Distributed Cooperative MAC for Multihop Wireless Networks

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ABSTRACT

This article investigates distributed cooperative medium access control protocol design for multihop wireless networks. Cooperative communication has been proposed recently as an effective way to mitigate channel impairments. With cooperation, single-antenna mobile terminals in a multi-user environment share antennas from other mobiles to generate a virtual multiple-antenna system that achieves more reliable communication with a higher diversity gain. However, more mobiles conscribed for one communication inevitably induces complex medium access interactions, especially in multihop wireless ad hoc networks. To improve the network throughput and diversity gain simultaneously, we investigate the issues and challenges in designing an efficient MAC scheme for such networks. Furthermore, based on the IEEE 802.11 DCF, a cross-layer designed cooperative MAC protocol is proposed. The MAC scheme adapts to the channel condition and payload length.

INTRODUCTION

The limited radio spectrum and channel impairments are two key challenges in wireless communications. Although multiple-input multiple-output (MIMO) antenna systems can improve the capacity and reliability of wireless communications by utilizing multiplexing gain and diversity gain, respectively, packing multiple antennas on a small mobile terminal poses implementation difficulty. The cooperative communication approach [1, 2] provides a design alternative, where mobile nodes share their information and transmit cooperatively as a virtual antenna array, thus providing diversity without the requirement of additional antennas at each node. The main advantages of cooperative communications include:

- Increasing the communication reliability over a time-varying channel
- Increasing the transmission rate and decreasing communication delay across the network
- Reducing transmit power, decreasing interference, and improving spatial frequency reuse
- Enlarging transmission range and extending network coverage

Most existing work on cooperative communications focuses on various issues at the physical layer, and the advantages are often demonstrated by analyzing signaling strategies based on information theory. The signaling strategies typically involve coordinated transmission by multiple network nodes; but despite recent progress, there are still significant barriers to applying these results to the development of practical network protocols [3]. For example, many information theoretical results are based on asymptotically large data block length, and usually ignore the overhead need to set up and maintain coordinated transmissions. In practice, however, the payload length is always limited due to error control and may change with various applications, and overhead from each protocol layer is not negligible, especially when the payload length is short. Thus, the cooperation gain may disappear if higher-layer protocols are not appropriately designed. Moreover, the higher-layer protocols should operate according to the time-varying channel status due to user mobility, as cooperation can be inefficient under certain network conditions such as very good channel quality [1].

Hence, a higher-layer protocol for cooperative wireless communications should be not only payload-oriented (or application-oriented as the payload length may depend on applications), but also channel-adaptive. For efficient cooperative communication, operations at the physical layer should be coupled with those at higher layers of the protocol stack, in particular the medium access control (MAC) and network layers. In this article we focus on how physical-layer cooperation can influence and be integrated with the MAC layer for higher throughput and more reliable communication, rather than advantages of cooperation at the physical layer.

The remainder of this article is organized as follows. We first review related work on cooperative MAC. Next, we discuss various issues and challenges on designing an efficient cooperative MAC protocol, and then propose a novel cross-layer cooperative MAC based on the IEEE 802.11 distributed coordination function (DCF). Finally, we conclude the article with some remarks on further research on cooperative MAC design.

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RELATED WORK

While fairly extensive research has been carried out for the physical layer of cooperative communication networks [3], to the best of our knowledge, only a handful of papers [4–9] have considered relevant MAC design. Cooperative communications require many unique features in MAC, which should be distributed and cooperative for a multipoint-to-multipoint environment.

The existing cooperative MAC protocols can be classified into proactive schemes [4–7] and reactive schemes [8, 9]. In the former, the cooperation of the partner(s) is always provided by either the prearranged optimal [7, 10] or the random [4–6] helper(s) before the acknowledgment (ACK) from the receiver; while in the latter, the help from the partner(s) is initiated only when the negative acknowledgment (NACK) is received/detected.

In [4, 5], two similar protocols (called CoopMAC and *r*DCF) based on the IEEE 802.11 DCF are proposed to mitigate the throughput bottleneck caused by low-data-rate nodes. A high-rate node is allowed to help a low-rate node through two-hop transmission. With joint routing and cooperation, a cross-layer approach is introduced in [6]. Clusters of nodes near each transmitter form virtual multiple-input single-output (VMISO) link to a receiver on the routing table and as far as possible to the transmitter. Space-time codes are utilized to support transmission over a long distance, thus reducing the number of transmission hops and improving communication reliability. In [7] we propose a busy-tone-based cross-layer cooperative MAC (CTBTMA) protocol. Adaptive modulation and coding (AMC) and multimode transmission are scheduled together according to the channel condition to improve the network throughput. The use of busy tones helps to solve collisions in a cooperation scenario and to address the optimal helper selection problem. Reactive schemes [8, 9] have a similar strategy, which let neighbor(s) (overhearing the packet) retransmit the packet instead of the source node when the NACK is detected.

ISSUES AND CHALLENGES IN MULTIHOP COMMUNICATIONS

When cooperative diversity is adopted in multihop wireless networks, a cooperation-based MAC scheme needs to be carefully designed. Some questions need to be answered, such as:

- Cooperate or not cooperate
- If cooperate, who the helper(s) should be and how to do the selection
- How to solve the new hidden and exposed terminal problem in cooperation scenarios
- Rate maximization or interference minimization

Indeed, all the questions are related to cooperative MAC, as discussed in more detail in the following.

COOPERATE OR NOT COOPERATE

For the first question, information theoretical analysis provides some indication whether or not cooperation outperforms noncooperation. A thorough comparison can be done from a diversity-multiplexing trade-off point view [3]. However, in practice, inefficiency will be inevitably introduced in communications by protocol overhead, and limited payload length will reduce the cooperation gain obtained under an asymptotically large block length. As cooperation introduces complexity, a MAC protocol should be carefully designed to prevent unnecessary cooperation, which means that an appropriate cooperative MAC protocol must have the ability to adapt to the payload length and the channel condition simultaneously. Cross-layer design between the physical and MAC layers is required.

The two MAC protocols, CoopMAC [4] and *r*DCF [5], have some ability to address the problem. Enquiries are sent out to one selected potential helper to check whether it can improve the source-destination single hop rate by high-rate two-hop transmission; however, the helper selection is not optimal as it is based on the observation of historical transmissions. Furthermore, the required information exchanges or waiting for an unresponsive helping request may result in inefficiency. The CTBTMA protocol [7] using instantaneous throughput maximization as a criterion can answer this first question. Nevertheless, the optimal helper selection needs to be refined, as discussed next.

WHO THE HELPER(S) SHOULD BE AND HOW TO SELECT

When cooperation is beneficial, which node should be the helper(s), and how should the node(s) be selected? There may be a number of helpers that can potentially improve the transmission quality (e.g., resulting in higher throughput and lower bit error rate) from a source to a destination. Without a central controller, how to find the optimal one(s) effectively and efficiently is vital to a practical MAC protocol.

First, let us look into the relation between the helper number and the cooperation gain. In general, from an information theory point of view, the more the helper number, the larger the diversity gain, which means that the reliability of communications is enhanced with an increased helper number. However, due to the half-duplex constraint or orthogonal transmission constraint, without complex physical-layer techniques such as distributed space-time codes, the data rate will certainly decrease. The essential dilemma may be traced back to the diversity-multiplexing trade-off in multiple-antenna channels, and the constraint of distributed cooperation further deteriorates this phenomenon.

From a MAC layer point of view, when many helpers are conscribed for one communication, two issues are well worth our attention. First, interference range will be enlarged proportionally to the helper number, and it may affect the spatial frequency reuse in wireless networks. A comparison of the interference range for multi-helper and single-helper cooperation is shown in Fig. 1. Second, more control overhead is required in multi-helper scenarios. When multi-helper cooperation fails in finding a sufficient number of helpers in a high traffic load situa-

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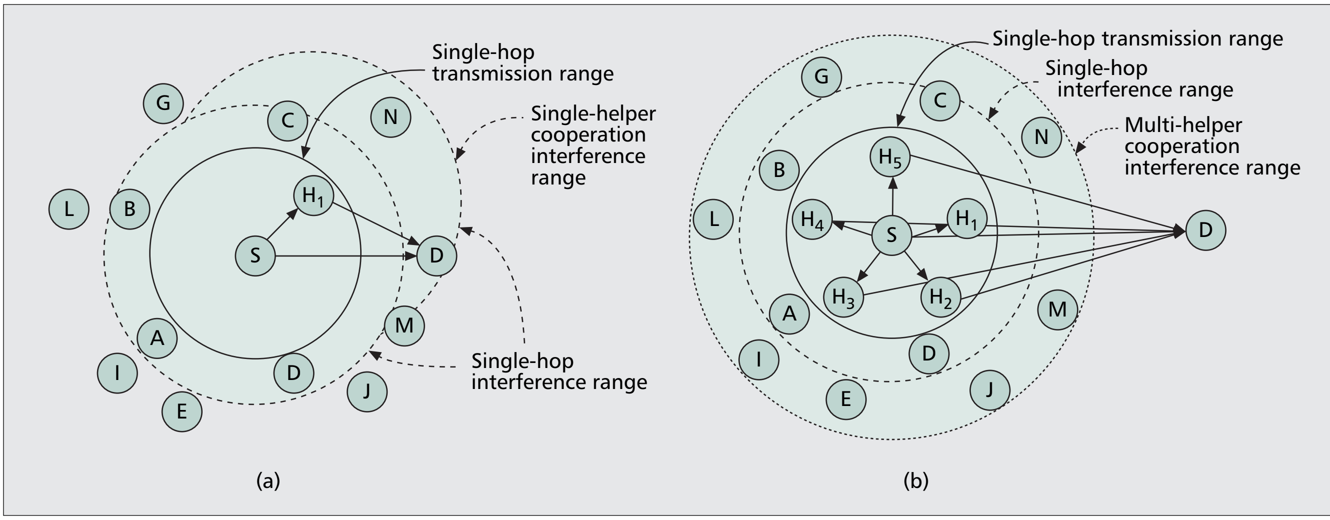


■ **Figure 1.** *a) Interference range in single-helper cooperation; b) interference range in multi-helper cooperation.*

tion, radio resources are wasted in information exchanges and unsuccessful transmissions. The VMISO protocol in [6] faces this problem. Some trade-off has to be made between the performance improvements by successful multi-helper cooperation and radio resource waste otherwise.

As to the helper selection, the CTBTMA protocol [7] uses a busy tone to select the optimal helper. The helper sends the longest busy tone to win the helper selection. However, the busy-tone duration consumes resources in terms of time and spectrum. It is desired to let the optimal helper win the channel as soon as possible. The backoff scheme for service differentiation in IEEE 802.11e can be imitated to overcome the problem. The better the helper, the shorter the backoff time. A similar idea can be found in [10], where the instantaneous channel condition is used as a parameter related with the backoff time. Information theoretical analysis of outage probability shows that the backoff scheme in [10] achieves the same diversity-multiplexing trade-off as a multi-helper cooperative protocol, where coordination and distributed space-time coding are required. In the following, we focus on the case of a single helper.

Hidden and Exposed Terminal Problems

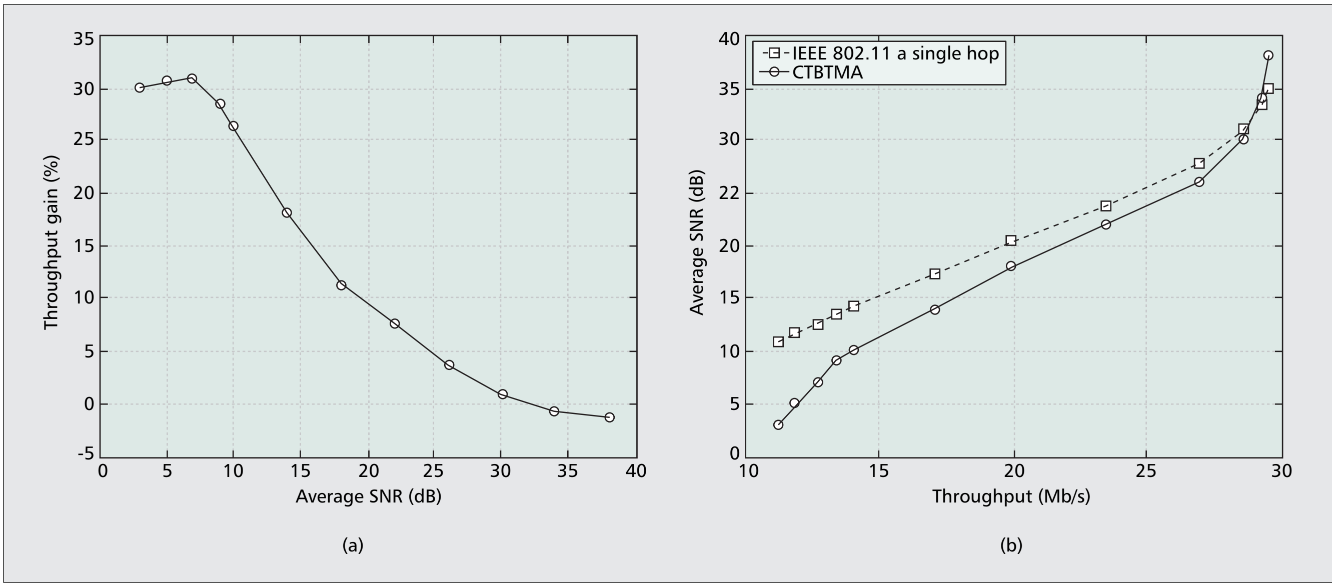
Cooperative communication introduces new aspects to the notorious hidden and exposed terminal problems in mobile ad hoc networks. A helper here not only receives packets from the source, but also transmits the packets to the destination. Thus, the transmissions from neighbors of the helper should also be carefully scheduled to avoid collisions. Otherwise, the cooperation gain can be reduced. Busy-tone-based protocols such as CTBTMA [7] can address the problem, at the cost of busy tones in both transmit power and spectrum and in implementation complexity (which is unavoidable in all busy-tone-based MAC schemes). IEEE 802.11 DCF-based protocols use request-to-send (RTS)/clear-to-send (CTS) handshake to alleviate the hidden and exposed terminal problem. Modifications to the handshake process and its setting of net allocation vector (NAV) strategy are all needed to accommodate the cooperative communication.

Rate Maximization or Interference Minimization

The trade-off between rate maximization and interference minimization comes from the merit of cooperative communication, diversity gain. With the diversity, throughput or transmission rate can be improved as shown in Fig. 2a, and the average signal-to-noise (SNR) requirement or transmit power can be decreased as shown in Fig. 2b [7].

With constant transmit power of all the senders, cooperative communication can increase transmission rate of an ongoing link, but also enlarge the interference range (as shown in Fig. 1), which is hostile to spatial frequency reuse. However, if the transmit power is set to the lowest requirement for a certain transmission rate, interference decreases, but the ongoing link may not have any rate increase. Thus, we need to balance the two aspects.

Most existing cooperative MAC protocols [4–9] use the strategy of rate maximization. One important consideration is that the control packets are always sent with fixed power. Taking IEEE 802.11 DCF as an example, the NAV setting is done using control packets, and no transmission is initiated if NAV is blocked and/or the channel is sensed busy at the physical layer. That is, decreasing transmit power in sending data packets is not only harmful to the node's ongoing transmission rate, but can also allow the nodes in the original interference range (rather than in the single-hop transmission range) to initiate new transmissions (e.g., sending control packets with fixed power), which spoils the ongoing transmission. Although it seems that interference minimization is inferior to rate maximization, cooperative communication gives us a good chance to make use of spatial frequency reuse. Thus, a large throughput gain is still possible to achieve by an interference minimization strategy.



■ **Figure 2.** *a) Throughput gain of CTBTMA with IEEE 802.11a for a single-hop transmission; b) average SNR vs. throughput of CTBTMA and IEEE 802.11a for a single-hop transmission [7].*

CROSS-LAYER MAC DESIGN

In this section we propose a cross-layer cooperative MAC scheme, taking into account the preceding issues and challenges. The proposed scheme is based on IEEE 802.11 DCF and is capable of addressing the issues associated with cooperative communications. We first assume that cooperation is always needed and design the MAC protocol; then we investigate the impact of the protocol on the value of cooperation so as to let the protocol intelligently determine whether cooperation is worthwhile. We use a utility-based optimization problem on the protocol parameters and cooperation gain to achieve the goal and further optimize the performance of the protocol.

HELPER SELECTION AND HANDSHAKE PROCESS

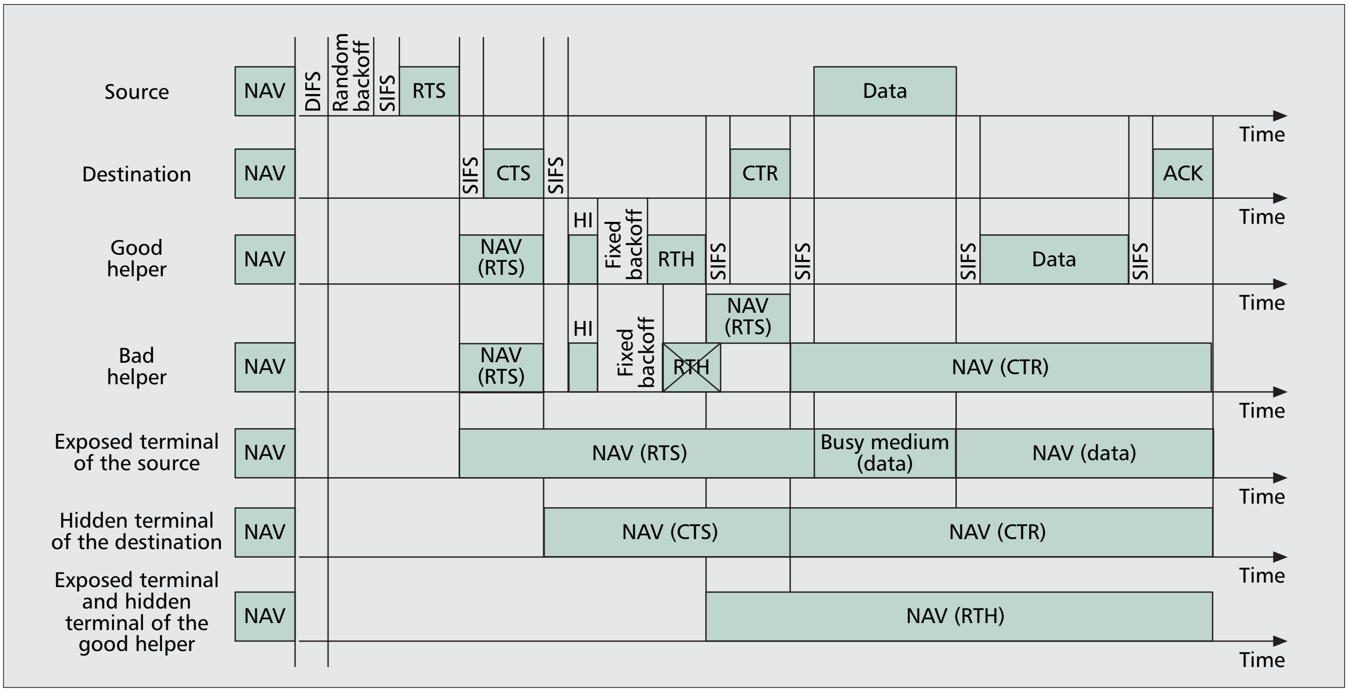
We design our cooperative MAC scheme based on the proactive approach, and the reactive approach can be automatically integrated with the protocol when we consider packet retransmissions later. Under the assumption of cooperative communication, we first devise a helper selection method.

We adopt the helper selection method proposed in [10], where the helper nodes monitor instantaneous channel conditions toward the source and destination via the RTS and CTS packets, and then decide in a distributed fashion which node has the strongest path for information relaying by letting the stronger path holder send a flag packet earlier. In [10] only one constant transmission rate is considered. Since the handshake between the pair of source and destination nodes has already taken place via exchanging the RTS/CTS packets, data transmission should be successful most of the time. Hence, using a helper means losing half the transmission rate. For uncoded proactive cooperation, due to the half-duplex constraint for orthogonal transmission, the overall data rate with cooperation is half that without cooperation. Coded cooperation based on channel coding has the ability to reduce the rate loss to a certain degree. Coding for different channel conditions under a specific rate requirement can be a challenge, as the overall code rate for coded cooperation should be less than half because half of the symbols will be erased [3], while the most common coding rates in popular communication protocols are all at least half, which means that rate loss can still happen. Thus, it is desirable to have multirate transmissions to compensate for the rate loss.

To extend the relay selection method in [10] to a scenario of multiple rates, we let a helper that can support a *higher source-destination link rate* send a flag packet *earlier*, similar to [7]. A mapping relationship between the received signal-to-noise-and-interference ratio (SINR) and rate setting of the IEEE 802.11 MAC protocol should be explored to facilitate the multirate setting, under the assumption that a packet is transmitted successfully if the received SINR is above the corresponding threshold for the packet length. The relation simplifies calculation of the effective transmission rate, relieving mobile nodes of the complex calculation of packet error as in [7]. The SINR threshold for a known payload length for required transmission accuracy can be acquired by analysis or simulation.

We use Fig. 3 to explain the proposed IEEE 802.11 DCF-based cooperation MAC. A source node initiates its transmission by sending an RTS packet to its destination node after finishing its backoff. The destination node that is idle responds to the source node with a CTS packet including the estimated SINR. Each of the common neighbors (including both good and bad helpers) of the source and destination nodes hears both the RTS and CTS packets, and finds out the potential maximal cooperative source-destination transmission rate. If a neighbor is capable of increasing the transmission rate, it contends to be the helper as follows.

First, the neighbor sends out a helper indica-



■ **Figure 3.** *An illustration of IEEE 802.11 DCF-based cooperative MAC.*

tion (HI), similar to busy-tone-based helper selection methods; but the purpose of HIs is to make the source and destination nodes aware of the willingness and existence of the helpers rather than to determine which neighbor is the optimal helper. As there may not be any helper, the HI is vital. If there is no HI, the source starts sending the data packet immediately, which means our MAC has the ability to quickly switch between cooperation and non-cooperation modes.

Second, the optimal helper should be determined as soon as possible. After sending an HI, each competing helper sends out a ready-to-help (RTH) packet (i.e., the flag packet in [10]), after a backoff time. The backoff time is equal to $\tau(M - i)$, where M is the helper rate number, i is the index of the achieved maximal rate, and τ is a constant unit time. The variable M is a design parameter to be optimized based on channel condition and payload length. The value of τ can be set to the symbol duration [10].

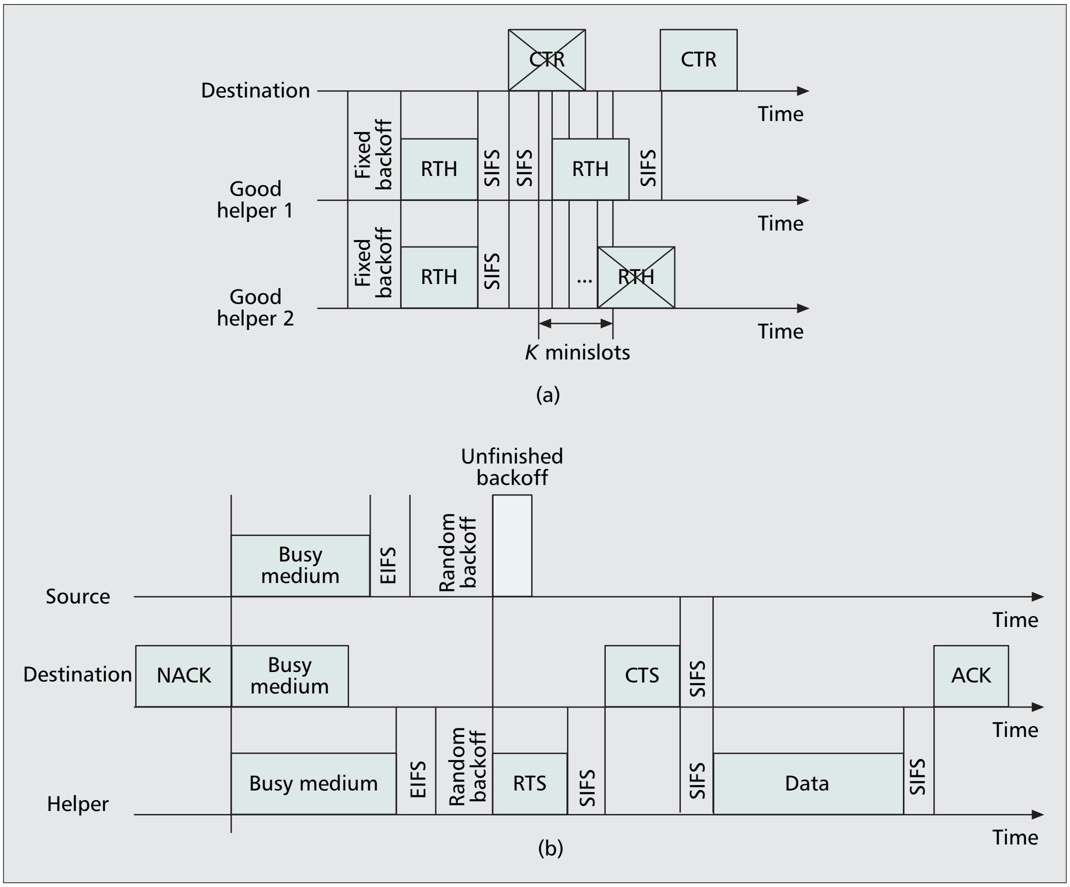
As in Fig. 3, the good helper ends the backoff process earlier than the bad helper; thus, it sends out an RTH packet first. The bad helper gives up contention and sets up its NAV after hearing the RTH packet from the good helper. After receiving the RTH packet, the destination node sends a clear-to-receive (CTR) packet (i.e., the broadcast message in [5]) to notify all helpers to stop contention (the helpers may be hidden to each other) and inform the source node to send data.

When there are multiple good helpers, the destination node does not send out the CTR packet, which will be detected by the good helpers after two short interframe spaces (SIFS), as shown in Fig. 4a. Then the good helpers resend their RTH packets in a random selected minislot from K minislots. The duration of a minislot is set equal to τ. The probability of RTH packet collision depends on the number of minislots. In this case the destination node sends out a CTR packet whenever an RTH packet collision happens, which has a one-bit stop label to notify all helpers to give up contention and invite the source node to start transmission without cooperation.

Retransmission Mechanism

Another issue that needs to be tackled is packet retransmission when the destination node responds with a NACK packet. We schedule the medium access for retransmission as shown in Fig. 4b. Usually, the helper has a better channel condition than the source node (otherwise, the helper should not be selected); hence, retransmission by the helper should be a better choice. Note that it is possible that user mobility can result in the helper being far away from the destination node after the medium becomes idle again. To deal with this situation, one approach is to let both the source and helper nodes contend to retransmit the data packet, with the helper increasing the contention window (CW) only by a step within [1, 2) and the source node doubling its CW. In Fig. 4b the helper accesses the medium earlier than the source node and sends the RTS packet to the destination node. To avoid retransmissions by different helper nodes, the retransmission is limited only by the prearranged helper or source node, without further cooperation in the retransmission; however, the destination node can jointly decode the newly received data packet and the previously received packet in error for improved accuracy.

For the reactive approach, since help from a relay node is activated only when the NACK packet is received, the mechanism is similar to the retransmission process of the proactive



■ **Figure 4.** *a) Solution to RTH packet collision by contention over* K *minislots; b) retransmission scheduling in cooperative transmission.*

approach. Thus, the reactive approach is incorporated in the proposed MAC protocol inherently.

Cooperation Decision and Protocol Optimization

Next, we present how the MAC protocol can determine whether cooperation is worthwhile. As discussed earlier, channel condition and payload length are the most important parameters that govern the optimal transmission mode. Cooperation is helpful only if the following condition is satisfied:

$$\max\{R_2, R_{coop}\} > R_1, \quad (1)$$

where R_2 is the effective payload transmission rate from the source to the destination with two-hop transmission, R_{coop} is the rate with cooperative communication, and R_1 is the rate in one-hop transmission without cooperation, taking into account the transmission overhead in the MAC protocols. The transmission rates can be determined based on channel conditions for the source-destination, source-helper, and helper-destination links. Note that without cooperative diversity, the rate of one- and two-hop transmissions depends on the single link, while the transmission rate of cooperative communication depends on all the links from the source to the destination. Taking the scenario in Fig. 1a as an example, the transmission rate of two-hop transmission from S to H_1 is only decided by link S-H_1, and the transmission rate of cooperative communication from S to D is based on all three links, S-H_1, S-D, and H_1-D.

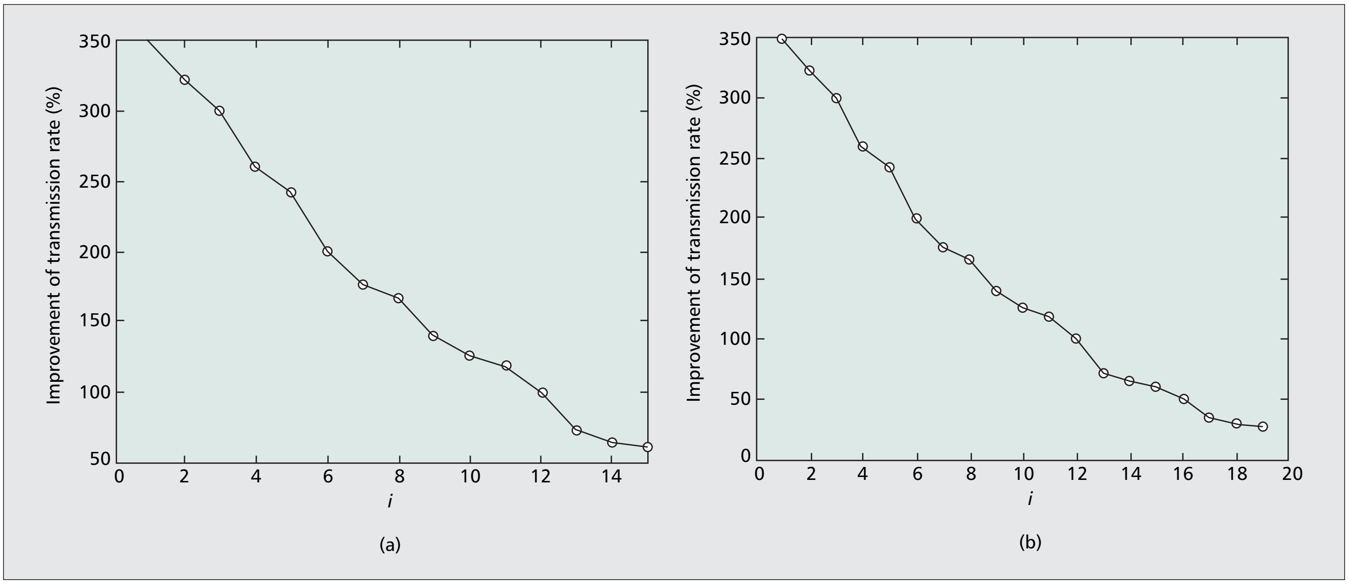
Payload (bytes)	Source-destination link rate (Mb/s)							
	6	9	12	18	24	36	48	54
500	15	6	0	0	0	0	0	0
1000	19	11	6	0	0	0	0	0
1500	20	12	8	1	0	0	0	0
2000	20	12	8	3	0	0	0	0

■ **Table 1.** *The optimal backoff length* M *for different payload length and source-destination link rate.*

The condition of inequality 1 can be equivalently represented by

$$\min\{T_2, T_{coop}\} < T_1, \quad (2)$$

where T_2, T_{coop}, and T_1 are the time duration



■ **Figure 5.** *The improvement of transmission rate with a payload of a) 500 bytes; b) 1000 bytes.*

required to send the same payload from the source to the destination, respectively, taking into account the overhead time in the MAC protocols.

A careful examination of inequality 2 reveals a relationship among the payload length, communication overhead, and the value of cooperation. The cooperation is meaningful only when the source-destination link has a low transmission rate and/or the payload length is sufficiently large compared with the communication overhead.

The condition of inequality 2 also gives us a straightforward way to find out whether a relay is needed under a specific channel condition and payload length. To find out whether a helper is useful or not, we only need to use the maximal supportable rate according to the SINR-rate mapping table to check whether or not inequality 2 is satisfied.

In addition, inequality 2 can help maximize the performance of the proposed MAC protocol, in terms of an optimal value for parameter *M*, the maximal fixed backoff length of the helper selection process. Using system parameters as in IEEE 802.11a and the length of RTH and CTR packets equal to the size of ACK packet, Table 1 shows computer exhaustive searching results of the optimal *M* values for four payload lengths, 500, 1000, 1500, and 2000 bytes, under eight channel conditions represented by the source-destination link rates. Figure 5 shows two examples of the improvement of transmission rate using the optimized *M* value, the source-destination link rate of 6 Mb/s, and payload of 500 and 1000 bytes, respectively. The numerical results are consistent with the relationship from inequality 2 among payload length, channel condition, and cooperation chances:

- Cooperation chances increase with the payload length.
- A meaningful cooperation happens when the source-destination channel can only support a low transmission rate.

With an optimal *M* value, the proposed cooperative MAC protocol always achieves higher throughput than that without cooperation for the cooperative links.

Concluding Remarks

Cooperative communication for wireless systems has recently attracted significant attention in the research community. Unlike conventional point-to-point communications, cooperative communications offers tremendous advantages such as allowing users (or nodes) to share resources to create collaboration through distributed transmission and processing. This new form of distributed spatial diversity can offer more reliable communications, increased network capacity, extended coverage area, and more energy-efficient transmissions. However, the higher-layer protocols of cooperative communication networks must be properly designed to take advantage.

We investigate how physical-layer cooperation can influence and be integrated with the MAC layer for higher throughput and more reliable communication. Several MAC layer issues and challenges are discussed for cooperative communication. A cross-layer design for cooperative MAC is presented to address the issues and meet the challenges. With channel and payload length adaptation, the proposed cooperative MAC protocol supports multiple transmission rates and transmission modes, and outperforms the traditional noncooperative MAC.

There are many open research issues in network protocol design for cooperative communications. For example, how to route a packet should be revisited. With cooperative communication, each node in the network assumes an additional new role: the helper. A routing protocol should balance traffic load in the presence of helpers. Also, as a helper uses its resources (e.g., transmit power) to assist transmission of other users, fairness in medium access should be studied. Furthermore, cooperation should not be limited to only transmission over links, but extended to a network-level approach to maximize the performance of the overall network.

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BIOGRAPHIES

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This new form of distributed spatial diversity can offer more reliable communications, increased network capacity, extended coverage area, and more energy efficient transmissions. However, the higher-layer protocols of cooperative communication networks must be properly designed to realize the advantages.