one of the main causes of unfairness in the IEEE 802.11 standard implementation. Adaptive by transmitting the RTS or CTS packets at maximum power suffers from fairness due to the exposed terminal. It was verified by simulation that at least 5 CBR flows were concurrently occurring when implementing PRAS-CP2, where in IEEE 802.11 on average there was 2 CBR flows, Correlative 4 CBR flows, Adaptive 4 CBR flows, BASIC 2 CBR Flows. Without loss of generality, we will use PRAS-CP2 in the other topology and refer to it as PRAS-CP.

C. Random Topology

Here, the network topology consists of 100 nodes randomly distributed into a 1000×1000 m^2 area with multi-hop CBR flows of packet size 1000 bytes are set between randomly chosen end-to-end source destination pairs.

1) Impact of Network Load: We consider varying the packet sending rate of the CBR flows. The number of multihop CBR flows is set to 10. Here, the rate varies from 200 to 1000 packets per second. Figure 2 shows the network throughput obtained by all protocols for source data rates of 200, 400,

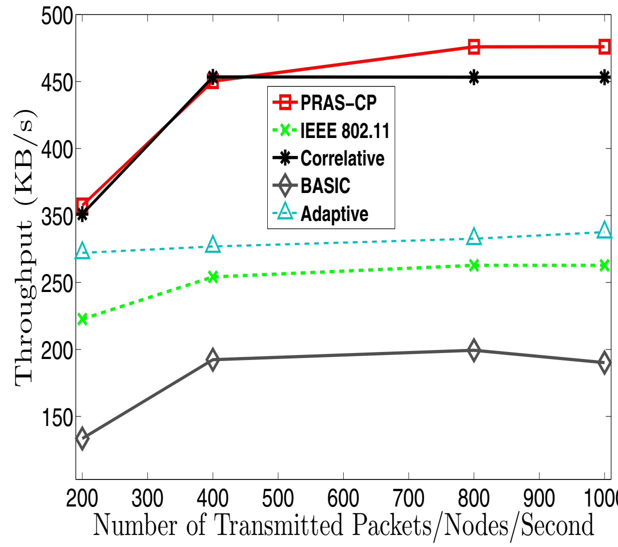


Fig. 2. Throughput vs packet load

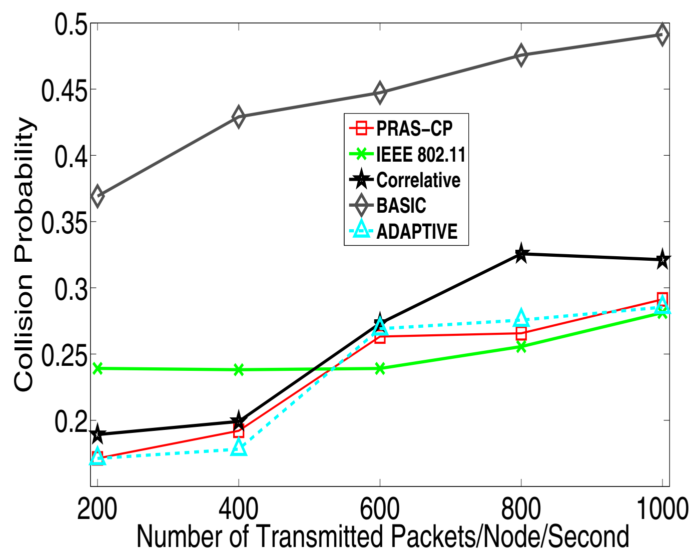


Fig. 3. Collision Probability vs packet load

800, 1000 packets/second respectively. As can be viewed from Figure 2, the throughput achieved by PRAS-CP outperforms the throughput of other schemes for all traffic loads. When the traffic generation rate is low (200 and 400 packets/second) PRAS-CP and Correlative achieves similar throughput results, while the throughput achieved by PRAS-CP is better than the throughput achieved by Correlative under heavy traffic(800 and 1000 packets/second). The effectiveness of DATA rate selection gives PRAS-CP its superior performance over Correlative. IEEE 802.11 showed throughput limitations for two main reasons: high rate of RTS collision and low spatial reuse (exposed terminal problem) since all packets are sent at maximum power. When traffic load increases (400, 800, 1000

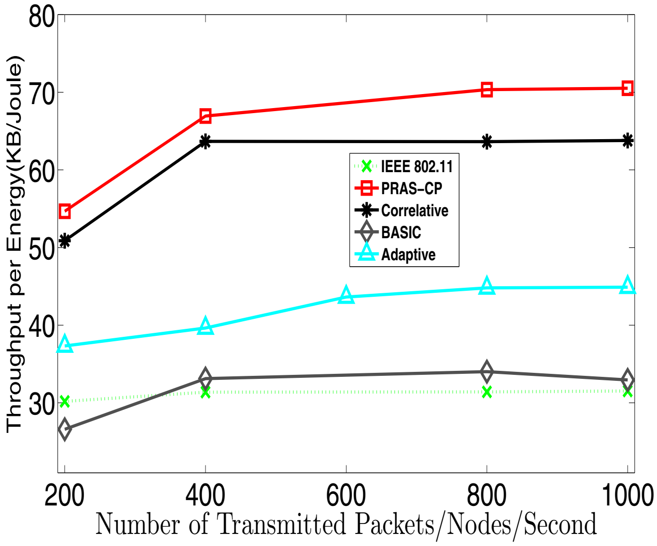


Fig. 4. Energy Efficiency vs packet load

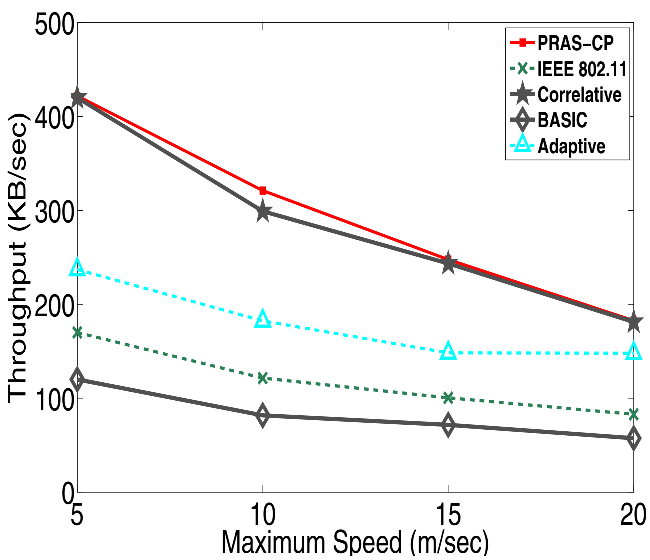


Fig. 5. Throughput vs mobility

packets/second), more nodes will contend to win the channel, thus the collision rate for the RTS packet increases which affects the overall collision rate as can be verified in Figure 3. BASIC suffers severely from hidden nodes; in BASIC, DATA and ACK packets are sent at the minimum required power whereas the RTS/CTS of other communicating nodes are sent at maximum power. This increases the interference range of the DATA/ACK packet receiver and thus the probability of the DATA/ACK collision which can be verified from Figure 3. Moreover, transmitting the RTS/CTS at maximum power will unnecessarily suppress neighbors communication and decrease the throughput. Adaptive shows better throughput that IEEE 802.11 and BASIC due to the fact that DATA and ACK are well protected in these schemes, nevertheless the RTS and most of the instances the CTS packet is sent at maximum power which has reduced the spatial reuse. Moreover, the assignment of the DATA power value in Adaptive is done on the assumption that the interfering node always transmits at maximum power, which may not be true in random power-aware topology. Hence, the power value assigned to the DATA packet will be more than the sufficient power to protect its reception and thus this highly impact the spatial reuse. This is why these protocols achieves less throughput than PRAS-CP and Correlative.

Figure 4 depicts the energy efficiency in Kbps/Joules per traffic load. As the load increases, more packets are transmitted and accordingly the throughput increases and the energy consumption increases. Here, BASIC suffers from hidden terminals; nevertheless, the energy consumed is shown to be less than the IEEE 802.11 in this scenario due to the minimum power assigned to the DATA packet, which makes its achieved energy efficiency slightly outperforms that of the IEEE 802.11 as traffic load increases. In addition to the reasons stated for energy consumption for the chain topology regarding the performance of all the mentioned protocols, it is worth to mention that the reduction in the mutual interference in a multihop environment makes it feasible for nodes to deliver packets efficiently. As the load increases, more packets tend to be transmitted aggressively, reducing the mutual interference resulting from sending either the control or DATA packets in this case will definitely reduce energy consumption and enhance spatial reuse. Thus, PRAS-CP ought to achieve the higher energy efficiency in this scenario, since PRAS-CP reduces mutual interference through setting constraints on the packets power values.

2) Impact of Node Mobility: We study the effect of node mobility on throughput in this subsection. The mobility model adopted is the Random Way Point model. The node's maximum speed is varied from 5 meters per second to 20 meters per sec. The packet rate is 400 packets per second and the number of multihop CBR flows is 10. We can see from Figure 5 that mobility impact the aggregate throughput. With the mobility, the source and receiver nodes may not be able to communicate with each other due to the reason that either one of them will be out of range of the other. This may trigger link failures that may occur frequently due to disconnection of adjacent nodes in a route. Routing table entries thus may get stale due to node mobility and may require updating. This will add more congestion on the network. This is the reason why for all protocols, the throughput becomes low when mobility increases.

VI. Conclusion and Future Work

In this paper, we proposed a distributed transmission power and rate adaptive control scheme with collision prevention (PRAS-CP) for mobile ad hoc networks. Both the transmitter and receiver in MANET environment make use of the PCS and VCS mechanisms to protect the transmission of control and DATA packets. PRAS-CP dynamically adapts transmission power of control and DATA packets. Moreover, PRAS-CP also dynamically adjusts transmission rate for DATA packet depending on channel condition. Thus, PRAS-CP balances spatial reuse and collision prevention. It has been shown by simulation that the proposed power control scheme is efficient in terms of throughput, energy consumption and fairness. We have compared our PRAS-CP with the IEEE 802.11, BASIC [10], Correlative [14], and Adaptive [17]. Verification of the simulation results with real-life scenario implementation will be a target future work.

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