Cross-Layer Cooperative MAC Protocol in Distributed Wireless Networks

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***Abstract*—In this paper, we study medium access control (MAC) protocol design for distributed cooperative wireless networks. We focus on beneficial node cooperation by addressing two fundamental issues of cooperative communications, namely when to cooperate and whom to cooperate with, from a cross-layer protocol design perspective. In the protocol design, taking account of protocol overhead we explore a concept of cooperation region, whereby beneficial cooperative transmissions can be identified. We show that a rate allocation in the cooperation region provides higher link utilization than in a non-cooperation region. To increase network throughput, we propose an optimal grouping strategy for efficient helper node selection, and devise a greedy algorithm for MAC protocol refinement. Analysis of a successful transmission probability with cooperative or direct transmission is presented. Simulation results show that the proposed approach can effectively exploit beneficial cooperation, thereby improving system performance. Further, analytical and simulation results shed some light on the tradeoff between multi-user diversity gain at the physical layer and the helper contention overhead at the MAC layer.**

***Index Terms*—Cooperative communications, medium access control, beneficial node cooperation, cooperation region.**

I. Introduction

In wireless communications, multiple-input and multiple-output (MIMO) technology is effective to meet the challenges of limited radio spectrum and to mitigate channel impairments. However, deploying multiple antennas on a small mobile node poses hardware difficulty. Cooperative communications utilizing the antennas on neighbor nodes provide a viable alternative [2,3]. The basic idea of cooperative communications is that, by utilizing the broadcasting nature of wireless transmissions, some nodes can act as helpers (i.e., relay nodes) to help deliver the information from a source node to a destination node. Thus, cooperation enhances the communications reliability and/or increases the bandwidth efficiency, but without the requirement of additional antennas at each node.

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To facilitate cooperative communications, we need to address two issues: 1) when to cooperate; and 2) whom to cooperate with, if cooperation is beneficial. These two fundamental issues have been researched extensively from an information-theoretic perspective [4]–[9]. In [4], an opportunistic decode-and-forward (DF) cooperation approach is proposed to improve both system capacity and outage performance. In [5], an opportunistic amplify-and-forward (AF) cooperation approach is proposed to improve bit-error-rate (BER) performance. However, helper selection is not addressed in [4,5]. On the other hand, there is a rich body of research work on helper selection schemes in the literature, aiming at improving outage/diversity performance (e.g., [6,7]) and/or increasing system throughput (e.g., [7,8]). Nonetheless, the issue of protocol overhead is mostly ignored. In a distributed wireless network, to select the best helper node or a group of good helper nodes, message exchange among a source node, a destination node, and a set of potential helper nodes is necessary. Despite the fact revealed in [9] that the average channel capacity of the selection cooperation increases with the number of the potential helper nodes, it is not clear to what extent the cooperation gain at the physical layer can be outweighed by the signaling overhead from the higher layers. Thus, for a distributed cooperative network, cross-layer protocol design considering the practical aspect of signaling overhead is vital.

To improve the performance of a cooperative network, applying cross-layer optimization is found to be useful [10]–[13]. In [10], with an emphasis on fairness assurance, a cross-layer framework for allocating energy and transmission time among nodes effectively extends network lifetime. Aiming at minimizing network power consumption, joint routing, relay selection, and power allocation are studied in [11]. Leveraging in cooperation, a cross-layer algorithm is devised in [12] to maximize the throughput of network coding-based broadcast. The concept of effective bandwidth is employed in [13] to study the impact of cooperation on buffer occupancy. However, the impact of transmission scheduling at the medium access control (MAC) layer and the issue of signaling overhead are ignored in above cross-layer research work. It is possible that the expected performance will degrade due to an inefficient MAC scheme.

With the purpose of offering effective and efficient interaction between the physical and higher protocol layers, MAC protocol design for distributed cooperative communications has recently been a hot topic [14]–[21]. In [14], we investigate the issues and challenges in designing an efficient cooperative MAC scheme for multi-hop wireless networks. Proposed in [15] is a proactive MAC scheme empowered by

the DF mode of cooperation. It is observed that throughput performance of a cooperative network can be poorer than that of a non-cooperative network. Coop-MAC [16] and rDCF [17] enable relay-based two-hop transmission to mitigate the throughput bottleneck caused by low-data-rate nodes. With joint routing, MAC, and cooperative transmission design, virtual multiple-input single-output (VMISO) [18] can improve network throughput by reducing the number of transmission hops. To enhance the multi-rate capability of IEEE 802.11 protocols, a cooperative relay-based auto-rate MAC protocol is proposed in [19]. However, beneficial cooperation considering signaling overhead is not addressed in [16]–[19]. To facilitate optimal helper selection, busy tone-aided MAC can be employed [20,21], whereby the problem of signaling overhead can be mitigated.

In this research, we address issues of node cooperation in a fully-connected wireless network, from a cross-layer protocol design perspective. Our goal is to devise an efficient and effective MAC protocol that can exploit beneficial node cooperation. To this end, we emphasize the impact of a link-layer protocol on the efficiency of conveying information among nodes at the physical layer by integrating signaling overhead control with the protocol design. The main contributions and significance of this paper are three-fold: First, considering the MAC layer overhead, we propose a cross-layer cooperative MAC protocol that can distinguish beneficial cooperation from unnecessary cooperation. Effective helper selection is integrated into the MAC protocol to achieve and increase cooperation gain, based on optimal grouping of helpers; Second, different from [22], we introduce a concept of *cooperation region* (CR) in the MAC-layer design, to identify beneficial cooperative rate allocations that offer higher link utilization than the direct transmission; Third, the probabilities of successful cooperation and direct transmission in the network with our cooperative MAC protocol are derived. Simulation results verify the accuracy of the analysis, and show that the proposed approach with beneficial cooperation outperforms its non-cooperative counterpart in terms of throughput and delay performance. It is shown that there is a performance tradeoff between multi-user diversity gain and MAC-layer overhead due to helper contention.

II. Preliminary and Problem Formulation

A. MAC Layer Preliminaries

Consider a single-channel fully-connected wireless network supporting best effort service, where each node can be a source (S), a destination (D), or a helper (H). Here, we base our cooperative MAC on the IEEE 802.11 distributed coordination function (DCF) [23]. The legacy standard uses carrier sense multiple access with collision avoidance (CSMA/CA). Thus, only one transmission pair in the network can be active after a successful channel contention. In general, to increase network throughput, there are two viable approaches: 1) by improving the efficiency of channel access when the nodes contend with each other before data transmission (e.g., controlling the collision probability by adapting the DCF backoff parameters [24] or enabling channel-aware medium access [25]), and 2) by improving the efficiency of link utilization when an actual packet transmission takes place (i.e., by controlling the signaling overhead and increasing transmission data rate). In this work, we focus on the second approach. As the channel is reserved for a node that has won the channel contention, it is rational for the node to send its data packets at a maximum transmit power level for a maximal rate. For simplicity, we assume all nodes in the network have the same power constraint. We define the link utilization as the effective payload transmission rate (EPTR), taking account of the MAC layer protocol overhead. Let W, T_P, and T_O denote the payload length of a data packet, the times needed to transmit the payload and overhead of the packet, respectively. The EPTR is given by $W/(T_P + T_O)$. To improve link utilization, we should decrease T_O and T_P, by exploring effective signaling overhead control at the MAC layer and advanced transmission techniques at the physical layer, respectively.

B. Physical Layer Preliminaries

To simplify the throughput comparison between a cooperative network and a non-cooperative network, we assume that, in each cooperation opportunity occurred in the cooperative network, the source employs the helper(s) to transmit the same information bits as those without cooperation in the non-cooperative network. Further, nodes in both networks operate in half-duplex mode. Consider repetition-based[1] selection cooperation [9], where a two-timeslot cooperative transmission is adopted. Focusing on the data rates in transmission, we detail the cooperation scheme as follows. In timeslot 1, the source broadcasts its packet to the optimal helper[2] and the destination with a transmission rate, $R_{C1} \in \mathcal{R} = \{r_1, r_2, ..., r_Q\}$, where $\mathcal{R}$ is the rate set supported by applying adaptive modulation and coding at the physical layer, and $r_i < r_j$ if $i < j$. In timeslot 2, the optimal helper forwards the received information bits cooperatively with the source to the destination, with a transmission rate, $R_{C2} \in \mathcal{R}$. Cooperation built on distributed space-time coding (e.g., [26]) or interleaver (e.g., [27]) can facilitate the transmission in timeslot 2. Here, the two rates, R_{C1} and R_{C2}, are chosen such that they are the maximal rates for the optimal helper and the destination to successfully decode the data in timeslots 1 and 2, respectively. As one way to support a high data rate, the destination can collect the signal power from the source and the helper during the two timeslots, whereby according to the modulation and coding schemes a reception with packet combining at the modulation level (e.g., diversity combining [2]) or the coding level (e.g., rate-compatible punctured convolutional (RCPC) coding-based modified Chase combining [28], random binning [29]) can be facilitated.[3] Notice that, if the destination only collects the signal power from the helper node, the relaying scheme is simplified to a pure multi-hop transmission.

[1]Notice that coded cooperation [3] can be integrated into our cross-layer MAC protocol design. However, in this work, we base the MAC protocol on repetition-based cooperative techniques.

[2]The optimal helper is defined as the one helping the source-destination pair achieve the largest EPTR (to be selected before the data transmission) among all the helper candidates.

[3]Related to non-repetition-based cooperation, other techniques such as superposition coding [30] can also facilitate packet combining.

To model a successful packet reception, given a packet length for each transmission rate in $\mathcal{R}$, there is a minimum signal-to-noise-ratio (SNR) above which the packet can be decoded successfully at a receiver. In this work, we assume that, the channels among the nodes change slowly such that the channel coefficient remains constant for the whole duration of one data packet transmission, which can be justified in a low or moderate-mobility scenario.

C. Problem Formulation

We address the research problems on beneficial cooperation from a cross-layer MAC protocol design perspective. In this research, we do not consider selfish nodes. Aiming at increasing link utilization via strategically activating cooperative transmission, we consider the link utilization in a cooperative network, which is enhanced if any direct transmission in the network with a low EPTR is replaced by cooperative transmission with a higher EPTR. Furthermore, if such a replacement occurs, the helper that supports the highest EPTR is employed in the cooperation. Let R_1 (in $\mathcal{R}$) denote the transmission rate of direct transmission from the source to the destination. Given a specific cooperative MAC protocol design (with known signaling overhead) and payload length W, the CR is defined as a set of rate triples, $\mathcal{C} := \{(R_1, R_{C1}, R_{C2})\} \subseteq \mathcal{R}^3$, such that the EPTR with cooperation is always larger than that without cooperation. Thus, for a specific payload length, a non-empty CR means beneficial cooperation exists. Utilizing the concept of CR, we can formulate the research problems on beneficial cooperation in cross-layer MAC protocol design as follows.

- When to cooperate: Find the CR $\mathcal{C}$ with the maximum link utilization improvement and achieve it via cooperative MAC.
- Whom to cooperate with: Given a group of helper candidates which can support a rate in the CR, identify the optimal helper which achieves the maximum EPTR with cooperation in a distributed way.

III. Cross-Layer MAC Protocol Design

We propose a novel cross-layer cooperative MAC protocol. The study consists of three phases: 1) initial protocol setup, where we devise the signaling exchange and helper selection, and identify tunable MAC protocol parameters; 2) analysis of payload and overhead transmission times; and 3) cooperation region determination and protocol parameter setting.

A. Initial Protocol Setup

Fig. 1 depicts the signaling and data packet transmission of our proposed cooperative MAC protocol. After a random backoff, a source node establishes a communication link with its destination via the request-to-send (RTS)/clear-to-send (CTS) handshake. If the CR is empty (i.e., cooperation is not beneficial), after receiving a CTS packet and waiting for a short interframe space (SIFS), the source sends its data packet to the destination directly, according to the IEEE 802.11 DCF [23].

On the other hand, when a cooperation opportunity arises (i.e., the CR is non-empty), the source and the destination first ascertain whether there exists a helper such that a cooperative transmission is feasible. To locate such a helper, if any, we make use of a helper indication (HI) signal. If no HI signal is detected shortly after an RTS/CTS exchange, direct transmission is triggered. If an HI signal is detected, a cooperative transmission can be initiated (to be discussed). Since the helpers (rather than the source or the destination) initiate node cooperation, we refer to it as helper-initiated cooperation. Compared to a source or destination-initiated cooperation (e.g., [7]), helper-initiated cooperation is preferred in a distributed wireless system. The rationale is that, due to the RTS/CTS exchange, any potential helper has already been aware of the channel condition between itself and the source (destination) after it overheard the RTS (CTS) packet.

To facilitate helper selection, the information on payload length and channel state of the source-destination (*S-D*) link (estimated by the destination) can be broadcast in the RTS and CTS packets, respectively. Therefore, every neighbor node can fully collect the channel state information (CSI) to estimate cooperative rate allocation, thereby evaluating its maximal supportable EPTR. However, to reduce overhead in helper selection, there is no information exchange among those potential helpers. That is, a potential helper has no instantaneous CSI of the channels between other potential helpers and the source (destination). Thus, a challenge of helper-initiated cooperation is how to effectively and efficiently select the optimal helper based on local CSI in a distributed way. To solve this problem, we propose the following group-based backoff mechanism.

Define a composite cooperative transmission rate (CCTR), R_h, to denote the payload transmission rate from the source to the destination. With repetition-based two-timeslot cooperation, it can be calculated as $R_h = W/(W/R_{C1} + W/R_{C2}) = R_{C1}R_{C2}/(R_{C1} + R_{C2})$. When competing for the optimal helper, the helper candidates will be organized according to their supportable CCTRs. Given payload length W and direct transmission rate R_1, let M denote the number of CCTRs generated from the non-empty CR (to be determined in Section III-C), and each of them labeled by $R_h^*(i)$, $i = 1, 2, ..., M$. To facilitate helper selection, we sort these M rates in descending order (i.e., $R_h^*(i) > R_h^*(j)$, if $i < j$) and partition them into G groups, each one with n_g (≥ 1) members, where $\sum_{g=1}^{G} n_g = M$. Here, M, G, and n_g are protocol parameters to be optimized. Note that, reflected in the value of $R_h^*(i)$, different groups have different channel access priorities, and different members in the same group also have different channel access priorities.

To reduce overhead in helper selection, we propose both inter-group contention and intra-group contention. In the inter-group contention, a helper candidate in the g^{th} group waits for a period of time, $T_{fb1}(g)$, before sending out its group indication (GI) signal, if it overhears no GI from any higher rate group, where $T_{fb1}(g) = (g-1) \cdot t_{fb},\ 1 \leq g \leq G$, and t_{fb} is referred to as the backoff slot time. Thus, only the members of the highest rate group will keep contending. Then, in the intra-group contention, if a helper candidate (with group

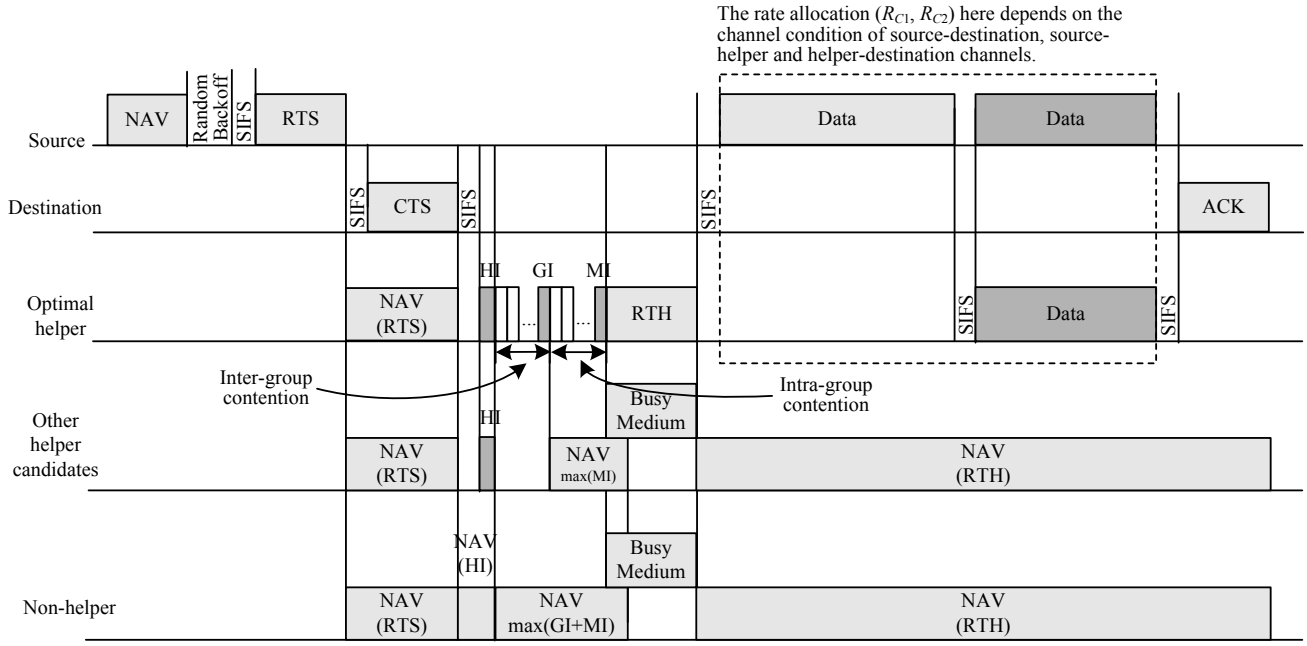


Fig. 1. An illustration of the proposed cooperative MAC protocol.

index g and member index m) overhears no member indication (MI) signal, it sends out its MI signal after $T_{fb2}(g,m) = (m-1)\cdot t_{fb},\ 1 \le m \le n_g$. Thus, the helper that supports the highest R_h can be elected in a distributed manner, which also assures that the EPTR of the selected helper is larger than that of any other nodes failed in the helper contention. To facilitate a distributed yet effective helper selection, on one hand, the backoff slot time should not be smaller than the duration of any indication signal (i.e., the HI, GI, and MI signals). Denote by t_{tx} the duration of any indication signal. It can be found that, $t_{fb} - t_{tx} \ge \max_H\{2\tau_{HD}\}$ is a sufficient condition to assure an asynchronized yet collision-free helper contention, where τ_{HD} is the propagation delay of a helper-destination (*H-D*) channel. On the other hand, with the proposed helper selection method, it is vital that all helper candidates share the same grouping structure with respect to the CR for the current *S-D* pair. We are to address the issue in determining the CR in Section III-C. After the contention, the optimal helper sends out a ready-to-help (RTH) packet with rate setting to the source to initiate a cooperative transmission (see Fig. 1).

In the case of multiple optimal helpers where two or more RTH packets collide, we employ a simple strategy that lets collided helper candidates re-contend once. Given such a collision, the collided helper candidates can be aware of it by using a timer (T_d) for checking the transmission from the source. When the collision is detected, they resend their RTH packets in a randomly selected minislot from K minislots, as shown in Fig. 2. The probability of RTH packet re-collision depends on the number of minislots and the number of collided nodes. Obviously, a larger K gives a smaller re-collision chance, but induces more overhead in the channel time. The value of K should be carefully determined, to be discussed in Section III-C. If a re-contention fails, direct transmission is triggered immediately, taking account of signaling overhead and throughput performance.

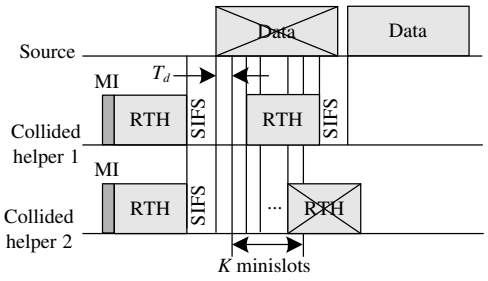


Fig. 2. Solution to RTH packet collision by contention over K minislots.

In summary, the proposed MAC protocol facilitates beneficial cooperation based on the CR and CSI obtained from the RTS/CTS signaling, and elects the instantaneous optimal helper in a distributed manner via the inter-group and intra-group contention. However, to maximize the link utilization in each data packet transmission and thus improve network throughput, we need to determine the CR and to optimize the protocol parameters, based on the analysis of payload and overhead transmission times discussed in the following.

B. Analysis of Payload and Overhead Transmission Times

We analyze the transmission times of the payload and the overhead of our MAC protocol in each of the following five cases.

Case I: Once a source node receives a CTS packet, it sends a data packet to its destination directly without cooperation. The payload and overhead transmission times are $T_{1,P} = W/R_1$ and $T_{1,O} = T_{RTS} + T_{CTS} + T_{D,O} + T_{ACK} + 3T_{SIFS}$

respectively, where T_{RTS}, T_{CTS}, T_{ACK}, and T_{SIFS} are time durations for the RTS, CTS, ACK packet transmission and SIFS interval, respectively, and $T_{D,O}$ is the transmission time of packet header in a data packet.

Case II: Cooperative transmission is set to be triggered, but no HI signal is detected after an RTS/CTS exchange. Thus, direct transmission is eventually employed. The payload and overhead transmission times are therefore given by $T_{2,P} = T_{1,P}$ and $T_{2,O} = T_{1,O} + T_{HI}$ respectively, where T_{HI} is the time duration of HI signal.

Case III: When detecting an HI signal from neighbors, the source and the destination wait for the contention signals (i.e., the GI and MI signals) and the RTH packet from the optimal helper. In the case of a single best helper, there is no RTH collision. Thus, the payload and overhead transmission times are respectively given by $T_{3,P} = W/R_{C1} + W/R_{C2} = W/R_h$ and $T_{3,O}(g,m) = T_{2,O} + T_{fb1}(g) + T_{GI} + T_{fb2}(g,m) + T_{MI} + T_C$, where $T_C = T_{RTH} + 2T_{SIFS} + T_{D,O}$, and T_{RTH}, T_{GI} and T_{MI} are time durations of the packet, RTH, the GI and MI signals, respectively.

Case IV: When collision happens in the intra-group contention, it is possible to mitigate the problem by utilizing the minislot re-contention. Compared to Case III, a successful re-contention activates the helper-based transmission, where the payload transmission time $T_{4,P}$ equals to $T_{3,P}$; however, the overhead transmission time for selecting the k^{th} minislot, is increased to $T_{4,O}(g,m,k) = T_{3,O}(g,m) + T_{RTH} + T_{SIFS} + T_d + k \cdot t_{fb}$. Given K minislots, the probability that one of the n re-contending helpers wins the contention by selecting the k^{th} minislot is

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

Case V: If a re-transmission of an RTH packet fails, a source node initiates direct transmission. Thus, the payload transmission time $T_{5,P}$ equals to $T_{1,P}$, while the overhead transmission time is increased to $T_{5,O}(g,m,k) = T_{2,O} + T_{fb1}(g) + T_{GI} + T_{fb2}(g,m) + T_{MI} + 2T_{RTH} + 2T_{SIFS} + T_d + k \cdot t_{fb}$. Given n helpers re-contending in the K minislots, the probability that re-contention fails due to more than one helper selecting the k^{th} minislot is

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

C. Cooperation Region Determination and Protocol Parameter Setting

It is interesting to note that the signaling overhead control at the MAC layer and the cooperative rate allocation at the physical layer are dependent when deciding the CR. The EPTR with cooperation is affected by the overhead of the cooperative MAC that a helper candidate needs to successfully contend for the optimal helper. On one hand, helper selection with properly controlled overhead decreases T_O, thus increasing the EPTR when utilizing a specific cooperative rate allocation and, more importantly, enlarging the feasible region for a specific payload length W and direct transmission rate R_1 (i.e., more cooperative rate allocations are feasible to provide beneficial cooperation). On the other hand, an enlarged CR changes the overhead to elect the instantaneous optimal helper. This interdependence of the MAC layer and the physical layer poses a challenge to find the CR and imposes a requirement to define an optimal CR for the maximum link utilization improvement.

Define the optimal CR as the one achieving the maximal average EPTR. Under the constraint that only local CSI is available at each potential helper, when contending for the optimal helper, each candidate assumes that all useful CCTRs are available with the same probability. Thus, the optimal CR for an *S-D* pair can be defined as the solution of the following optimization problem (OP):

$$\begin{aligned} \max \quad & L = \sum_{g=1}^{G} \sum_{m=1}^{n_g} J_{g,m}(n)/M && \text{(3a)} \\ \text{s.t.} \quad & J_{g,m}(n) > \rho W/(T_{1,P} + T_{1,O}) && \text{(3b)} \\ & 1 \le g \le G && \text{(3c)} \\ & 1 \le G \le M && \text{(3d)} \\ & 1 \le m \le n_g && \text{(3e)} \\ & \sum\nolimits_{g=1}^{G} n_g = M && \text{(3f)} \\ & 1 \le k \le K_{g,m},\ K_{g,m} \ge 2 && \text{(3g)} \end{aligned}$$

where

$$J_{g,m}(n) = \begin{cases} \frac{W}{T_{3,P}(R_{C1},R_{C2}) + T_{3,O}(g,m)}, & n = 1 \\ \sum_{k=1}^{K_{g,m}} \left[\frac{W \cdot P_w(n,k)}{T_{4,P}(R_{C1},R_{C2}) + T_{4,O}(g,m,k)} \right. & n \ge 2 \\ \qquad \left. + \frac{W \cdot P_f(n,k)}{T_{5,P}(R_1) + T_{5,O}(g,m,k)} \right], & \end{cases}$$

is the EPTR when a single optimal helper supports a CCTR with group id g and member id m, or the average EPTR when n collided optimal helpers supporting this same rate re-contend over $K_{g,m}$ minislots; $K_{g,m}$ is referred to as the minislot number for re-contention when the collided helpers support the CCTR with group id g and member id m; $\rho \ge 1$ is a control parameter to balance cooperation and non-cooperation. A smaller value of ρ encourages more cooperation opportunities.

The objective function given in (3a) is to maximize the average EPTR provided by the CR. Inequality (3b) ensures that the link utilization of cooperation with rates in the CR is larger than that of direct transmission. Constraints in (3c) and (3d) specify the range of group id (g) and the range of group number (G). Inequalities (3e) and (3f) describe the constraints on the member id (m) of each group and the total member number of all groups. Inequality (3g) gives the constraints on minislot number ($K_{g,m}$). Further, the size of the set, CR, is described by the variable M. The optimization variables in (3) are the protocol parameters and cooperative rate allocation, $(M, G, \{n_g\}_{g=1}^{G}, \{K_{1,m}\}_{m=1}^{n_1}, \{K_{2,m}\}_{m=1}^{n_2}, ..., \{K_{G,m}\}_{m=1}^{n_G})$ and (R_{C1}, R_{C2}), and the system parameters are $(\mathcal{R}, \rho, R_1, W, n)$. Since the OP characterized by (3a)-(3g) is a non-convex non-concave integer OP, some common techniques to solve such an OP include iterated local searches [31] and genetic algorithms [32]. However, using such

techniques, the relationship between the notion of CR and corresponding physical/MAC protocol parameters cannot be well understood and exploited. Instead, by exploring the following relationship between the link utilization in the network and the CR with the proposed MAC protocol, we decompose the OP into two closely related subproblems.

Proposition 1: If the optimal helper selection is successful, the probability of link utilization improvement by beneficial cooperation is non-decreasing when the CR expands, and achieves the maximum when the CR is maximized.

We prove Proposition 1 in Appendix A.

Proposition 2: The probability of failed helper selection is impacted by the number of cooperative rate allocations generating a unique CCTR, but not the size of the CR.

We omit the proof as it is similar to the one given in Appendix A.

In light of the fact that an enlarged CR generally encourages more beneficial cooperation opportunities in the long run, we propose a two-phase decomposition method to determine the CR and to set the protocol parameters. In Phase-1, given W and R_1, we aim to maximize the size of a CR without considering contention collisions. In Phase-2, we decide the optimal protocol parameters from the feasible solutions generated in Phase-1 to maximize the average EPTR with respect to the CRs, taking account of possible contention collisions. The two decomposed OPs in Phases 1 and 2 are

Phase-1:

$$\begin{aligned} &\max \quad M \\ \text{s.t.} \quad &J_{g,m}(1) \geq \rho W/(T_{1,P}+T_{1,O}), \\ &(3c),\ (3d),\ (3e),\ \text{and}\ (3f) \end{aligned} \tag{4}$$

Phase-2:

$$\begin{aligned} &\max \quad L=\sum_{g=1}^{G}\sum_{m=1}^{n_g} J_{g,m}(n)/M_{\max} \\ \text{s.t.} \quad &1\leq G\leq M_{\max},\ \textstyle\sum_{g=1}^{G} n_g = M_{\max}, \\ &(3b),\ (3c),\ (3e),\ \text{and}\ (3g) \end{aligned} \tag{5}$$

where $M_{\max}$ is the optimal solution obtained in Phase-1. In the following, we propose an optimal grouping based greedy algorithm to solve the OPs (4) and (5).

Optimal Grouping: To reduce overhead in helper selection and thus enlarge a CR, we use a strategy named optimal grouping, i.e., grouping with optimal parameter setting. We define the optimal grouping as the one reduces the largest number of total slots in helper contention from that without grouping. Suppose there exist $M=\sum_{g=1}^{G} n_g$ CCTRs in the CR. For any G-group $(n_1, n_2, ..., n_G)$, compared to the strategy without grouping, let C_M denote the the backoff slot number reduction achieved by the proposed group contention method.

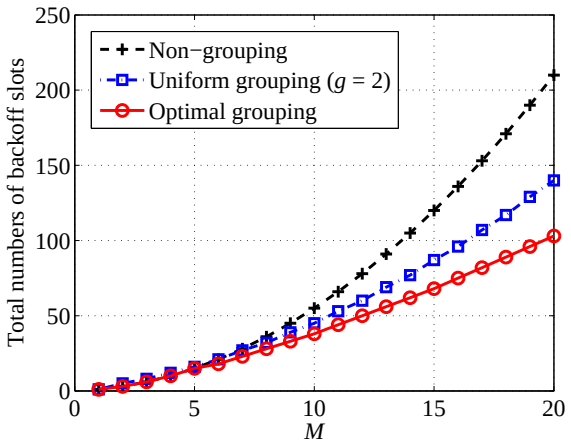


Fig. 3. A comparison of backoff slot number among non-grouping, uniform grouping (with $g=2$), and optimal grouping.

Then, we have

$$\begin{aligned} C_M &= \underbrace{(1-2)\times n_1}_{\text{group 1}} + \underbrace{[(n_1+1)-3]\times n_2}_{\text{group 2}} + ... \\ &\quad + \underbrace{\left[\left(\sum_{i=1}^{G-1} n_i + 1\right) - (G+1)\right]\times n_G}_{\text{group } G} \\ &= \sum_{j=1}^{G-1}\left[\sum_{i=1}^{j} n_i + 1 - (j+2)\right]\times n_{j+1} - n_1 \end{aligned} \tag{6}$$

where the members in group 1 take one more slot than the non-grouping alternatives (due to one additional slot for the GI signal); however, each member in other groups can save a significant number of backoff slots by utilizing grouping. Fig. 3 compares the overhead among non-grouping, uniform grouping (with $g=2$ and $|n_1-n_2|\leq 1$), and optimal grouping in terms of the total backoff slot number. We can see that, at an expense of computational complexity, the optimal grouping effectively reduces overhead as M increases. For instance, when $M=20$, more than 50% of backoff slots can be saved by the optimal grouping, as compared to the non-grouping one.

With optimal grouping, we propose a four-step greedy algorithm to solve the OPs in (4) and (5) to determine the CR and to set the protocol parameters. In step 1, without grouping we search all feasible rate combinations, thus determining the total initial number of useful CCTRs, M_0. In step 2, with optimal grouping, we do iterative search to check if more CCTRs can be useful due to the decreased helper selection overhead, thus obtaining $M_{\max}$. In step 3, after finding the groups with respect to $M_{\max}$ with the largest backoff slot number reduction, we set $\{G, n_1, n_2, ..., n_G\}$ according to the one maximizing $L=\sum_{g=1}^{G}\sum_{m=1}^{n_g} J_{g,m}(1)/M_{\max}$. In step 4, if the number of collided helpers n equals to 1, stop; otherwise (i.e., $n\geq 2$), for each CCTR in the CR, we set its minislot number $K_{g,m}$ according to the one maximizing $J_{g,m}(n)$ while satisfying (3b) and (3g). In the first two steps, we solve the OP in (4). The iterative search is to minimize the

overhead. The CR may increase as the overhead reduces. The last two steps are to address the OP in (5). We set the optimal protocol parameters from the feasible solutions generated from optimal grouping. The proposed greedy algorithm is shown in Algorithm 1.

Algorithm 1: Optimal grouping based greedy algorithm

input : rate set $\mathcal{R}$, balance factor ρ, direct transmission rate R_1, payload length W, number of collided helpers n

output: $\mathcal{C}$, $M_{\max}$, G, $\{n_g\}_{g=1}^{G}$, $\{K_{1,m}\}_{m=1}^{n_1}, \{K_{2,m}\}_{m=1}^{n_2}, ..., \{K_{G,m}\}_{m=1}^{n_G}$

$\mathcal{S}_1 \leftarrow \{(x,y,z)|x,y \in \mathcal{R}, z = xy/(x+y)\}$;
$\mathcal{S}_2 \leftarrow \{(x_i,y_i,z_i)|(x_i,y_i,z_i) \in \mathcal{S}_1, z_i \geq z_{i+1}$ for $i = 1,2,...,|\mathcal{S}_1|-1\}$;
$\mathcal{C} \leftarrow \emptyset$; $t \leftarrow \rho W/(T_{1,P}+T_{1,O})$; $R_{C1} \leftarrow x_1$; $R_{C2} \leftarrow y_1$; $R_h \leftarrow z_1$;
$g \leftarrow 1$; $m \leftarrow 1$; $i \leftarrow 0$; $M_0 \leftarrow 0$; $J_{g,m}(1) \leftarrow W/(T_{3,P}(R_{C1},R_{C2}) + T_{3,O}(g,m))$;
while $J_{g,m}(1) > t$ **do**
  while $J_{g,m}(1) > t$ **do**
    $\mathcal{C} \leftarrow \mathcal{C} \cup \{(R_1, R_{C1}, R_{C2})\}$; $i \leftarrow i+1$; $M_0 \leftarrow M_0 + 1$;
    while $z_i == R_h$ **do**
      $R_{C1} \leftarrow x_i$; $R_{C2} \leftarrow y_i$; $\mathcal{C} \leftarrow \mathcal{C} \cup \{(R_1, R_{C1}, R_{C2})\}$; $i \leftarrow i+1$;
    end
    $m \leftarrow m+1$; $R_{C1} \leftarrow x_i$; $R_{C2} \leftarrow y_i$; $R_h \leftarrow z_i$;
    $J_{g,m}(1) \leftarrow W/(T_{3,P}(R_{C1},R_{C2}) + T_{3,O}(g,m))$;
  end
  $(G_0^*, n_1^*, n_2^*, ..., n_{G_0^*}^*) \leftarrow \arg \max_{(G_0,n_1,n_2,...,n_{G_0}), \sum_{g=1}^{G_0} n_g = M_0} C_{M_0}$;
  $g \leftarrow G_0^*$; $m \leftarrow n_{G_0^*}^* + 1$; $J_{g,m}(1) \leftarrow W/(T_{3,P}(R_{C1},R_{C2}) + T_{3,O}(g,m))$;
end
$M_{\max} \leftarrow M_0$; $\{(\dot{G}^*, \dot{n}_1^*, \dot{n}_2^*, ..., \dot{n}_{\dot{G}^*}^*)\} \leftarrow \arg \max_{(\dot{G},\dot{n}_1,\dot{n}_2,...,\dot{n}_{\dot{G}}), \sum_{g=1}^{\dot{G}} \dot{n}_g = M_{\max}} C_{M_{\max}}$;
$(G, n_1, n_2, ..., n_G) \leftarrow \arg \max_{(G,n_1,n_2,...,n_G) \in \{(\dot{G}^*,\dot{n}_1^*,\dot{n}_2^*,...,\dot{n}_{\dot{G}^*}^*)\}} \{\sum_{g=1}^{G} \sum_{m=1}^{n_g} J_{g,m}(1)/M_{\max}\}$;
if $n > 1$ **then**
  for $g \leftarrow 1$ **to** G **do**
    for $m \leftarrow 1$ **to** n_g **do**
      $K_{g,m} \leftarrow \arg \max_{J_{g,m}(n) > t, K_{g,m} \geq 2} J_{g,m}(n)$
    end
  end
end

In practice, the number of collided helpers (n) needed in the algorithm can be estimated by letting the source observe the activities in its neighborhood (e.g., overhearing its neighbors' transmissions) and broadcast the information in the RTS packet. Then, with the same information on n, R_1 and W, any neighbor node can individually execute the proposed algorithm not only to check (for the current *S-D* pair) whether or not the CR is empty and its CCTR is in the CR, but also to identify the contention parameters for the optimal helper selection (i.e., the grouping structure) if the CR is not empty. Note that each node can have *a priori* information on ρ and $\mathcal{R}$ (thus being aware of all potential cooperative rate allocations), because both can be pre-allocated. The algorithm generates identical grouping structure for every helper candidate.

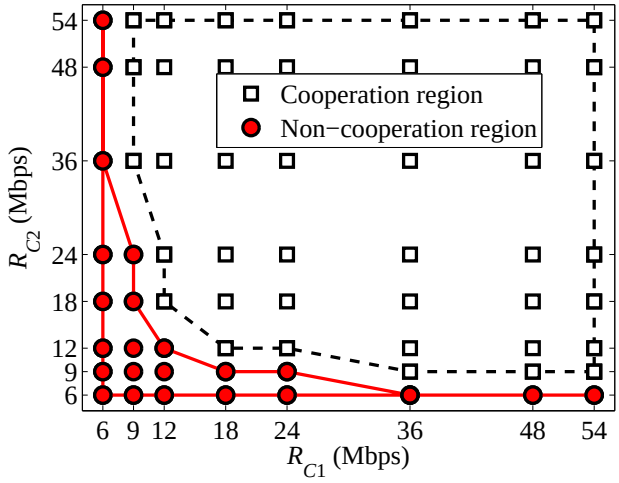


Fig. 4. Cooperation region versus non-cooperation region for $W = 1024$ bytes, $\rho = 1$, and $R_1 = 6$ Mbps.

Using the parameters of IEEE 802.11a [23], we evaluate the greedy algorithm via simulation. Fig. 4 illustrates a cooperation region, the feasible rate allocation of the $M_{\max}$ useful cooperative transmission rates obtained by the greedy algorithm, for $W = 1024$ bytes, $\rho = 1$, and $R_1 = 6$ Mbps. In the simulation, for simplicity, similar to [6], t_{fb}, T_{HI}, T_{GI}, T_{MI} and T_d are set to be the symbol duration, and the RTH packet to have the same size as the ACK packet.[4] In general, we find that the CR expands (shrinks) as R_1 decreases (increases). In other words, if the *S-D* link can support a high rate, direct transmission is preferred, as cooperative transmission would incur extra signaling overhead, lowering the EPTR. Besides, as W increases, more helper selection overhead is allowed to accommodate a cooperative transmission and more rate allocations can be supported in the CR. However, to assure a larger EPTR than the direct transmission, the overhead is always upper-bounded, thus not all cooperative rate allocations are beneficial. Further, the following observations are made: 1) Given W and ρ, there exists a threshold for a direct transmission rate R_1 (say $r_{th}(W,\rho)$) such that $M_{\max} = 0$ if $R_1 \geq r_{th}(W,\rho)$; 2) Given W, if $R_1 < r_{th}(W,\rho)$, $M_{\max}$ increases as R_1 decreases; 3) Given $R_1 < r_{th}(W,\rho)$, $M_{\max}$ is a non-decreasing function of W; 4) Given W or R_1, $M_{\max}$

[4]As we focus on the idea differentiating beneficial cooperation from unnecessary cooperation at the MAC layer, here we simplify the packet length setting. It should be noted that, a detailed approach of integrating the feedback information into the control packets can change the simulation results; but, the main trend should remain the same.

increases as ρ decreases.

IV. Probabilities of Successful Cooperation and Direct Transmission

To evaluate the significance of network performance gain via beneficial cooperation, we study and compare the probabilities of successful cooperation and direct transmission in the network with the proposed MAC protocol.

Let Λ denote the node set of potential helpers, including all nodes in the network except the source node S and the destination node D; and $\mathcal{D}_\ell \subseteq \Lambda$ denote the node subset consisting of ℓ useful helper candidates (i.e., cardinality $|\mathcal{D}_\ell| = \ell$) for the transmission from S to D. Specially, we define $\bar{\mathcal{D}}_0 := \{\mathcal{D}_\ell, \ell \geq 1\}$ to represent any non-empty helper candidate set. Further, given a data packet transmission with W-bit payload, let $\gamma_{th,q}$ denote the SNR threshold for a successful transmission with transmission rate $r_q \in \mathcal{R}$. Then, if the received SNR is in $[\gamma_{th,q}, \gamma_{th,q+1})$, r_q should be adopted in transmission, where $q = 1, 2, ..., Q$ and $\gamma_{th,Q+1} = \infty$ [33]. For a control packet, to guarantee a reliable delivery, only the lowest transmission rate r_1 is used. Define $\gamma_{th,0}$ as the SNR threshold for any control packet in the MAC protocol. As the length of a control packet is usually much shorter than that of a data packet, we assume $\gamma_{th,0} \leq \gamma_{th,1}$. For the transmission to the destination node in a cooperation mode, we consider DF based Alamouti-type distributed space-time coding (e.g., [26]) and packet combining (e.g., [28]). Under the assumption of perfect synchronization and channel estimation, the upper bound of the received SNR at the destination is $\gamma_C = 2\gamma_{SD} + \gamma_{HD}$ [34]. In the following, with this upper bound we evaluate the network performance.

Let $P(E_d)$ and $P(E_c)$ respectively denote the probability of successful cooperation and that of direct transmission. Since direct transmission happens only when control packets are successfully exchanged and cooperation is inactive, we have

$$P(E_d) = \int_{\gamma_{th,0}}^{\infty} p_{\gamma_{SD}}(\gamma) d\gamma - P(E_c) \tag{7}$$

where the integral gives the probability of a successful RTS/CTS handshake. In (7), $p_{\gamma_{SD}}(\gamma)$ is the probability density function of γ_{SD}. Consider a Rayleigh fading environment, where for the channel between nodes i and j, $p_{\gamma_{ij}}(\gamma) = \frac{1}{\bar{\gamma}_{ij}} e^{\gamma/\bar{\gamma}_{ij}}$, with $\bar{\gamma}_{ij} := E\{\gamma\}$ being the average received SNR [35]. Then, we can get $P(E_d) = e^{-\gamma_{th,0}/\bar{\gamma}_{SD}} - P(E_c)$. In the following, we derive $P(E_c)$, then $P(E_d)$ can be obtained from (7).

As discussed in Section III-C, given W and ρ, cooperation is not beneficial when the direct transmission rate R_1 is larger than or equal to a threshold $r_{th}(W, \rho)$. Let $\gamma_{th,g(W,\rho)}$ be the SNR threshold for the data rate $r_{th}(W, \rho)$, where $g(W, \rho)$ is the index of $r_{th}(W, \rho)$ in $\mathcal{R}$. Then, the proposed MAC protocol will utilize cooperation only when $\gamma_{th,0} \leq \gamma_{SD} < \gamma_{th,g(W,\rho)}$, where $\gamma_{SD} \geq \gamma_{th,0}$ is to ensure a successful exchange of the control packets. Let A_i denote the event $\gamma_{SD} \in [\gamma_{th,i-1}, \gamma_{th,i})$, for $i = 1, 2, ..., g(W, \rho)$, and B_i denote the event that there exists at least one helper candidate and A_i happens (i.e., $B_i = \bar{\mathcal{D}}_0 \cap A_i$). Further, if we respectively define G_l and I_n the events that the maximal CCTR appearing in the helper selection equals to $R_h^*(l)$ and the number of potential helpers with the maximal CCTR is n, then according to the proposed MAC protocol, we can characterize the scenario of the optimal helper selection by $B_i \cap G_l \cap I_n$. Whereby, taking account of the two cases of successful cooperation, no collision in the intra-group contention (i.e., Case III in Section III-B) and no collision in the minislot re-contention (i.e., Case IV in Section III-B), and applying the total probability theorem with respect to the channel quality of the direct link, the maximal CCTR appearing in the helper selection, and the number of the helper nodes with this CCTR, we can determine the probability of a successful cooperation as follows

$$\begin{aligned} P(E_c) = & \sum_{i=1}^{g(W,\rho)} \sum_{l=1}^{M_{\max}(i)} P(B_i, G_l, I_1) \\ & + \sum_{i=1}^{g(W,\rho)} \sum_{l=1}^{M_{\max}(i)} \sum_{n=2}^{|\Lambda|} P_c(n, K_l(i)) \cdot P(B_i, G_l, I_n) \end{aligned} \tag{8}$$

$$P(B_i, G_l, I_n) = \int_{\gamma_{th,i-1}}^{\gamma_{th,i}} P(\bar{\mathcal{D}}_0, G_l, I_n \,|\gamma_{SD} = \gamma) \cdot p_{\gamma_{SD}}(\gamma) d\gamma. \tag{9}$$

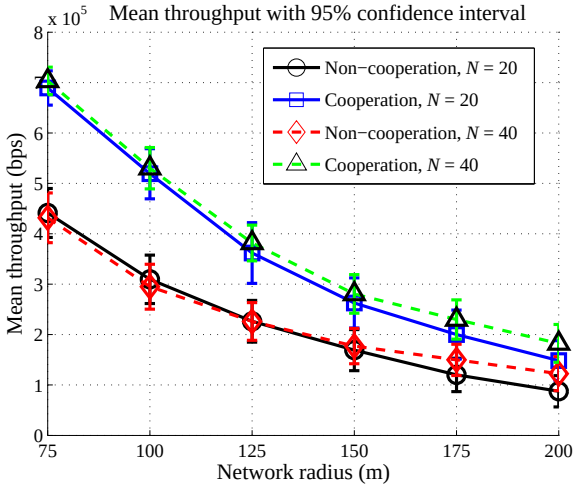
In (8), $P_c(n, K_l(i)) = \sum_{k=1}^{K_l(i)} P_w(n, k)$ is the probability that one of the n re-contending helpers wins the helper contention over the $K_l(i)$-minislot re-contention, $M_{\max}(i)$ and $K_l(i)$ are respectively referred to as the maximal number of CCTRs and the minislot number for the l^{th} largest CCTR in the CR when A_i happens. For presentation clarity, we derive $P(\bar{\mathcal{D}}_0, G_l, I_n \,|\gamma_{SD} = \gamma)$ in (9) in Appendix B.

V. Numerical Results

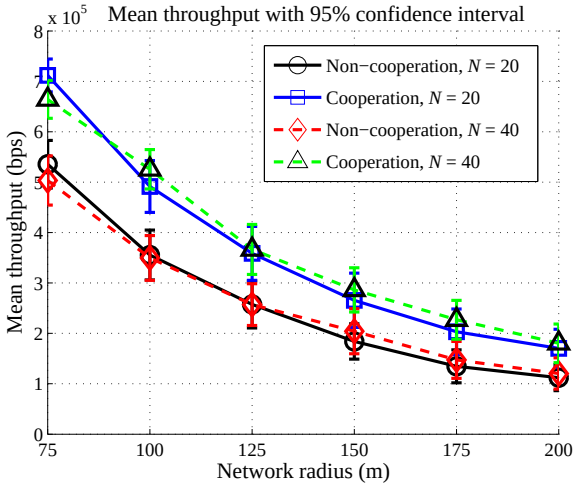
In this section, we evaluate the performance of the proposed cooperative MAC and verify the theoretical analysis. The tradeoff between multiuser diversity at the physical layer and the contention overhead at the MAC layer is to be presented. In the simulation, we adopt DF based distributed space-time coding, set $\rho = 1$ and $W = 1024$ bytes. Other parameters are set to be the same as in IEEE 802.11a 20MHz bandwidth transmission.

A. Network Performance

we evaluate the performance of the proposed cooperative MAC protocol versus node number N, channel quality, and network coverage area in terms of mean throughput and mean received packet delay. To unearth the impact of a fading channel, we model the channel with joint log-distance path loss and Rice fading where a larger K-factor means a better channel condition. The path-loss exponent is set to be 3.8. Nodes in the network are randomly deployed in a circular area. Ten traffic flows are simulated in the network, where packets in each traffic flow arrive according to a Poisson process with mean rate 10 packets per second. We perform the simulations for 30 runs and average the results, where each simulation run sustains a network time of 50 seconds.



(a) K-factor $= 0$.



(b) K-factor $= 10$.

Fig. 5. Mean network throughput versus network radius.

Fig. 5 depicts the relation between the mean throughput and the network radius. It is observed that the performance of each curve shown in Fig. 5(a) is upper-bounded by that of its corresponding curve shown in Fig. 5(b), due to a stronger line-of-sight component in propagation. Nonetheless, the network with beneficial cooperation outperforms that without cooperation in terms of mean throughput. The throughput improvement by beneficial cooperation is more significant in a poorer channel condition. This phenomenon asserts our understanding given in Section III-C that, if the *S-D* link cannot support a high data rate, its corresponding cooperation region is large, fostering more cooperation opportunities (see Fig. 4). Further, the performance gap between the cooperative and non-cooperative systems decreases as the network coverage radius increases. Since the channel condition between a relay and a source (destination) generally weakens as the network coverage radius increases which likely increases the distance between the nodes, the chance of beneficial cooperation decreases, thus reducing the mean throughput.

Notice that, in some cases, the performance improvement due to cooperation in a network with more nodes can be

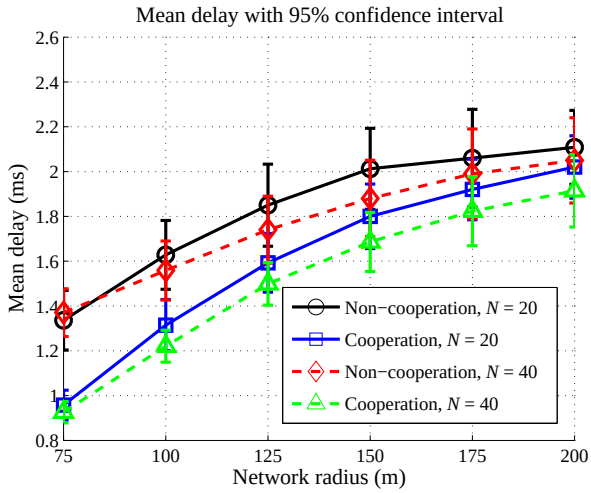


Fig. 6. Mean delay versus network radius for K-factor $= 0$.

less than that in a network with less nodes. In general, the number of helpers for a transmission pair increases as the node number in the network increases. From an information-theoretic perspective, the more the helpers, the higher multi-user diversity, and hence the better the system performance [9,36]. However, as observed in Fig. 5(b), the mean throughput of the cooperative system with 20 nodes is higher than that with 40 nodes, when the network radius is small. In fact, there are two factors determining the performance of the proposed cooperative MAC protocol: 1) physical-layer multi-user diversity gain; and 2) MAC-layer contention overhead. In general, the MAC-layer contention overhead increases with the node number, which can outweigh the gain due to multi-user diversity, and decrease network throughput.

Fig. 6 shows that cooperative communication achieves better delay performance than its counterpart, due to a higher throughput with cooperative communications. Thus, the waiting time (e.g., the backoff time before accessing and/or re-accessing the channel) for a node to transmit a packet is shortened. When the traffic load (i.e., the packet arrival rate) in the network increases, the proposed MAC protocol is still effective to improve the network performance, as the cooperative MAC protocol improves the efficiency of link utilization after a successful channel contention.

B. Transmission Probability

For the performance analysis, we perform simulations with the same communication model used in [37]. We normalize the distance between the source and the destination (i.e., the source and the destination are respectively at $(0, 0)$ and $(1, 0)$), and assume that the neighbor nodes are located between the source and the destination, on the straight line connecting them. We perform the simulations for 10 runs each with 10^4 data packet transmissions and average the simulation results. Figs. 7 and 8 show the simulation and analytical results of the probabilities of successful cooperation and direct transmission respectively in a single-neighbor case (at a distance of 0.1, 0.5, and 0.9 from the source). In the figures, d_{SN_j} denotes the

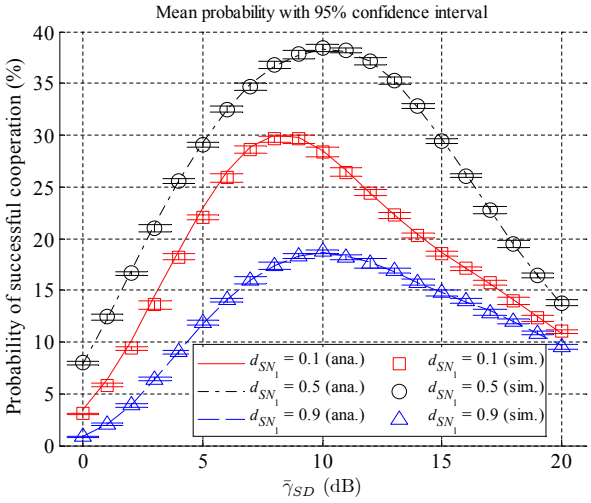


Fig. 7. Probability of successful cooperation with one neighbor node.

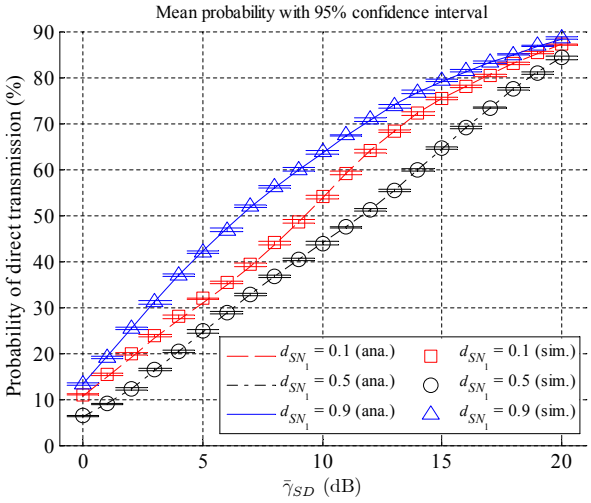


Fig. 8. Probability of direct transmission with one neighbor node.

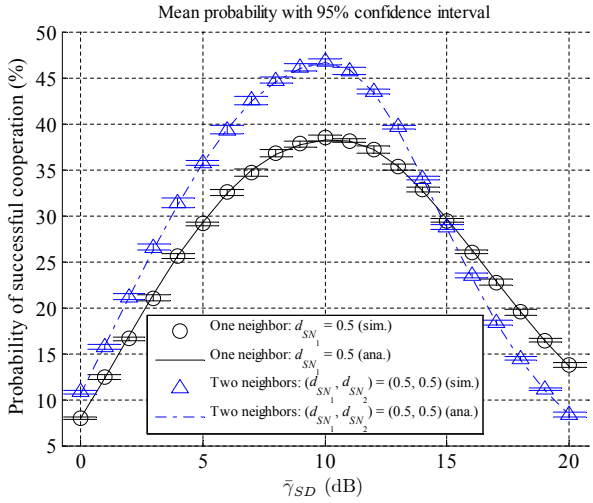


Fig. 9. Probability of successful cooperation with different number of neighbor nodes.

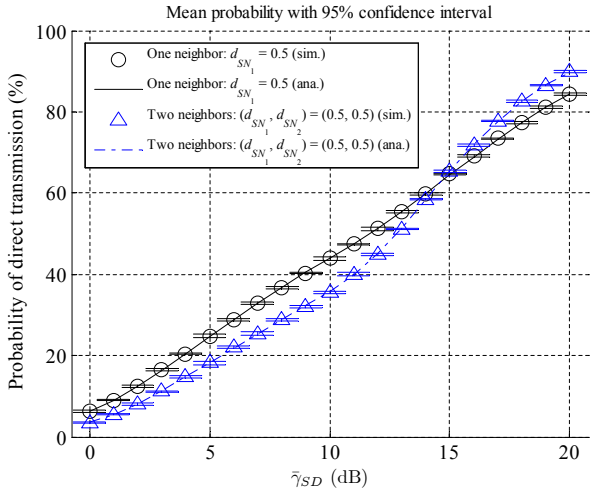


Fig. 10. Probability of direct transmission with different number of neighbor nodes.

distance between the source and the neighbor node N_j. It can be seen that the analytical results match with the simulation results. For the three neighbor positions, cooperative (direct) transmission obtains the most (least) opportunities when the neighbor is at the middle between the source and the destination. A neighbor closer to the source is easier to successfully initiate beneficial cooperation as compared to one closer to the destination. The observations are consistent with the results in [37,38] on the relation between the probability of successfully initiated beneficial cooperation and the position of a relay node. Further, the probability of successful cooperation first rises then declines as the quality of the direct link improves. The rationale is that: 1) if the propagation environment is hostile, the size of CR is large, whereby more cooperative transmissions are fostered when the channel quality improves to allow a successful RTS/CTS handshake; however, 2) if the channel quality further improves, the cooperation probability decreases as employing direct transmission is more likely to dominate cooperative transmission.

Figs. 9 and 10 show the relationship between the number of neighbor nodes and the two transmission probabilities for different channel conditions. In a low and middle SNR regime ($\bar{\gamma}_{SD} < 15$ dB), a larger number of neighbor nodes provide more chances to successfully utilize the beneficial cooperative communications; however, in a high SNR regime ($\bar{\gamma}_{SD} \geq 15$ dB), the situation is opposite, meaning that a smaller number of neighbor nodes lead to a bigger probability of beneficial cooperation. This phenomenon asserts the existence of a tradeoff between multi-user diversity gain at the physical layer and the MAC-layer contention overhead. As the quality of the direct link improves, the cooperation region shrinks, and cooperation is less likely to be beneficial. In this case, having more neighbor nodes does not provide a higher diversity gain, but resulting in more collisions in the optimal helper contention.

VI. Conclusions

To unearth benefits of cooperative communications in a distributed wireless network, we have studied two fundamental

issues, namely when to cooperate and whom to cooperate with, from a cross-layer protocol design perspective. In specific, based on the newly introduced concept of cooperation region, we have proposed a novel cross-layer MAC protocol that can differentiate beneficial cooperation from unnecessary cooperation. Effective helper selection is integrated into the MAC protocol. To improve link utilization and thus increase network throughput, optimal grouping of helpers for signaling overhead minimization is considered, and a greedy algorithm for protocol refinement is devised. Simulation results demonstrate that the proposed approach with beneficial cooperation outperforms its non-cooperative counterpart in terms of throughput and delay performance. The probabilities of successful cooperative communications and direct transmission are derived. We have investigated the impacts of channel quality, helper node position, and helper node number on the beneficial cooperation. Further, analytical and simulation results shed some light on the tradeoff between physical-layer multi-user diversity gain and MAC-layer contention overhead. For the future work, to exploit beneficial cooperation in a multi-hop wireless network, we will integrate the function of load balance into our cross-layer protocol design. Further, more cooperation techniques including coded cooperation will be exploited and evaluated.

APPENDIX A
PROOF OF PROPOSITION 1

Consider that the CR expands from the area of a high CCTR to the area of a low CCTR. Given ρ, W, and R_1, let $\mathcal{M}$ denote an initial set consisting of a group of beneficial cooperative rate (R_{C1}, R_{C2}) allocations, which corresponds to M CCTRs, $R_h^*(i)$, $i = 1, 2, ..., M$, where $R_h^*(i) > R_h^*(j)$, if $i < j$. Denote by $A(i)$ ($\bar{A}(i)$) the event that a node with CCTR $R_h^*(i)$ is present in (absent from) the helper selection. Then, according to our helper selection method, if the helper selection is successful, the probability of link utilization improvement can be expressed as $P_s(\mathcal{M}|\rho, W, R_1) = \sum_{i=1}^{M} P_i$, where $P_i = P\left(\left(\bigcap_{j=1}^{i-1} \bar{A}(j)\right) \cap A(i) \,|\rho, W, R_1\right)$ is the conditional probability that, given ρ, W, and R_1, any node with a CCTR higher than $R_h^*(i)$ is absent from the optimal helper contention, and the node with $R_h^*(i)$ is successfully selected (either with or without minislot re-contention).

Then, if the CR expands due to a new cooperative rate allocation (R'_{C1}, R'_{C2}) offering a higher EPTR than the direct transmission, the new CR becomes $\mathcal{M}' = \mathcal{M} \cup \{(R_1, R'_{C1}, R'_{C2})\}$. If $R'_{C1}R'_{C2}/(R'_{C1}+R'_{C2}) \neq R_h^*(M)$, let $R_h^*(M+1) = R'_{C1}R'_{C2}/(R'_{C1}+R'_{C2})$ denote the new CCTR, which satisfies $R_h^*(M+1) < R_h^*(i)$, $1 \leq i \leq M$. Then, if the helper selection is successful, the probability of link utilization improvement due to beneficial cooperation defined in $\mathcal{M}'$ increases to $P_s(\mathcal{M}'|\rho, W, R_1) = P_s(\mathcal{M}|\rho, W, R_1) + P\left(\left(\bigcap_{j=1}^{M} \bar{A}(j)\right) \cap A(M+1) \,|\rho, W, R_1\right) \geq P_s(\mathcal{M}|\rho, W, R_1)$. On the other hand, if $R'_{C1}R'_{C2}/(R'_{C1} + R'_{C2}) = R_h^*(M)$, P_M increases due to a new cooperative rate allocation (R'_{C1}, R'_{C2}) available for the potential helpers. Thus, we still have $P_s(\mathcal{M}'|\rho, W, R_1) \geq P_s(\mathcal{M}|\rho, W, R_1)$. Overall, given a successful helper selection, expanding CR does not decrease the probability of link utilization improvement by beneficial cooperation. Since $P_s(\mathcal{M}|\rho, W, R_1)$ is a monotonically non-decreasing function of $\mathcal{M}$, $P_s(\mathcal{M}|\rho, W, R_1)$ achieves the maximum when $\mathcal{M}$ expands to the maximum, which concludes the proof.

APPENDIX B
DERIVATION OF $P(\bar{\mathcal{D}}_0, G_l, I_n \,|\gamma_{SD} = \gamma)$

To find $P(\bar{\mathcal{D}}_0, G_l, I_n \,|\gamma_{SD} = \gamma)$, we note that, given I_n, the number of total helper candidates ℓ can range from n to $|\Lambda|$. Further, within the ℓ helper candidates, different nodes can be the optimal helpers (i.e., the nodes with the maximal CCTR). Let $\mathcal{O}_n$ ($\subseteq \mathcal{D}_\ell$) denote the node subset consisting of the n optimal helpers. With independent channels among the nodes and across different packet transmissions, whether or not a node is a helper candidate (or the optimal helper) is independent of other nodes. Thus, by applying the total probability theorem with respect to the helper candidate number, the helper candidate set, and the optimal helper set, we have

$$P(\bar{\mathcal{D}}_0, G_l, I_n \,|\gamma_{SD} = \gamma) = \sum_{\ell=n}^{|\Lambda|} \sum_{\mathcal{D}_\ell} \sum_{\mathcal{O}_n} \left(\prod_{N_j \notin \mathcal{D}_\ell} P_{1,j} \prod_{\substack{N_j \in \mathcal{D}_\ell \\ N_j \notin \mathcal{O}_n}} P_{2,j} \prod_{N_j \in \mathcal{O}_n} P_{3,j} \right) \quad (10)$$

where $P_{1,j} = 1 - P(N_j \in \bar{\mathcal{D}}_0 \,|\gamma_{SD} = \gamma)$, $P_{2,j} = P(N_j \in \mathcal{D}_\ell, R_h(N_j) < R_h^*(l) \,|\gamma_{SD} = \gamma)$, and $P_{3,j} = P(N_j \in \mathcal{D}_\ell, R_h(N_j) = R_h^*(l) \,|\gamma_{SD} = \gamma)$ denote the conditional probabilities that given γ_{SD}, node N_j is not a helper candidate, node N_j is a helper candidate but not an optimal helper, and node N_j is an optimal helper, respectively. Here, $R_h(N_j)$ denotes the CCTR achieved via node N_j. In the following, to find $P_{1,j}$ we give the detail to calculate the conditional probability $P(N_j \in \bar{\mathcal{D}}_0 \,|\gamma_{SD} = \gamma)$ that given γ_{SD} node N_j is a helper candidate. Probabilities $P_{2,j}$ and $P_{3,j}$ can be obtained using a similar approach.

Given γ_{SD} (in $[\gamma_{th,0}, \gamma_{th,g(W,\rho)})$), a neighbor node N_j is a helper candidate if 1) it can receive both RTS and CTS packets without error and 2) its CCTR ($R_h(N_j)$) is no less than $R_h^*(M_{\max})$. Let C_j and D_j denote $\gamma_{SN_j} \geq \gamma_{th,0}$ and $\gamma_{N_jD} \geq \gamma_{th,0}$, respectively. Condition 1) corresponds to $C_j \cap D_j$. Condition 2), $R_h(N_j) \geq R_h^*(M_{\max})$, is denoted by F_j. Let u_l index a group of cooperative rate allocations (R_{C1}, R_{C2}) offering a CCTR equal to $R_h^*(l)$, and $F_j^{(l,u_l)}$ denote the event that node N_j with rate allocation strategy u_l achieves CCTR $R_h^*(l)$, where $l = 1, 2, ..., M_{\max}$. Then, we have $F_j = \bigcup_{l=1}^{M_{\max}} \bigcup_{u_l} F_j^{(l,u_l)}$. Further, for a CCTR $R_h^*(l)$ achieved by rate allocation strategy u_l, let $\Omega_{l,u_l}^{(1)} = \left[\gamma_{th,1}^{(l,u_l,1)}, \gamma_{th,2}^{(l,u_l,1)}\right)$ and $\Omega_{l,u_l}^{(2)} = \left[\gamma_{th,1}^{(l,u_l,2)}, \gamma_{th,2}^{(l,u_l,2)}\right)$ respectively denote the two SNR intervals to adopt the two allocated transmission rates (i.e., R_{C1} and R_{C2}), where $\gamma_{th,1}^{(l,u_l,i)}$ and $\gamma_{th,2}^{(l,u_l,i)}$ are in $\{\gamma_{th,q}\}_{q=1}^{Q+1}$, $i = 1, 2$. Then, if we respectively define $F_j^{(l,u_l,1)}$ and $F_j^{(l,u_l,2)}$ as the events that $\gamma_{SN_j} \in \Omega_{l,u_l}^{(1)}$,

and $\gamma_C \in \Omega_{l,u_l}^{(2)}$, we have $F_j^{(l,u_l)} = F_j^{(l,u_l,1)} \cap F_j^{(l,u_l,2)}$. With aforesaid relations, we can identify a helper node by $C_j \cap D_j \cap F_j = \overset{M_{\max}}{\underset{l=1}{\cup}} \underset{u_l}{\cup} \left(F_j^{(l,u_l,1)} \cap F_j^{(l,u_l,2)} \cap D_j \right)$, where in the derivation we utilize $C_j \cap F_j^{(l,u_l,1)} = F_j^{(l,u_l,1)}$. Then, we have

$$\begin{aligned} &P(N_j \in \bar{\mathcal{D}}_0 \,|\gamma_{SD} = \gamma\,) \\ &= P\left(\overset{M_{\max}}{\underset{l=1}{\cup}} \underset{u_l}{\cup} \left(F_j^{(l,u_l,1)} \cap F_j^{(l,u_l,2)} \cap D_j \right) |\gamma_{SD} = \gamma \right). \end{aligned} \tag{11}$$

To tackle (11), we utilize a proposition given in the following.

Proposition 3: The $F_j^{(l,u_l)}$s are mutually exclusive for different values of l and/or u_l.

The proposition can be proved by individually considering two cases with contradiction, the case of different l's and the case of the same l and different u_l's. Here, however, we omit the proof due to space limitation. Based on Proposition 3, (11) can be further derived as follows

$$\begin{aligned} &P(N_j \in \bar{\mathcal{D}}_0 \,|\gamma_{SD} = \gamma\,) \\ &= \sum_{l=1}^{M_{\max}} \sum_{u_l} P\left(F_j^{(l,u_l,1)} \cap F_j^{(l,u_l,2)} \cap D_j \,|\gamma_{SD} = \gamma \right) \\ &= \sum_{l=1}^{M_{\max}} \sum_{u_l} P\left(F_j^{(l,u_l,1)} \,|\gamma_{SD} = \gamma \right) \\ &\qquad \times P\left(F_j^{(l,u_l,2)} \cap D_j \,|\gamma_{SD} = \gamma \right). \end{aligned} \tag{12}$$

Note that, the first equality of (12) holds because $\left(F_j^{(l,u_l,1)} \cap F_j^{(l,u_l,2)} \cap D_j \right)$s are also mutually exclusive if the $\left(F_j^{(l,u_l,1)} \cap F_j^{(l,u_l,2)} \right)$s are, according to Proposition 3, and the second equality holds because $F_j^{(l,u_l,1)}$ and $\left(F_j^{(l,u_l,2)} \cap D_j \right)$ are mutually independent. With some manipulation, $P\left(F_j^{(l,u_l,1)} \,|\gamma_{SD} = \gamma \right)$ and $P\left(F_j^{(l,u_l,2)} \cap D_j \,|\gamma_{SD} = \gamma \right)$ in (12) are

$$P\left(F_j^{(l,u_l,1)} \,|\gamma_{SD} = \gamma \right) = \begin{cases} e^{-\gamma_{th,1}^{(l,u_l,1)}/\bar{\gamma}_{SN_j}} - e^{-\gamma_{th,2}^{(l,u_l,1)}/\bar{\gamma}_{SN_j}}, & \text{if } \gamma_{th,1}^{(l,u_l,1)} \neq \gamma_{th,Q} \\ e^{-\gamma_{th,1}^{(l,u_l,1)}/\bar{\gamma}_{SN_j}}, & \text{if } \gamma_{th,1}^{(l,u_l,1)} = \gamma_{th,Q} \end{cases} \tag{13}$$

$$P\left(F_j^{(l,u_l,2)} \cap D_j \,|\gamma_{SD} = \gamma \right) = \begin{cases} e^{-\frac{a}{\bar{\gamma}_{N_j D}}} - e^{-\frac{b}{\bar{\gamma}_{N_j D}}}, & \text{if } \gamma_{th,0} < a \cap \gamma_{th,1}^{(l,u_l,2)} \neq \gamma_{th,Q} \\ e^{-\frac{\gamma_{th,0}}{\bar{\gamma}_{N_j D}}} - e^{-\frac{b}{\bar{\gamma}_{N_j D}}}, & \text{if } a \leq \gamma_{th,0} < b \cap \gamma_{th,1}^{(l,u_l,2)} \neq \gamma_{th,Q} \\ 0, & \text{if } \gamma_{th,0} \geq b \cap \gamma_{th,1}^{(l,u_l,2)} \neq \gamma_{th,Q} \\ e^{-\frac{a}{\bar{\gamma}_{N_j D}}}, & \text{if } \gamma_{th,0} < a \cap \gamma_{th,1}^{(l,u_l,2)} = \gamma_{th,Q} \\ e^{-\frac{\gamma_{th,0}}{\bar{\gamma}_{N_j D}}}, & \text{if } \gamma_{th,0} \geq a \cap \gamma_{th,1}^{(l,u_l,2)} = \gamma_{th,Q} \end{cases} \tag{14}$$

where $a = \gamma_{th,1}^{(l,u_l,2)} - 2\gamma$ and $b = \gamma_{th,2}^{(l,u_l,2)} - 2\gamma$. Whereby, we can calculate $P_{1,j}$ in (10). With a similar approach, we can find $P_{2,j}$ and $P_{3,j}$ in (10) based on (13) and (14) as follows

$$\begin{aligned} P_{2,j} = \sum_{k=l+1}^{M_{\max}} \sum_{u_k} &P\left(F_j^{(k,u_k,1)} \,|\gamma_{SD} = \gamma \right) \\ &\times P\left(F_j^{(k,u_k,2)} \cap D_j \,|\gamma_{SD} = \gamma \right) \end{aligned} \tag{15}$$

$$\begin{aligned} P_{3,j} = \sum_{u_l} &P\left(F_j^{(l,u_l,1)} \,|\gamma_{SD} = \gamma \right) \\ &\times P\left(F_j^{(l,u_l,2)} \cap D_j \,|\gamma_{SD} = \gamma \right). \end{aligned} \tag{16}$$

With $P_{1,j}$, $P_{2,j}$, and $P_{3,j}$, we complete the deviation of $P(\bar{\mathcal{D}}_0, G_l, I_n \,|\gamma_{SD} = \gamma\,)$ in (10).

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