Improved Cross-Layer Cooperative MAC Protocol for Wireless Ad hoc Networks

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***Abstract*—This paper considers the design of a cross-layer medium access control (MAC) protocol for wireless ad hoc cooperative networks. Specifically, we redesign the message exchange process of the MAC protocol previously proposed by Shan et al. By using a HRP signal with shorter length the proposed protocol can reduce the protocol overhead and thus improve the transmission reliability. We also propose to use only one HRP signal to resolve the collision among the helpers with the same cooperative rate. The proposed protocol achieves higher path throughput and lower end-to-end packet latency compared with that by Shan et al. and the traditional IEEE 802.11 MAC protocol.**

I. INTRODUCTION

Wireless ad hoc networks are increasingly deployed for various applications. This wide application requires ad hoc networks to support different types of service ranging from slow-rate data transmission to multimedia and real-time services. An effective solution to this problem is to use cooperative communications as it can exploit the spatial diversity from relaying paths via relaying nodes to increase the transmission reliability, enhance the network throughput, as well as reduce the transmission latency. The cooperation between network nodes can be done at the physical and/or medium access control (MAC) layer, and even higher layers.

Using cooperation between network nodes can create a virtual distributed antenna array which offers spatial diversity gain like the space-time multiple input multiple output (MIMO) systems [1]–[4]. For example, with the help of a cooperative node the distributed Alamouti space-time coding scheme can achieve diversity order two when the channel state information (CSI) is perfectly estimated [2]–[3]. Due to its simple design, this scheme was adopted as the transmission scheme in a number of cross-layer designs for cooperative wireless networks. In references [5]–[11] the authors proposed several cooperative MAC protocols to enhance network throughput over the traditional IEEE 802.11 MAC protocol. However, these proposed protocols still encounter high possibility of errors since the source only selects either direct path to the destination or the relaying path via a neighboring node (often referred to as the helper) to forward its data to the destination.

The CoopMAC protocol proposed by in [5] uses the so-called CoopTable to determine a best helper to relay data from the source to the destination. This method is not suitable for ad hoc networks with high mobility nodes. Although the relaying path in the CoopMAC protocol can provide higher throughput, it does not improve the probability of packet success since the effects of fading on the source-to-helper and the helper-to-destination links are independent. Unlike the CoopMAC, the UtdMAC protocol in [6] achieves a higher probability of packet success due to the backup relaying path, but has lower data rate depending on the source-destination distance. The cooperative MAC protocol proposed in [7] uses a distributed algorithm to select the best helper, and thus is suitable for mobile wireless networks. However, in this protocol neighboring nodes with low rate transmission capability can also unnecessarily participate in the contending process, leading to wasted network resource. Different from the above protocols, the BTAC protocol in [8] uses a busy tone signal of short length for the helper to inform the source about its availability. This protocol can reduce the overhead of exchanging control frames between the helper and the source. The IrcMAC protocol recently proposed by Khalid in [10] monitors the instantaneous signal-to-noise rate (SNR) during the RTS/CTS handshake process to select the best transmission path via a helper, and thus is suitable for varying channel conditions. Similarly, the authors of [11] considered the reliability of the RCO-MAC protocol under the bad channel condition. This protocol was shown to achieve good throughput even under bad channel condition thanks to the cross-layer design approach.

The cross-layer cooperative MAC protocols in [12]–[14] have advantages in achieving both higher diversity gain and system throughput. The MAC-PHY cross-layer protocol in [12] is developed based on the MAC scheme of the CoopMAC protocol in [5] and uses cooperative diversity for improving the SNR level at the destination. Unlike the work in [12], the CD-MAC protocol in [13] uses the distributed space-time block coding (DSTBC) scheme to increase the received signal quality. In addition, this protocol can reduce the network overhead as it does not need to use additional control frames for selecting a helper. In general, both protocols in [12] and [13] are not flexible for selecting the best helper in the varying channel conditions. The helper collision is also not yet resolved effectively. Considering both the system throughput and the transmission reliability, the cross-layer MAC cooperative protocol in [14] uses the Alamouti DSTBC scheme and a MAC protocol which can resolve the optimal helper selection problem. The main idea of this protocol is to use an optimized clustering algorithm of potential cooperative rates. In order to solve better the conflict among helpers, the protocol uses a simple strategy that lets collided helper candidates re-contend once in K mini-slots after their unsuccessful transmission of a ready-to-help (RTH) frame. However, this protocol still lacks some important considerations. First, when there is more than one

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optimal helper having the same cooperative rate, the protocol needs 2 RTH frames, leading to the overhead increase and the decreased system throughput. Second, if the contention in K mini-slots is unsuccessful, the protocol automatically switches to the direct transmission mode. Therefore, the overhead time for contending also increases significantly and the protocol is not effective. Third, under practical fading channels, erroneous RTH frames can be confused with the helper collision leading to additional contending process or automatic switching to the direct transmission mode.

In this paper, we propose an improved cross-layer cooperative MAC protocol based on that in [14]. Our idea is to simplify the signal message exchange process to reduce the protocol overhead. Specifically, instead of using a control frame such as the RTH frame in [14] to inform the source, we use a helper response pulse (HRP) signal with shorter length (up to two mini-slots in IEEE 802.11 DCF). Compared with the previous one, our protocol has the following advantages:

- The shortened length of the HRP signal helps to reduce the protocol overhead, and thus improves the path throughput.
- The HRP signal with shorter length is transmitted more reliably over erroneous channels leading to higher cooperative opportunity.
- In our protocol, only one HRP signal is used at the kth randomly picked up mini-slot to inform the source even if there are more than one optimal helper. This design allows the protocol to switch from the unsuccessful cooperative mode to the direct transmission faster.

Our main contributions can be summarized as follows:

- A cross-layer cooperative MAC protocol with improved mean path throughput and reduced end-to-end latency is introduced for wireless ad hoc networks.
- Detailed mathematical analysis of the network performance in terms of mean path throughput and end-to-end latency is presented for both the case of error-free and erroneous channel. Simulation results are also used to verify the analytical results.

The remainder of the paper is organized as follows. Sect. II presents the network model under consideration. The proposed protocol is introduced in Sect. III, followed by performance analysis in Sect. IV. Simulation and numerical results are shown in Sect. V. Finally, conclusions are drawn in Sect. VI.

II. NETWORK MODEL

We consider an ad hoc wireless network consisting of a source (S) and a destination (D) placed apart at a distance of d. The network is surrounded by neighboring nodes commonly known as helpers (H) randomly distributed in a circular area with diameter d as illustrated in Fig. 1. Without loss of generality, we assume that all network nodes, including the source, the helper and the destination, can communicate with one another at the basic rate of R_o =2 Mbps and have limited transmit power. It is also assumed that the source can cooperate with one of the helpers H_n to transmit its data to the destination. The channels between each node pair are assumed independent and identically distributed (i.i.d.) and affected by slowly varying flat Rayleigh fading with log-normal shadowing.

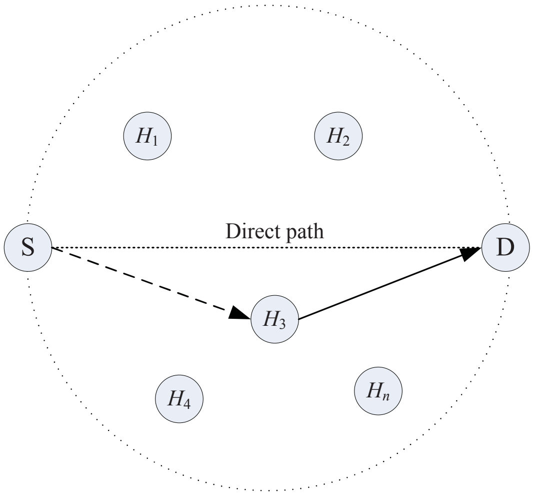

Fig. 1. System model of an ad hoc cooperative network.

A. MAC Layer Operation

The cooperative MAC protocol that we consider is designed based on the distributed coordination function (DCF) of the IEEE 802.11 standard. In order to improve the network throughput, we can either improve the effectiveness of channel access or improve the link utilization during transmission. In this paper, we will focus on the latter. By definition, the link utilization is in fact the ratio of the effective payload transmission rate (EPTR) over the MAC layer protocol overhead. Denote W, T_p and T_o the payload length of a data frame, the payload transmission time, and the overhead transmission time, respectively. The link utilization is then given by:

$$\mathrm{EPTR} = \frac{W}{T_p + T_o}. \quad (1)$$

It is obvious that in order to improve the link utilization, we should design a MAC layer protocol and use an effective physical layer transmission scheme to minimize the transmission times T_o and/or T_p.

B. Physical Layer Operation

The physical-layer transmission scheme is done in either direct transmission mode or cooperative mode via a helper. When cooperation is used the transmission occurs in two phases. During the first phase, the source broadcasts its frame to the optimal helper and destination node at the transmission rate $R_{c1} \in \mathfrak{R} = \{r_1, r_2, ..., r_Q\}$, where $\mathfrak{R}$ is a set of transmission rates obtained using an suitable adaptive coding and modulation scheme, $r_i < r_j$ if $i < j$. In the second phase, the optimal helper cooperates with the source to transmit its received information symbols to the destination at the transmission rate $R_{c2} \in \mathfrak{R}$. This cooperative mode can be implemented by using the distributed Alamouti space-time coding scheme as presented in [2]–[4]. Each node is assumed to use a specific transmission rate estimated from the minimum achievable SNR to send its data.

III. PROPOSED COOPERATIVE MAC PROTOCOL

A. *Protocol Description*

Fig. 2 illustrates the operation of our proposed cooperative MAC protocol which is modified from that in [14]. The working principle of the protocol is described as follows.

1) Source Initiation: After a backoff interval, the source establishes the connection with the destination by broadcasting the request-to-send (RTS) frame at the rate R_o.

2) Destination Response: Upon receiving the RTS frame correctly, the destination replies the source with the clear-to-send (CTS) control frame at the same rate R_o.

3) Helper Selection: Based on the overheard RTS and CTS control frame, each neighboring helper can estimate the channel status information (CSI) between it and the source and the destination. Using the obtained CSI the helpers can determine their cooperative rates from the cooperative region as defined in [14]. Next, the optimal helper with group index g and member index m sequentially sends its following indication signals to contend for the channel: (i) the helper indication (HI) to inform the existence of a helper candidate; (ii) the group indication (GI) and the member indication (MI) signal to inform the source and other helper candidates its priority order; and finally (iii) our proposed HRP signal in the k-th time slot to express its willing to forward data to the destination. Upon completion of the contention, the source will receive an HRP signal from an optimal helper successfully.

4) Transmission Mode Selection: If there is no HI signal detected by the source, it will initiate the direct transmission mode after an HI interval. In contrast, if the HI signal is detected, the cooperative transmission mode will be started. In the cooperative transmission mode, if the source node receives the HRP signal from the helper node, it broadcasts its data frame to both the helper and the destination at the rate R_{sh} during the first phase. During the next phase, the optimal helper decodes the data received from the source and cooperates with the source to transmit the data encoded using the Alamouti STBC to the destination. If there is no HRP signal received, the source sends its data frame directly to the destination.

5) Destination Acknowledgement: Upon successful reception of the data frame, the destination sends an ACK frame after an SIFS interval.

In our proposed protocol we use the HRP signal with the length equal to two mini-time slots. This signal length is enough for estimating the mean SNR of the link between the helper and the source. The CSI for calculating the cooperative transmission rate at the helper includes the payload length W, the direct data transmission rate R_{sd} from the source to the destination, the data rate from the source to the helper R_{sh}, and the data rate R_{hd} from the helper to the destination. The destination calculates the rate R_{sd} by estimating the mean SNR value from the received RTS frame. It then inserts this rate information in the Address 4 field of the CTS frame. The helper calculates W, R_{sh}, R_{hd} and R_{sd} by estimating the mean SNR values from the RTS and CTS control frames. In addition, in order to send the data frames, the source also needs to calculate the rates R_{sh} and R_{sd} by estimating the mean SNR from the HRP signal and the CTS frame, respectively.

We denote the equivalent cooperative transmission rate (ECTR) by R_h to represent the payload transmission rate from the source to the destination. With the repetition-based two phase cooperation scheme, the rate R_h is given by

$$R_h = \frac{W}{\frac{W}{R_{c1}} + \frac{W}{R_{c2}}} = \frac{R_{c1}R_{c2}}{R_{c1} + R_{c2}}. \qquad (2)$$

Given the payload length W and the direct transmission rate R_1, let M denote the number of ECTRs generated from the network and each of them labelled by $R_h^*(i), i = 1, 2, ..., M$. In order to facilitate helper selection, we sort these M rates in a descending order and partition them into G groups, each with $n_g \geq 1$ members as in [14]. There are two types of contention among the helpers, namely, inter-group contention and intra-group contention. In the inter-group contention, a helper candidate in the g-th group waits for an interval of $T_{fb1}(g)$ and then sends a GI signal if it does not overhear any GI from higher rate groups, where $T_{fb1}(g) = (g-1)t_{fb}, 1 \leq g \leq G$, and t_{fb} is referred to as the back-off slot time. According to this procedure, only members of the highest rate group will contend with each other. In the intra-group contention, if a helper candidate with group index g and member index m overhears no member indication (MI) signal, it sends its MI signal after $T_{fb2}(g, m) = (m-1)t_{fb}, 1 \leq m \leq n_g$. Thus, the helper that supports the highest rate R_h can be selected in a distributed manner and its EPTR is guaranteed to be larger than that of any other nodes failed in the helper contention. To solve the conflict among helpers better, we modify the approach proposed in [14] by letting the optimal helper send its HRP signal immediately in a randomly selected k-th time slot from the K minislots after the MI signal. The number of minislots K can be various from 15 to 20 time slots. The time duration of K minislots plus the HRP interval is approximately equal to the interval of one RTH frame in [14]. It is worth noting that in the case there exists more than one optimal helper the protocol in [14] requires two RTH frames for resolving the conflict among optimal helpers. This leads to significantly increased overhead time compared to our protocol. Obviously, in that case our protocol will outperform the protocol in [14].

IV. PERFORMANCE ANALYSIS

A. *Payload and Overhead Transmission Time Analysis*

1) Case 1-Direct Transmission: After the source has received the CTS frame it sends a data frame to the destination via the direct path without using cooperation. The transmission time of the payload and overhead are given respectively by: $T_{1,p} = \frac{W}{R_1}$ and $T_{1,o} = T_{\text{RTS}} + T_{\text{CTS}} + T_{d,o} + T_{\text{ACK}} + 4T_{\text{SIFS}} + 4t_{\text{prop}}$, where T_{RTS}, T_{CTS}, T_{ACK} are the transmission time of the RTS, CTS, ACK control frame; $T_{d,o}$ is the transmission time of the data frame overhead; T_{SIFS} is the SIFS interval; and t_{prop} is the propagation time.

2) Case 2-Cooperation Without Collision: Upon receiving an HI from neighboring helpers, the source waits for GI, MI contention signals, and then the HRP signal from an optimal helper. If there is only one optimal helper, there will be no collision. As a result, the payload transmission time is given

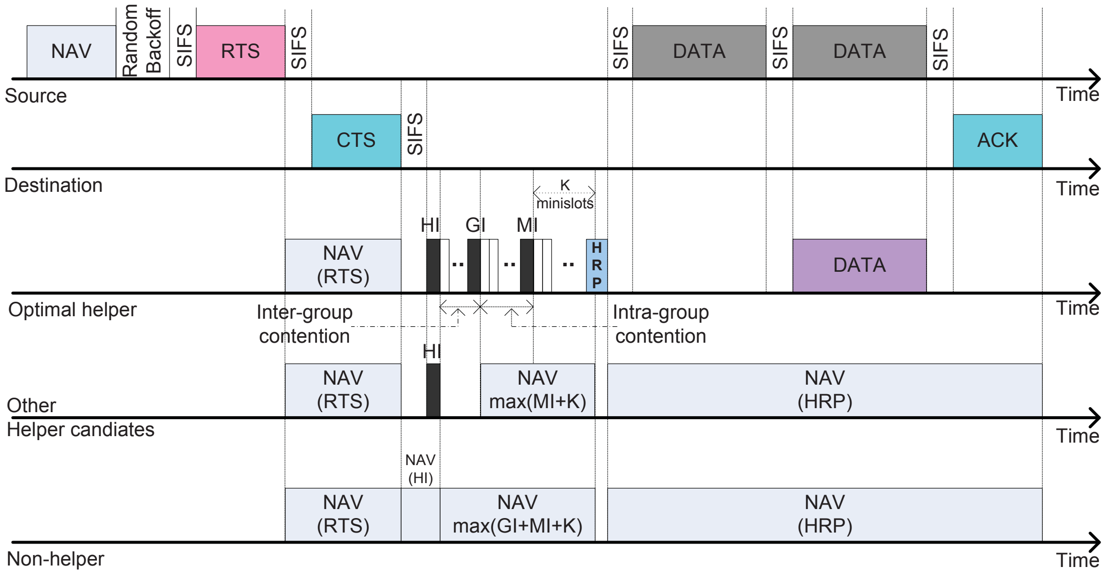

Fig. 2. Proposed cooperative MAC protocol.

by $T_{2,p} = \frac{W}{R_{c1}} + \frac{W}{R_{c2}} = \frac{W}{R_h}$ and the transmission time of the overhead is $T_{2,o}(g,m,k) = T_{1,o} + T_{\mathrm{HI}} + T_{\mathrm{fb1}}(g) + T_{\mathrm{GI}} + T_{\mathrm{fb2}}(g,m) + T_{\mathrm{MI}} + k \cdot t_{\mathrm{fb}} + T_{\mathrm{HRP}} + T_{d,o} + 2T_{\mathrm{SIFS}} + 2t_{\mathrm{prop}}$, where k is the index of the time slot randomly selected in K minislots; T_{GI}, T_{MI} are respectively the transmission time of the GI and MI signal. The probability that an optimal helper selects the k-th time slot is $P_k = \frac{1}{K}$.

3) Case 3-Cooperation With Optimal Helper Contention: When there exists more than one optimal helper supporting the same cooperative rate, it is possible to mitigate the collision problem by utilizing the minislot contention as soon as after the MI signal is transmitted. In this case, the payload and overhead transmission time are calculated similar to Case 2, i.e., $T_{3,p} = T_{2,p}, T_{3,o} = T_{2,o}$. However, given K mini-slots, the probability that one of n optimal helpers wins the contention to choose the k-th mini-slot is given by [14]:

$$P_w(n,k) = \begin{cases} \frac{n(K-k)^{n-1}}{K^n}, & k = 1,\ 2,\ \cdots,\ K-1 \\ 0, & k = K \end{cases} \tag{3}$$

4) Case 4-Unsuccessful Cooperation: If the source did not receive any HRP signal (possibly due to collisions), it sends the data frame to the destination via the direct path. Thus, the payload transmission time is given by $T_{4,p} = T_{1,p}$. The overhead transmission time is now given by $T_{4,o} = T_{1,o} + T_{\mathrm{HI}} + T_{fb1}(g) + T_{\mathrm{GI}} + T_{fb2}(g,m) + T_{\mathrm{MI}} + k \cdot t_{fb} + T_{\mathrm{SIFS}}$. With n optimal helpers contending in the K minislots, the probability that the contention fails due to more than one optimal helper selecting the same k-th minislot is given by [14]:

$$P_f(n,k) = \begin{cases} \sum_{i=2}^{n} \binom{n}{i} \frac{1}{K^i} \left(\frac{K-k}{K}\right)^{n-i}, & k = 1, \ldots, K-1 \\ \frac{1}{K^n}, & k = K \end{cases} \tag{4}$$

B. Throughput Under Error-Free Transmission

Based on the above analysis, we can determine the protocol parameters for maximizing the path throughput by solving parameters K, M and G, the payload length W, and the average number n of collided helpers. The optimization problem for the maximum mean throughput is formulated as follows

$$\begin{aligned} &\max J(n) \\ &\text{s.t. } J(n) > \frac{\rho W}{T_{1,P} + T_{1,O}} \end{aligned} \tag{5}$$

where

$$J(n) = \begin{cases} \sum_{k=1}^{K} \frac{W P_k}{T_{2,P} + T_{2,O}}, & n = 1 \\ \sum_{k=1}^{K} \left(\frac{W P_w(n,k)}{T_{3,P} + T_{3,O}} + \frac{W P_f(n,k)}{T_{4,P} + T_{4,O}} \right), & n \geq 2 \end{cases} \tag{6}$$

is the EPTR when a single optimal helper supports a ECTR with group ID g and member ID m, or the average EPTR when n collided optimal helpers supporting this same rate contend over K minislots.

C. Throughput Under Erroneous Transmission

In order to analyze the achieved throughput we denote the bit error probability of the link between the source and the destination, the source and the helper, and between the helper and the destination respectively by P_b, P_{b1}, and P_{b2}. With the distributed Alamouti STBC, the error probability depends on all the links over the path to the destination. Let P_b^c be the cooperative transmission error probability. Then, P_b^c is a function of P_b, P_{b1}, and P_{b2}. The upper bound of the received SNR at the destination is [14]: $\gamma_c = \gamma_{hd} + 2\gamma_{sd}$, where γ_{sd} is the mean SNR of the link between the source and the destination node and γ_{hd} is that of the link between the helper and the destination. Denote by $P_{e_1}^c$, $P_{e_2}^c$, $P_{e_3}^c$, $P_{e_4}^c$ the error probability of RTS, CTS, DATA, and ACK frame, respectively. Then we have:

$$\begin{aligned}
P_{e_1}^c &= 1-(1-P_b)^{L_{\mathrm{RTS}}} && (7)\\
P_{e_2}^c &= (1-P_b)^{L_{\mathrm{RTS}}}\left[1-(1-P_b)^{L_{\mathrm{CTS}}}\right] && (8)\\
P_{e_3}^c &= (1-P_b)^{L_{\mathrm{RTS}}+L_{\mathrm{CTS}}}\left[1-(1-P_b^c)^{L_{\mathrm{DATA}}}\right] && (9)\\
P_{e_4}^c &= (1-P_b)^{L_{\mathrm{RTS}}+L_{\mathrm{CTS}}}(1-P_b^c)^{L_{\mathrm{DATA}}} && (10)\\
&\quad\times\left[1-(1-P_b)^{L_{\mathrm{ACK}}}\right] && (11)
\end{aligned}$$

where L_{RTS}, L_{CTS}, L_{DATA}, L_{ACK} is the length of the RTS, CTS, DATA and ACK frame, respectively. Now the probability of frame transmission error in case of cooperative communication is given by

$$P_e^c = \sum_{j=1}^{4} P_{e_j}^c. \quad (12)$$

The probability of successful frame transmission for the cooperative transmission mode is given by

$$P_s^c = 1-P_e^c = 1-\sum_{j=1}^{4} P_{e_j}^c. \quad (13)$$

The time duration corresponding to the above four cases can be given by

$$\begin{aligned}
T_{e_1}^c &= T_{\mathrm{RTS}}+T_{\mathrm{CTS}}+2T_{\mathrm{SIFS}}+2t_{\mathrm{prop}} && (14)\\
T_{e_2}^c &= T_{\mathrm{RTS}}+T_{\mathrm{CTS}}+2T_{\mathrm{SIFS}}+2t_{\mathrm{prop}} && (15)\\
T_{e_3}^c &= T_{\mathrm{RTS}}+T_{\mathrm{CTS}}+T_{\mathrm{cont}}+T_{\mathrm{HRP}}+\frac{L_{\mathrm{DATA}}}{R_h}\\
&\quad+T_{\mathrm{ACK}}+5T_{\mathrm{SIFS}}+5t_{\mathrm{prop}} && (16)\\
T_{e_4}^c &= T_{e_3}^c && (17)
\end{aligned}$$

where $T_{\mathrm{cont}} = T_{\mathrm{HI}}+T_{fb1}(g)+T_{\mathrm{GI}}+T_{fb2}(g,m)+T_{\mathrm{MI}}+k\cdot t_{fb}$; R_h, T_{HRP}, and t_{prop} are the cooperative transmission rate, the transmission time of the HRP signal, and the propagation time, respectively; k is the index of the time slot selected randomly. The average retransmission time due to error is given by

$$\mathrm{E}[T_e^c] = \sum_{j=1}^{4} P_{ej}^c T_{ej}^c. \quad (18)$$

Similar to the cooperative mode, in the direct mode, we denote the probability of frame error for RTS, CTS, DATA, and ACK frames by P_{e1}^d, P_{e2}^d, P_{e3}^d, P_{e4}^d, respectively. These probabilities are given by

$$\begin{aligned}
P_{e_1}^d &= 1-(1-P_b)^{L_{\mathrm{RTS}}} && (19)\\
P_{e_2}^d &= (1-P_b)^{L_{\mathrm{RTS}}}\left[1-(1-P_b)^{L_{\mathrm{CTS}}}\right] && (20)\\
P_{e_3}^d &= (1-P_b)^{L_{\mathrm{RTS}}+L_{\mathrm{CTS}}}\left[1-(1-P_b)^{L_{\mathrm{DATA}}}\right] && (21)\\
P_{e_4}^d &= (1-P_b)^{L_{\mathrm{RTS}}+L_{\mathrm{CTS}}+L_{\mathrm{DATA}}}\left[1-(1-P_b)^{L_{\mathrm{ACK}}}\right]. && (22)
\end{aligned}$$

As a result, the probability of frame error in the direction path is given by

$$P_e^d = \sum_{j=1}^{4} P_{e_j}^d. \quad (23)$$

The probability of correct transmission in this case is given by

$$P_s^d = 1-P_e^d. \quad (24)$$

The time duration corresponding to the 4 cases in the direct mode is given respectively by

$$\begin{aligned}
T_{e1}^d &= T_{\mathrm{RTS}}+T_{\mathrm{CTS}}+2T_{\mathrm{SIFS}}+2t_{\mathrm{prop}} && (25)\\
T_{e2}^d &= T_{\mathrm{RTS}}+T_{\mathrm{CTS}}+2T_{\mathrm{SIFS}}+2t_{\mathrm{prop}}\\
T_{e3}^d &= T_{\mathrm{RTS}}+T_{\mathrm{CTS}}+\frac{L_{\mathrm{DATA}}}{R_1}+T_{\mathrm{ACK}}\\
&\quad+4\mathrm{SIFS}+4t_{\mathrm{prop}} && (26)\\
T_{e4}^d &= T_{e3}^d. && (27)
\end{aligned}$$

The average delay due to retransmission in the direct mode is the given by

$$\mathrm{E}[T_e^d] = \sum_{j=1}^{4} P_{ej}^d T_{ej}^d. \quad (28)$$

In case of erroneous channel, the expression of $J(n)$ can be rewritten as follows

$$J(n) = \begin{cases} \displaystyle\sum_{k=1}^{K} \frac{P_s^c W P_k}{P_s^c(T_{2,P}+T_{2,O})+\mathrm{E}[T_e^c]}, & n=1\\ \displaystyle\sum_{k=1}^{K}\left(\frac{P_s^c W P_w(n,k)}{P_s^c(T_{3,P}+T_{3,O})+\mathrm{E}[T_e^c]}\right. & \\ \displaystyle\quad\left.+\frac{P_s^d W P_f(n,k)}{P_s^d(T_{4,P}+T_{4,O})+E[T_e^d]}\right), & n\geq 2 \end{cases} \quad (29)$$

V. SIMULATION AND NUMERICAL RESULTS

In this section, we evaluate the performance of the proposed protocol using computer simulation and numerical calculation. The network topology is created as in Fig. 1 with 20 helpers distributed randomly between the source and the destination. The link between any pair of nodes is affected by slowly varying flat Rayleigh with the log-normal shadowing. The data transmission rate is calculated based on the mean SNR value at the receiving node (the helper and the destination). The data payload length is $W = 2000$ bytes, the number of the minislot is equal to $K = 20$ and the payload balance factor $\rho = 1$. In addition, we also adopt the distributed Alamouti space-time coding scheme with the decode and forward (DF) protocol for transmission at the physical layer. Other parameters are set the same as in IEEE 802.11a standard at 20 MHz bandwidth. The performance of our proposed protocol is compared with the previous protocol proposed in [14] and the IEEE 802.11a DCF protocol in terms of the mean throughput and the mean end-to-end latency.

A. *Performance Under Error-Free Channel*

In order to compare with the previous protocol in [14], we use the same channel conditions and assume that there is no packet transmission error. The simulation and numerical results are shown in Fig. 3 and Fig. 4.

Observed from Fig. 3 is a common trend of significantly deteriorated throughput for all protocols as the network radius increases. This can be explained by the fact that when the network radius (also the distance between any two nodes)

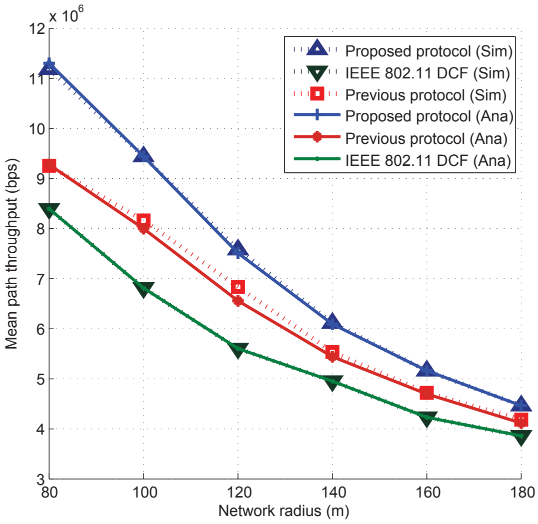

Fig. 3. Mean throughput versus network radius under error-free channel.

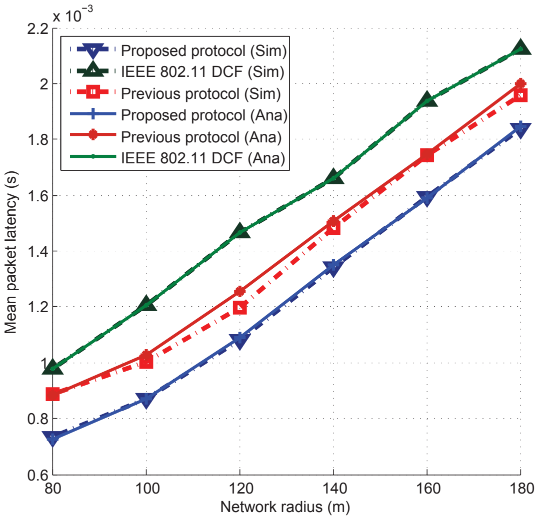

Fig. 4. Mean latency versus network radius under error-free channel.

increases the path loss becomes exponentially larger leading to reduced average SNR at the receiving nodes. The data transmission rate thus decreases accordingly and so does the path throughput. Another observation can be made from the figure is that the path throughput achieved by the proposed protocol is always higher than the previous protocols. Fig. 4 shows the mean end-to-end packet latency as a function of the distance. It can be seen that the end-to-end packet latency linearly increases with the network radius. This increase is not only due to the larger propagation time but also the increased transmission delay resulted from reduced transmission rate. As our protocol achieves higher throughput its latency is thus clearly lower than others.

We can also see from the figures that the simulation results agree well with the analytical results, which helps to validate our analysis.

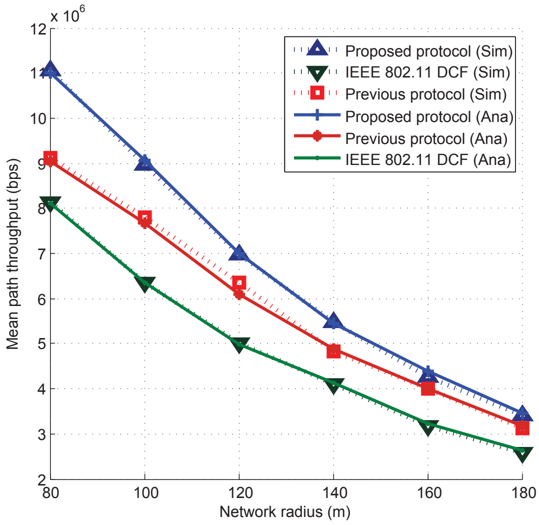

Fig. 5. Mean throughput versus network radius under erroneous channel.

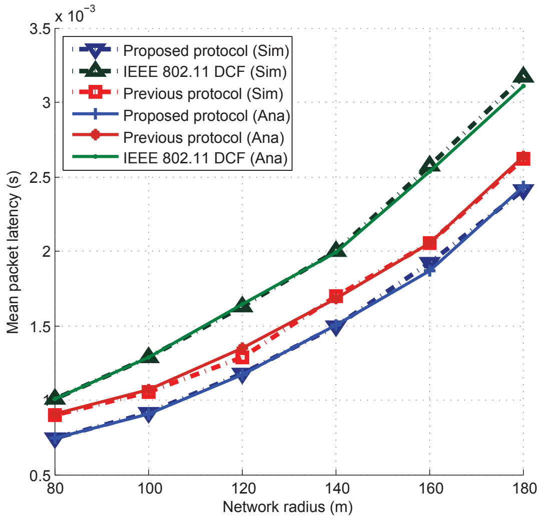

Fig. 6. Mean latency versus network radius under erroneous channel.

B. Performance Under Erroneous Channel

The mean path throughput and end-to-end packet delay under channel with errors are shown in Fig. 5 and Fig. 6, respectively. Comparing results in Fig. 5 and in Fig. 3, we can see that the network throughput decreases significantly under erroneous channel, especially at the large radius. This reduction ranges from hundreds of kbps at 80 m radius upto about 1 Mbps at 180 m radius. The reason is due to packet retransmission caused by bad channel condition with larger path loss. However, even under erroneous channel our protocol still achieves better throughput than the previous cooperative MAC protocol in [14] and the IEEE 802.11a DCF protocol.

Observing Fig. 6 and Fig. 4 we can see the packet latency of all three protocols increases significantly as the network radius increases. Still, our proposed protocol outperforms the others in terms of the end-to-end latency.

VI. CONCLUSIONS

In this paper, we have presented an improved cross-layer design of cooperative MAC protocols for wireless ad hoc networks. Our protocol can decrease signaling overhead and increase the channel accessing ability. Analytical and simulation results demonstrate that the proposed protocol achieves higher mean throughput and lower end-to-end latency compared to the previous cooperative MAC and IEEE 802.11 DCF protocol under both error-free and erroneous channel. For the future work, we will consider the case of cross-layer design of the cooperative MAC protocol for multi-hop wireless networks.

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