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Cross-Layer Design of Bidirectional-Traffic Supported Cooperative MAC Protocol

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Abstract—**In this paper, we consider the cross-layer design of a cooperative medium access control (MAC) protocol for wireless ad hoc networks. In particular, we propose a cooperative MAC protocol which can work either in the cooperative transmission mode for unidirectional traffic or physical-layer network coding (PNC) mode for bidirectional traffic. By designing a suitable control frame exchange the proposed protocol achieves better performance than the previous ECCMAC and the IEEE 802.11 MAC protocol in terms of both network throughput and end-to-end latency. Theoretical analysis and computer simulations are also used to evaluate the effectiveness of the proposed protocol.**

I. INTRODUCTION

Cooperative communication is considered as a promising approach to enhance the performance of wireless ad hoc networks. By cooperation with surrounding relaying nodes the communication between a source and a destination node can have either extended coverage or achieve diversity gain to improve the link reliability [1]–[4]. In order to implement the cooperation it is necessary to consider effective designs in different layers. Up to present, various physical-layer relaying approaches have been proposed in the literature. Many of them were well cited in [1]. Some of others directly related to our current work are the distributed Alamouti space-time block coding schemes proposed in [3] and [4]. Other approaches focused on the medium access control (MAC) protocols that support cooperative communications among network nodes in the wireless broadcast medium [5]–[7]. The CoopMAC protocol in [5] proposed a control frame called Helper-ready-To-Send (HTS) and a CoopTable to determine a helper node participating in the cooperative process. To update the CoopTable, every network node needs to passively overhear the channel status information (CSI) and thus it is not really efficient for wireless networks with a large number of nodes. The work by Shan et al. [6] considered a cooperative MAC protocol with distributed helper selection which is suitable for mobile wireless networks. The IrcMAC protocol proposed in [7] focused on reducing the overhead exchange by using only a single feedback bit transmitted by the helper in the relay response frame duration. Although all these protocols were shown to achieve better performance than the traditional IEEE 802.11 MAC protocol, there is still a high possibility of errors since the source only picks either the direct or relaying path via a helper to transmit data to the destination.

In order to achieve both the transmission reliability and the system throughput, some studies have focused on the method of cross-layer design such as in [8]–[10]. The modified CoopMAC in [8] redesigned the MAC protocol to leverage the cooperation in the physical layer. The enhanced CD-MAC protocol in [9] proposed a solution to differentiate the errors due to collisions and channel impairments. The cross-layer cooperative MAC protocol in [10] distinguished the beneficial cooperation from unnecessary cooperation in order to achieve cooperation gain. Further, to resolve the conflict among helpers supporting the same cooperative rate, this protocol uses a simple strategy that lets collided helper candidates contend again once in K minislots after their unsuccessful transmission of a ready-to-help (RTH) frame. However, when there is more than one optimal helper in the network, the protocol overhead can significantly increase due to retransmission of the RTH frame. In addition, this protocol is not designed to resolve the problem of the bidirectional traffic when both the source and the destination have data to send to each other.

Aiming to support bidirectional traffic between the source and the destination, recent MAC protocols have included network coding (NC) support in their design [11]–[15]. The MAC protocols called CODE in [12] and the ECCMAC in [13] achieve the network coding gain when there is bidirectional traffic. The ECCMAC protocol was also shown to be able to provide better throughput than the CODE protocol. However, there are still some drawbacks that need to improve in the ECCMAC protocol. First, the optimal helper selection process requires several direct transmissions, which leads to significant increase in the overhead time. Second, this protocol uses the p-persistent contention mechanism to resolve collision among the helpers with the same priority order. In addition, in the ECCMAC protocol, the broadcast nature is not yet effectively used to increase the transmission reliability and the total system throughput in both the case of unidirectional and bidirectional traffic. In order to achieve both the diversity gain and the the network coding gain, the authors of [15] proposed a cooperative network coding scheme which uses the physical-layer network coding (PNC) proposed in [16]. However, this work did not consider the MAC layer procedures as well as the relay selection. The recently introduced distributed MAC protocol in [17] has included PNC in its design to improve the system throughput. This protocol, however, requires a change in the format of the data frame from the destination, thus is not compatible with the current IEEE 802.11 standard.

In this paper, we propose a cross-layer design of the cooper-

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ative MAC protocol which can support both cooperative mode for unidirectional and PNC mode for bidirectional traffic. The transmission at the physical layer uses either the distributed Alamouti space-time block coding in [3] or PNC in [16] to improve the link reliability and network throughput. At the MAC layer, we design a control frame exchange which helps to minimize the protocol overhead. Compared with existing cooperative MAC protocols, our protocol has some advantages. First, even if the traffic is only unidirectional or the quality of communication links in the networks is poor, the proposed protocol still achieves higher transmission rate and reliability due to the diversity gain of the distributed Alamouti STBC. Second, the cross-layer cooperative protocol with PNC at the physical-layer provides improved throughput over the previous protocols using only network coding.

The remainder of the paper is organized as follows. The system model and layer operations are described in Sect. II. Our proposed cooperative MAC protocol with PNC support is presented in Sect. III. Sect. IV performs transmission time and throughput analysis. Analytical and simulation results are presented in Sect. V followed by Conclusions in Sect. VI.

II. SYSTEM MODEL AND LAYER OPERATIONS

A. System Model

We consider a wireless cooperative ad hoc network in which each network node can support multiple transmission rates $r_i, i = 1, 2.., Q$. In order to be consistent with the current standards, we assume that only data frames can be transmitted in multirate mode while the control frames are sent at the basic rate of 2 Mbps. The considered network consists of a source (S) and a destination (D) placed apart a distance d with intermediate nodes randomly distributed in a circular area with diameter d. All nodes in the network are assumed to have a single antenna and have limited transmit power. In addition, all the channels in the network are assumed to undergo flat Rayleigh fading with log-normal shadowing. In our network, a distributed relay selection algorithm is used to select an optimal helper from intermediate nodes. The optimal helper (H) acts as the relay to support the transmission from the source to the destination. Depending on the channel conditions and the data exchange between the source and the destination, the network can operate in one of the three modes: (i) Direct transmission from the source to the destination without using cooperation with the helper; (ii) Cooperative transmission from the source to the destination with the help of the helper; (iii) Bidirectional transmission between the source and the destination using PNC.

1) 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 performance there are two feasible approaches, i.e. improving the effectiveness of channel access and improving the link utilization during transmission. In this paper, we use the second approach. The link utilization is defined as the effective payload transmission rate (EPTR) taking into account the MAC layer protocol overhead. Let W, T_p, and T_o denote respectively the payload length of a data frame, the payload transmission, and the overhead transmission time of the MAC layer protocol. The link utilization is defined as $\text{EPTR} = \frac{W}{T_p+T_o}$. It is clear that in order to improve the link utilization, we should decrease T_o and/or T_p. Here the payload transmission time T_p is given by $\frac{W}{R}$, where R is the transmission rate for the payload. Possible approaches to the improved utilization can be achieved by cooperation and protocol design. By using cooperation the network can transmit at a higher transmission rate to reduce the time duration T_p while designing a better protocol with more effective control message exchange order helps to decrease T_o.

2) Physical Layer Operation: At the physical layer, cooperative transmission for uni-directional traffic, i.e. from the source to destination, is done in two consecutive time slots (or two phases). During the first time slot the source broadcasts its data frame to both the optimal helper and destination at the transmission rate $R_{c1} \in \Re = \{r_1, r_2, ..., r_Q\}$, where $\Re$ is the set of transmission rates obtained by using an adaptive coding and modulation scheme at the physical layer, and $r_i < r_j$ if $i < j$. During the second time slot the optimal helper cooperates with the source to transmit the received information bits to the destination at the transmission rate $R_{c2} \in \Re$. This cooperative mode can be implemented using the distributed Alamouti space-time code as presented in [3],[4]. It is noted that the set of transmission rates $\Re$ is determined based on the minimum signal-to-noise ratio (SNR) required for each receiving node to correctly decode the received signal. In this paper, we assume that the channel between any two nodes in the network is slowly varying, and control frames are correctly decoded due to the fact that their frame size is short and its basic transmission rate is low. Data frames, however, may encounters errors due to the longer payload length. With the bidirectional traffic, the cooperative transmission process is also done in two consecutive time slots. However, instead of the distributed Alamouti STBC, PNC is used at the optimal helper to generate network-coded symbols based on the PNC mapping in [16]. In this mode, both the source and the destination send their data to the optimal helper simultaneously during the first time slot. In order to facilitate PNC we assume perfect symbol-level time and carrier synchronization. The signal received at the optimal helper from both ends is then detected using maximum-likelihood estimation, performed PNC mapping, and modulated using BPSK. During the next time slot, the optimal helper broadcasts PNC symbols to both the source and destination.

B. Optimal Helper Selection

In order to select an optimal helper to act as the relay in the cooperative and PNC mode. The helper selection is done using a distributed algorithm such as proposed in [2]. However, in the case there are several intermediate nodes with the same capability there will be a conflict among these nodes. In order to solve this problem, the cooperative MAC protocol in [10] is applied. Using this protocol, intermediate nodes are divided into groups with the same capability. Contention to

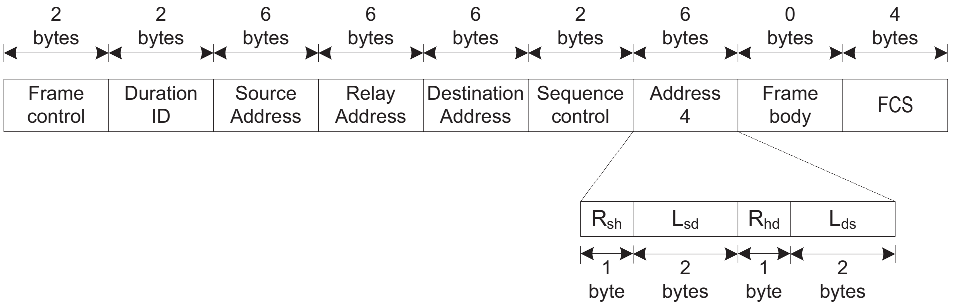

Fig. 1. FTS frame format.

be the optimal helper is then done between groups and among members of each group.

In order to define contention groups, we use the equivalent cooperative transmission rate (ECTR), denoted by R_h, to represent the payload transmission rate from the source to the destination. With the repetition-based two time-slot cooperation scheme, R_h is given by:

$$R_h = \frac{W}{\frac{W}{R_{c1}} + \frac{W}{R_{c2}}} = \frac{R_{c1}R_{c2}}{R_{c1} + R_{c2}}. \quad (1)$$

Given the payload length W and the direct transmission rate R_1, each intermediate node knows if it is a helper candidate by checking the condition $R_h > R_1$. Let M denote the number of ECTRs generated from the network and each of them be labeled by $R_h^*(i), i = 1, 2, ..., M$. In order to facilitate the optimal helper selection, we sort these M rates in a descending order and divide them into G groups, each with $n_g \geq 1$ members. We then use the optimal grouping based greedy algorithm as in [10] for helper selection. According to this setting there are two types of contention, namely, intra-group and inter-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 group indication (GI) signal if it does not overhear any GI signal from higher rate groups. Here, $T_{fb1}(g) = (g-1)t_{fb}, 1 \leq g \leq G$ and t_{fb} is referred to as the back-off slot time. Therefore, only members of the highest rate group will contend with each others. In the intra-group contention, if a helper candidate (with the group index g and the member index m) does not overhear any member indication (MI) signal, it transmits its own MI signal after the interval $T_{fb2}(g, m) = (m-1)t_{fb}, 1 \leq m \leq n_g$. If there exists only one optimal helper, a forwarder-to-send (FTS) frame is sent by this helper candidate immediately after the MI signal. Clearly, using this algorithm the helper with the highest cooperative rate R_h can be selected in a distributed manner and its EPTR will be larger than that of any other intermediate nodes. Note that each EPTR must belong to the cooperation region (CR) defined as a set of rate trips $C := (R_1, R_{c1}, R_{c2}) \in \Re^3$, such that the EPTR with cooperation is always lager than that without cooperation.

To solve the conflict among the optimal helpers supporting the same cooperative rate, i.e. in the same group, we use the simple strategy which lets these helpers to randomly select the k-th time-slot in K specific time slots for sending the FTS frame. The proposed FTS frame has the similar format of other control frames such as RTS and CTS. However, as shown in Fig. 1, the Address 4 field is modified to include additional information for cooperative transmission and network coding. In the FTS frame, R_{sh} and R_{hd} are data rates from the source to the helper and from the helper to the destination, respectively. R_{sh} can be calculated by the helper by estimating the SNR from the RTS frame. We assume that the link is symmetric so that the rate R_{hd} can be determined by estimating the SNR from the CTS frame. L_{sd} and L_{ds} are the frame lengths of the data sent from the source to the destination and from the destination to the source, respectively. The L_{ds} information is used as an indication of bidirectional traffic for network coding mode. When the destination receives the RTS frame, if it also wants to send its own data to the source, the destination informs the source by L_{ds} included in the duration field of the CTS frame. Then, through the CTS frame, the helper can extract the information L_{ds}. Note that when the bidirectional traffic is expected, the helper that supports the highest R_h must ensure that its bidirectional EPTR is larger than that of any other nodes failed in the helper contention.

III. PROPOSED COOPERATIVE MAC PROTOCOL

A. Protocol Description

In this section, we propose a cross-layer cooperative MAC protocol which has capability to support PNC for bidirectional traffic. The proposed protocol can work in three modes: direct transmission without cooperation, cooperative transmission via helper using distributed Alamouti STBC for unidirectional traffic, and PNC transmission via helper for bidirectional traffic. Operations in the cooperative and PNC mode are described in Fig. 2 and Fig. 3, respectively. In our protocol, in addition to the three control frames RTS (Request-to-Send), CTS (Clear-to-Send) and ACK (ACKnowlegement) supported in IEEE 802.11 DCF protocol, a new frame abbreviated as FTS (Forwarder-to-Send) is introduced as explained in the previous section. The proposed protocol is explained as follows.

1) *Source Initiation.* After a back-off interval, the source establishes the link to the destination node using RTS/CTS handshake. In order to start, the source broadcasts the RTS frame to both the destination and the helper.

2) *Destination Response*. If the destination receives the RTS frame correctly, it broadcasts the CTS frame to both the source and the helper after an SIFS (Short Inter-Frame Spacing) interval. In the case the destination also has its own data to send to the source, the information of the payload length L_{ds} is included into the CTS frame, if not the length L_{ds} is set to null.
3) *Helper Processing*. When the helper overhears the RTS and CTS frame exchange between the source and the destination, it estimates the channel status information (CSI) to determine its cooperative rate R_h^* in the cooperation region. The helper then uses this rate to send the indication signals and the FTS frame to both the source and the destination. From the length information of L_{ds} included in the CTS frame, the helper can alternatively switch between the cooperative and PNC transmission mode.
4) *Helper Contention and Mode Selection*. When the source receives the CTS frame from the destination, it continues to wait for both the helper indication (HI) signal and the group indication (GI) signal for the inter-group contention, as well as the member indication (MI) signal for the intra-group contention. When contention has been resolved the source receives an FTS frame from the optimal helper. The cooperation will be decided as follows:

    - If L_{ds} = null (meaning the destination has no data to send to the source), the source then activates the cooperative transmission mode and sends its data to both the helper and the destination node during the first time slot after an SIFS interval;
    - If there exists L_{ds} the PNC transmission mode is then activated. Both the source and destination send their data to the helper simultaneously during the first time slot. In case there exists an optimal helper but the FTS frame is not correctly received by the source and destination (such as due to FTS collision), the source sends its own data to the destination, directly while the destination stops to send its own data to the source node.
    - If the source does not overhear any HI signal, direct transmission mode, as illustrated in Fig. 4, is automatically activated.

5) *Helper Transmission*. In the cooperative transmission mode, after receiving the data from the source, the helper decodes this data and cooperates with the source to transmit the data from the source to the destination in the second time slot. The cooperative transmission is done using the distributed Alamouti STBC proposed in [4]. In the PNC transmission mode, after the PNC symbols have been generated the helper transmits the PNC data $\mathrm{Data}_{\mathrm{PNC}}$ to both the source and the destination in the second time slot.
6) *Destination Acknowledgement*. In the cooperative transmission mode, if the destination has correctly decoded the data from the source, it responds an ACK frame to the source after an SIFS interval. In the case of PNC, after the source and destination have correctly received the data, they simultaneously send their $\mathrm{ACK}_{\mathrm{S}}$ and $\mathrm{ACK}_{\mathrm{D}}$ frames to the helper after an SIFS interval. The helper then broadcasts the $\mathrm{ACK}_{\mathrm{PNC}}$ to both the source and destination.

IV. PERFORMANCE ANALYSIS

In this section, we intend to calculate the payload and overhead transmission time in order to obtain the network throughput.

A. Case 1: Non-Cooperation 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 payload and overhead transmission time are given respectively by: $T_{1,p} = \frac{W_1}{R_1}$ and $T_{1,o} = T_{\mathrm{RTS}} + T_{\mathrm{CTS}} + T_{D,o} + T_{\mathrm{ACK}} + 4T_{\mathrm{SIFS}} + 4\sigma$, where W_1 is the payload length sent by the source; T_{RTS}, T_{CTS}, T_{ACK}, T_{SIFS} and $T_{D,o}$ are the time interval of RTS, CTS, ACK frame, SIFS and data frame overhead, respectively; σ is the propagation time.

B. Case 2: Transmission Without Helper

If there is not any HI signal detected by the source after the RTS/CTS exchange process, direct transmission mode is activated. This case happens when no helper is selected. The payload and overhead transmission time are given by $T_{2,p} = T_{1,p}$ and $T_{2,o} = T_{1,o} + T_{\mathrm{HI}}$ respectively, where, T_{HI} is the time duration for the HI signal.

C. Case 3: Cooperation Without Collision

If there is only one optimal helper with the group index g and the member index m, this optimal helper sends the FTS frame at the k-th randomly selected timeslot without contention. There are two possible situations corresponding to the two transmission modes. In the cooperative mode for the unidirectional traffic from the source to the destination, the payload transmission time are given by $T_{3,p}^1 = \frac{W_1}{R_{c1}} + \frac{W_1}{R_{c2}} = \frac{W_1}{R_h}$ and $T_{3,o}^1(g,m,k) = T_{2,o} + T_{fb1}(g) + T_{\mathrm{GI}} + T_{fb2}(g,m) + T_{\mathrm{MI}} + k \cdot t_{fb} + T_{\mathrm{FTS}} + T_{D,o} + 2T_{\mathrm{SIFS}} + 2\sigma$. Here k is the index of the time slot randomly selected in K minislots; T_{GI}, T_{MI} are the interval for the GI and MI signal transmission, respectively; T_{FTS} is the transmission time of the FTS frame. The probability that a helper selects the k-th time slot is determined by $P_k = \frac{1}{K}$; W_1 is the payload length sent by the source. In the PNC mode for the bidirectional traffic, both the source and the destination send their data to the optimal helper during first time slot and the optimal helper uses the second time slot to send the PNC symbols to both the end nodes. Therefore, the payload and overhead time are $T_{3,p}^2 = 2\frac{\max(W_1,W_2)}{\min(R_{c1},R_{c2})}$ and $T_{3,o}^2(g,m,k) = T_{3,o}^1(g,m,k) + T_{\mathrm{ACK}} + T_{\mathrm{SIFS}} + \sigma$, where W_2 is the data length sent from the destination to the source. Given K minilots, the probability that one optimal helper selects the k-th minislot for sending the FTS frame is $\frac{1}{K}$.

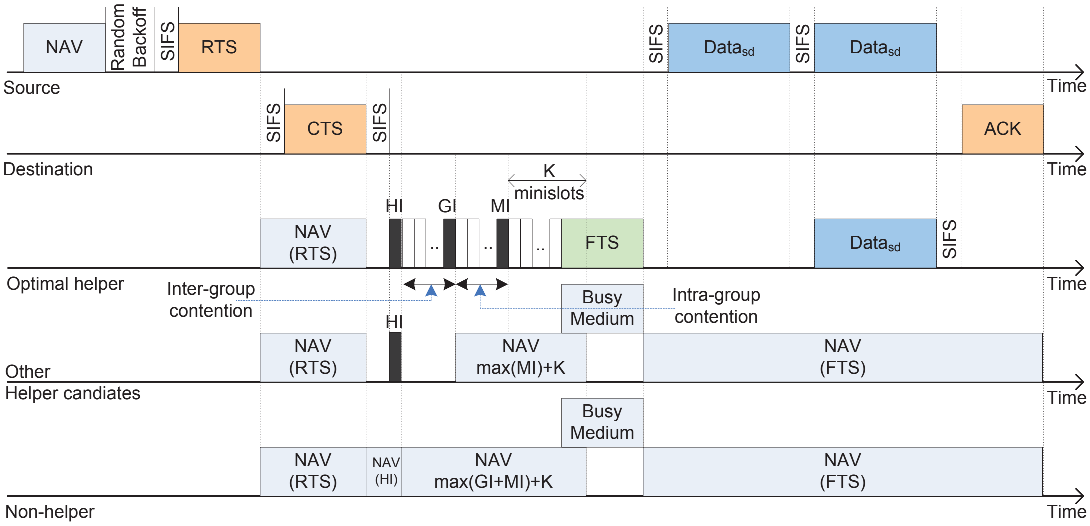

Fig. 2. Cooperative transmission mode.

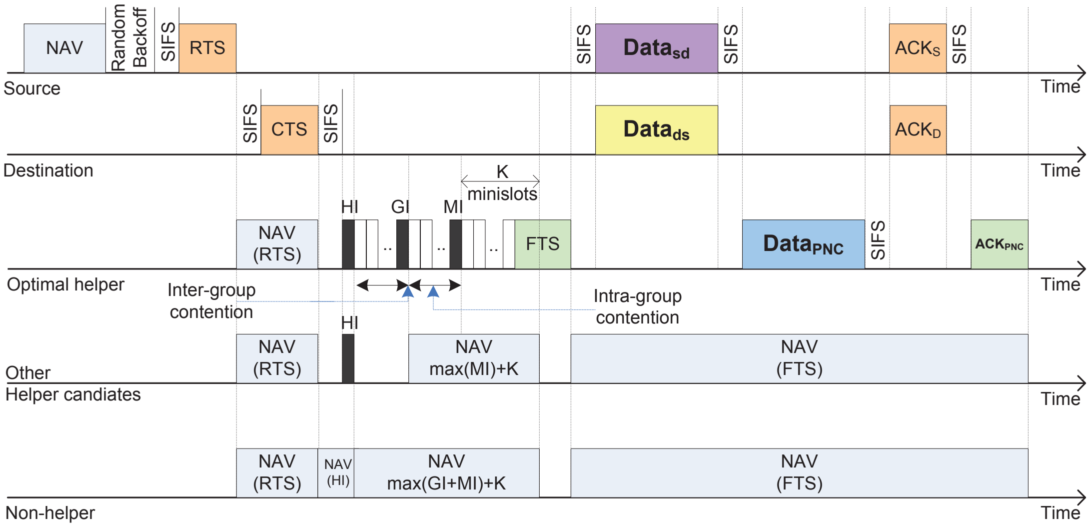

Fig. 3. PNC integrated cooperative transmission mode.

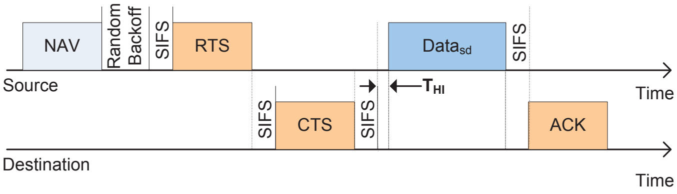

Fig. 4. Direct transmission mode

D. Case 4: Cooperation With Optimal Helper Contention

When there are more than one optimal helper supporting the same cooperative rate there will be possible collisions among the optimal helpers. The collisions can be resolved by using minislot contention. In this case, the payload and overhead transmission time for both the unidirectional and the bidirectional traffic are given similar to Case 3: $T^1_{4,p} = T^1_{3,p}$, $T^1_{4,o} = T^1_{3,o}$; $T^2_{4,p} = T^2_{3,p}$, $T^2_{4,o} = T^2_{3,o}$. However, with K minilots the probability that one of n optimal helpers wins the contention by selecting the k-th minislot is determined by [10]

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

E. Case 5: Unsuccessful Cooperation

If there is no FTS frame received by the source and the destination (possibly due to collisions), the source sends its data to the destination via the direct path. In this case, the traffic is unidirectional and thus the payload and overhead transmission time are given by $T_{5,p} = T_{1,p}$, $T_{5,o} = T_{2,o} + T_{fb1}(g) + T_{\mathrm{GI}} + T_{fb2}(g,m) + T_{\mathrm{MI}} + k \cdot t_{fb} + T_{\mathrm{FTS}} + T_{\mathrm{SIFS}} + \sigma$. Given K minislots the probability that contention fails due to more than one helper selecting the k-th mini slot is given by [10]

$$P_f(n,k) = \begin{cases} \displaystyle\sum_{i=2}^{n} \binom{n}{i} \frac{1}{K^i} \left(\frac{K-k}{K}\right)^{n-i}, & k = 1, 2, \cdots, K-1 \\ \dfrac{1}{K^n}, & k = K \end{cases} \qquad (3)$$

F. Throughput Calculation

Based on the above analysis, the protocol parameters can be determined for link throughput maximization by solving parameters K, M and G according to the channel condition, payload lengths W_1, W_2, and the average number n of collided helpers to achieve the maximal link throughput. An optimization problem for the maximum mean throughput is formulated as follows.

Case of the unidirectional traffic:

$$\max J_1(n) \qquad (4)$$
$$\text{s.t. } J_1(n) > \frac{\rho W_1}{T_{1,p} + T_{1,o}}$$

where

$$J_1(n) = \begin{cases} \displaystyle\sum_{k=1}^{K} \frac{W_1 P_k}{T^1_{3,p} + T^1_{3,o}}, & n = 1 \\ \displaystyle\sum_{k=1}^{K} \left(\frac{W_1 P_w(n,k)}{T^1_{4,p} + T^1_{4,o}} + \frac{W_1 P_f(n,k)}{T_{5,p} + T_{5,o}} \right), & n \geq 2 \end{cases} \qquad (5)$$

is the EPTR when a single optimal helper supports an 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, and $\rho \geq 1$ is a control parameter used to balance between the the cooperative and non-cooperative mode. ρ is often referred to as the payload balance factor. Small ρ encourages more cooperative opportunities.

Case of the bidirectional traffic:

$$\max J_2(n) \qquad (6)$$
$$\text{s.t. } J_2(n) > \frac{\rho(W_1 + W_2)}{2T_{1,p} + 2T_{1,o} + t_{cw}}$$

where

$$J_2(n) = \begin{cases} \displaystyle\sum_{k=1}^{K} \frac{(W_1 + W_2) P_k}{T^2_{3,p} + T^2_{3,o}}, & n = 1 \\ \displaystyle\sum_{k=1}^{K} \left(\frac{(W_1 + W_2) P_w(n,k)}{T^2_{4,p} + T^2_{4,o}} + \frac{W_1 P_f(n,k)}{T_{5,p} + T_{5,o}} \right), & n \geq 2 \end{cases}, \qquad (7)$$

t_{wc} is back-off time between two consecutive transmissions, W_2 is the length of payload sent by the destination.

V. ANALYTICAL AND SIMULATION RESULTS

In this section, we evaluate the performance of the proposed protocol using both computer simulations and numerical analysis. The network consists of 20 intermediate nodes distributed randomly inside a circle bounded by the source and the destination. Each link connecting any two nodes is affected by Rayleigh fading with the log-distance and shadowing path loss. The data transmission rate is calculated based on the mean SNR at the receiving node. The data frame payload length is $W_1 = W_2 = W = 2000$ bytes, the number of minislots for random contention is equal to $K = 20$ and the payload balance factor $\rho = 1$. For cooperative transmission, the decode and forward (DF) protocol is used at the helper. Other parameters are set to be the same as in IEEE 802.11a standards with 20 MHz bandwidth.

A. Case of Bidirectional Traffic

In this case, we assume that both the source and the destination have data to send to each other. PNC transmission mode is thus used in the network. The performance of the proposed protocol in terms of average network throughput and end-to-end latency is compared with that of the ECCMAC in [13] and that of the IEEE 802.11 DCF protocol. A general trend observed from Fig. 5 is that the network throughput decreases as the network radius increases. This is clear as the increase in the radius leads to larger path loss and the adaptive modulation and coding scheme will adjust the transmission rate accordingly. However, by using PNC the proposed protocol provides largest throughput, followed by the ECCMAC, and the IEEE 802.11 DCF protocol. This is true due to the fact that the proposed protocol uses PNC while the ECCMAC utilizes the network coding. It can also be seen from the figure that when the network radius increases the throughput curve of the ECCMAC protocol tends to deteriorate to the same level of the IEEE 802.11 DCF protocol.

Fig. 6 shows the average packet end-to-end latency of the three protocols. The proposed protocol exhibits the lowest latency, followed by the ECCMAC protocol. The traditional IEEE 802.11 DCF protocol requires the largest latency. This

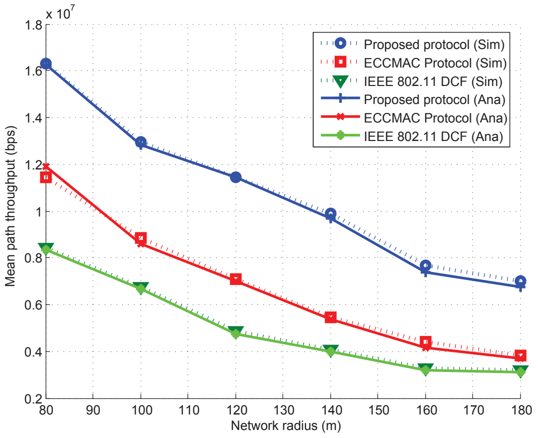

Fig. 5. Throughput performance of the bidirectional traffic.

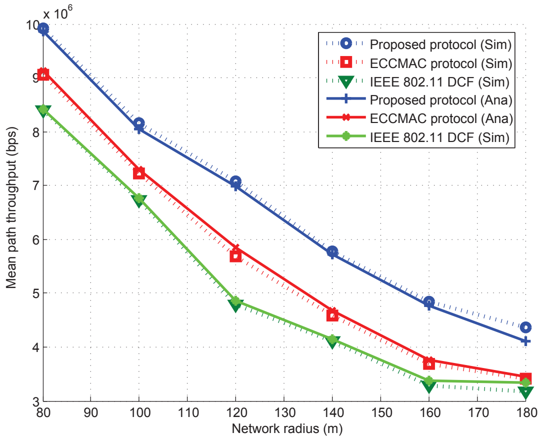

Fig. 7. Throughput performance of unidirectional traffic.

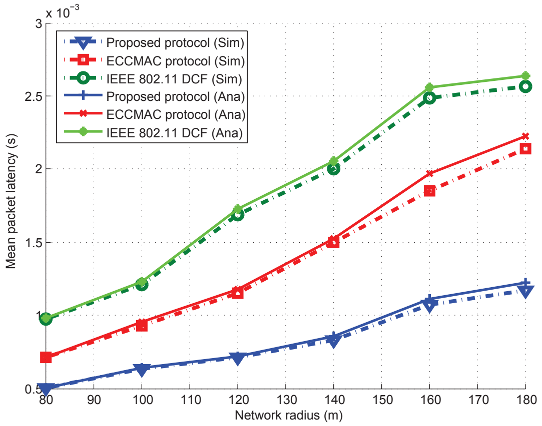

Fig. 6. Packet latency performance of the bidirectional traffic.

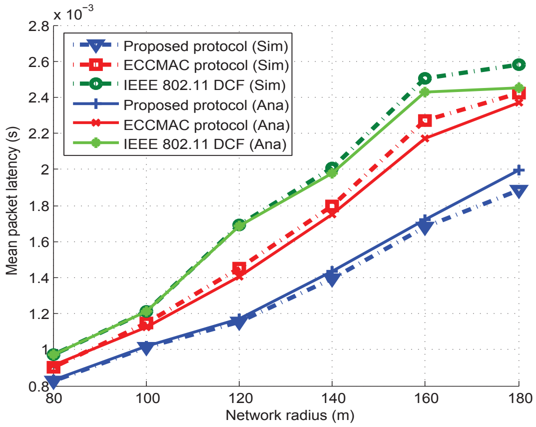

Fig. 8. Packet latency performance of unidirectional traffic.

is clear as the higher throughput the lower transmission time, and also the lower waiting time.

Finally, it can be seen from both the figures that the simulation results agree well with the analytical ones, which validates our theoretical analysis.

B. Case Of Unidirectional Traffic:

When the traffic is unidirectional the proposed protocol switches to the cooperative transmission without using the physical layer network coding. In this case, we compare the performance in the cooperative transmission mode of the proposed protocol with that of the ECCMAC and the IEEE 802.11 DCF protocol. A similar trend for the case of PNC can also be observed from Fig. 7 and Fig. 8. Clearly, the proposed protocol also exhibits the best performance in the case of cooperative transmission.

VI. CONCLUSIONS

In this paper, we have presented a method to improve the performance of the wireless ad hoc network. A cooperative MAC protocol supporting PNC was designed from a cross-layer perspective. The proposed protocol was shown to have improved performance over the previous ECCMAC and the IEEE 802.11 DCF protocol in terms of both network throughput and end-to-end latency. We have also carried out a performance analysis and used Monte-Carlo simulation to validate the analytical results. For the future work, we will integrate cooperative mechanism at higher layer such as the network layer into our cross-layer protocol design for multi-hop wireless networks.

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