This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the WCNC 2008 proceedings.

A MAC-PHY Cross-Layer Protocol for Wireless Ad-Hoc Networks

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***Abstract*—Cooperative communications is a promising technology that tends to change the conventional access and transmission schemes in wireless networks. By enabling additional collaboration from nodes that otherwise will not directly participate in the transmission, it enables spatial diversity and dramatically improves the performance of the network. In this paper we propose a cross-layer cooperative protocol based on a MAC protocol called *CoopMAC* [1]–[3] for ad-hoc wireless networks in order to leverage cooperation in both MAC and PHY layer[1]. Exploiting physical layer combining at the receiver, this simple yet efficient scheme illustrates a new paradigm for realistic cross-layer cooperative protocol design for next generation wireless ad-hoc networks. We have evaluated the performance of the proposed protocol by extensive simulations in a large scale wireless ad-hoc network. Simulation results show that the new protocol significantly improves the network performance in terms of throughput and delay.**

***Index Terms*—Cooperative communications, medium access control, IEEE 802.11, ad-hoc network**

I. INTRODUCTION

The initial attempts for developing cooperative communications focused on physical layer schemes [4]–[6]. In these approaches, relay nodes close to the source process and retransmit the overheard information. The destination, by combining different copies of the same signal transmitted by the source and the relay nodes, can improve its ability to decode the original packet.

Although previous work proves the tremendous potential of cooperation in wireless communications, it does not define access methods that would support the new cooperative schemes in the physical layer. In order to take full advantage of the physical layer cooperative techniques, new access schemes are needed. The new MAC schemes must change the communication model of transmitter-receiver to transmitter-relay(s)-receiver. In the new environment, more than two nodes need to participate in an ongoing communication in a constructive way, enjoying the benefits of cooperation. A typical example toward this direction is a cooperative MAC protocol called CoopMAC presented in [1] [2], which introduces in the communication between two nodes a relay node (called helper) that forwards the packets from the transmitter to the receiver each time the direct channel between the transmitter and the receiver is inferior. In conventional wireless networks, when a source experiences a bad channel with a particular destination, it lowers its modulation scheme and coding rate in order to achieve a certain level of transmission reliability. In CoopMAC, the source can use an intermediate node (called helper) that experiences a relatively good channel with both the source and the intended destination. Instead of sending its packets directly to the destination at a low transmission rate, it transmits at a high rate to the helper, and then the helper forwards the packet to the destination in a high rate. By using a two-hop "alternative path" via the helper, which collectively is faster than the original direct link, the protocol can take advantage of the spatial diversity between the three nodes.

In this paper we propose and evaluate a new cooperative cross-layer mechanism, which forms a complete MAC-PHY layer framework that can realistically apply cooperation in next generation wireless ad-hoc networks. It leverages cooperation in the physical layer, yet provides the full MAC layer mechanism for the support of the cooperative scheme in the physical layer. The new mechanism uses an access scheme similar to CoopMAC in that it also relies on an intermediate node to "assist" in the communication between two nodes. However, the MAC layer protocol now has been substantially modified in order to support and leverage the PHY layer cooperation. Under the new scheme, the destination receives two copies of the original packet, one from the source and one from the helper, and combines them for the decoding. Decisions such as which node will be selected as the helper, and what should be the transmission rates in the second hop, are the main focus of this paper.

The rest of the paper is organized as follows. In section II we give a brief description of the main concepts of cooperative communications that is necessary for understanding the proposed protocol. In section III we describe the details of the mechanism in the MAC as well as the physical layer. A set of simulation results for a large scale ad-hoc network of 300 nodes along with the insights revealed therein are reported in Section IV. Section V completes the paper with our final conclusions and possible future work.

II. COOPERATIVE COMMUNICATIONS

In this section we introduce the basic concepts underlying cooperative communications. Cooperative techniques utilize the broadcast nature of wireless signals by observing that a source signal intended for a particular destination can be "overheard" at neighboring nodes. These nodes, called *relays*, *partners*, or *helpers* process the signals they overhear and transmit towards the destination. The relay operations can consist of repetition of the overheard signal (obtained for

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[1] This work is supported in part by the National Science Foundation (*NSF*) under award 0520054, the New York State Center for Advanced Technology in Telecommunications (*CATT*) and the Wireless Internet Center for Advanced Technology (*WICAT*), an NSF Industry/University Cooperative Research Center at Polytechnic University.

example by decoding and then re-encoding the information or by simply amplifying the received signal and then forwarding), or can involve more sophisticated strategies such as forwarding only part of the information, compressing the overheard signal and then forwarding. We refer the reader to [7] for a detailed overview of relaying methods. The destination combines the signals coming from the source and the relays, enabling higher transmission rates and robustness against channel variations due to fading. We note that the spatial diversity arising from cooperation is not exploited in current cellular, wireless LAN or ad-hoc systems; only one copy of the signal, whether it comes from the mobile directly or from a relay, is processed at the destination. Hence cooperative relaying is substantially different than traditional multi-hop or infrastructure based methods.

III. THE PROPOSED CROSS-LAYER PROTOCOL

A. *Motivation for Cooperation in 802.11 Wireless Networks*

A main feature that 802.11 networks use to cope with the changes in the quality of the wireless channel is rate adaptation. Based on the path loss and instantaneous channel fading conditions, a node defines its transmission rate for each packet. The better the channel is, the higher the transmission rate, and vice versa. For IEEE 802.11g, in particular, eight different rates, 6, 9, 12, 18, 24, 36, 48 and 54 Mbps are supported.

Using rate adaptation, nodes that are far away from each other experience poor channel quality and thus communicate at a lower rate (e.g., 6 or 9Mbps). This inefficiency not only affects the performance of the node that transmits, but also the performance of the neighboring nodes since now all the neighbors need to wait for the slow node to finish its transmission before sending their packets. The authors of [8] have shown that when there are several flows with different physical transmission rates, the throughput of all flows are bounded by the slowest transmission rate. Our cross-layer scheme solves this problem by using cooperation to significantly improve the performance of these slow nodes.

The main feature of our proposal is the involvement of a neighboring node in the communication between a source and a destination that experience poor channel conditions. In the following discussion we will call this node a *helper*. The helper node should ideally have a good channel with both the source and the destination. Under the proposed scheme, the source transmits the packet using a high transmission rate. The rate should be as high as is possible for the helper to be able to decode the signal. Both helper and destination will receive the transmitted signal. However, the destination will most likely not be able to decode it due to poor channel conditions with the source. Thus it stores the signal without decoding it. Once the helper receives the packet, it decodes it and resends it using a high transmission rate. The destination now receives a second copy of the same packet. It combines the two copies of the signals and decodes the signal that results from this combination.

B. *Cooperation in the MAC Layer*

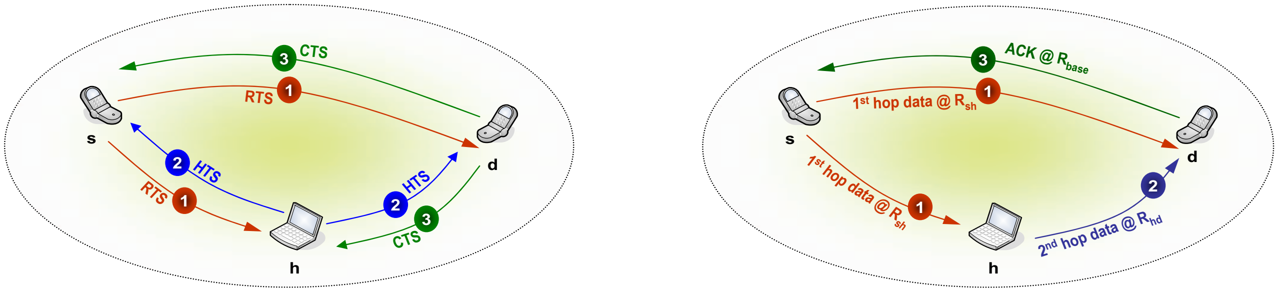
The MAC scheme of our cross-layer mechanism is based on a cooperative MAC protocol that is called CoopMAC [2] [3]. However, for the new scheme we have significantly modified CoopMAC to enable PHY layer cooperation. CoopMAC enhances the legacy IEEE 802.11 distributed coordination function (DCF) [9] in order to forward the packets from a slow source to the destination through a helper. Since the helper experiences good channel with both the transmitter and the receiver, the two hop transmission is done at high rates, improving in this way the network performance. Although this scheme enjoys some of the benefits of cooperation since it involves the helper in the communication, these benefits are limited since it does not use any cooperative scheme in the PHY layer. Actually, the receiver only receives and decodes the packet transmitted by the helper and ignores the initial packet. However, the new scheme combines the benefits of CoopMAC and PHY layer cooperation by using combining at the receiver, thereby maximizing the gains of cooperation at MAC layer.

In the following, we are going to give the details of the protocol. As shown in Figure 1, s, h and d represent the source, helper and destination node, respectively. R_{sd}, R_{sh} and R_{hd} denote the sustainable rates between s and d, between s and h, and between h and d, respectively.

1) The Access Control Scheme: The basic operation of the cooperative MAC protocol is described in Figure 1. Before the transmission of a packet, node s decides whether it will use cooperation or not. This depends on the availability of a candidate helper and the rates it can support in this cooperative communication. In order to obtain this information, each node maintains a data table called *CoopTable* with all the available helpers and their ability to cooperate. By looking up the CoopTable, the station decides whether a cooperative transmission would be more efficient than the direct transmission. Details about the structure and the maintenance of CoopTable are given in the next subsection.

Once s decides to leverage a cooperative transmission involving helper h, it transmits the packet at a rate R_{sh}. R_{sh} is chosen in a way that h would be able to decode the packet. However, since d has an inferior channel with s, most probably it will not be able to decode the packet. When h receives the packet it decodes it and retransmits it after a SIFS time, using rate R_{hd}. The way h chooses rate R_{hd} will be discussed further in the next paragraph. Destination d receives two copies of the transmitted signal; one from the source s in a rate R_{sh} and the other from the helper h in a rate R_{hd}. The receiver is typically not able to decode either of these signals since the rates are two high. However, by combining the two signals, it improves the signal to noise ratio (SNR) to a level that now the resulted signal can be decoded. Once the decoding is successful, d indicates its reception of the packet by issuing an acknowledgment packet (i.e., ACK) directly back to s. The details of the receiver combining procedure are given in the next subsection.

A key issue in the design of the above scheme is the appropriate choice of rate R_{hd} by the helper h. In CoopMAC without combining this decision was straight forward. The helper, by taking under consideration the channel between itself and the destination, would choose a rate that would enable the destination to successfully decode the packet.



(a) Three-way handshake

(b) Data transmission

Fig. 1: Illustration of the proposed cooperative MAC protocol.

However, this decision is more complicated here, as now d combines the signals of two transmissions (from s and h) and therefore can probably sustain a higher rate than the one that it can sustain in the direct link h to d. In the rest of the discussion, we will denote with R_{hd} the sustainable rate in the link between h and d when the receiver only decodes the signal from station h and with $R_{hd}^{'}$ the sustainable rate in the same link when receiver combining is used. The following is true: $R_{hd} \leq R_{hd}^{'}$.

In order to estimate $R_{hd}^{'}$, station h needs to know the channel condition between itself and d as well as between s and d. Since it exchanges packets with d, it can estimate the SNR in the link h to d. In order for h to recognize the link quality between s and d, we propose a modification in the structure of the data packet that is transmitted by s in the first hop. In particular, s will include an additional field in the data packet with the SNR approximation for the link between s and d. Therefore, when station h receives the packet from s, h is also informed about the s to d link. Based on the information about the channel quality of both links, it calculates the packet error rate (PER) in d for different $R_{hd}^{'}$. If the resulting PER for one or more of these $R_{hd}^{'}$ is below a certain threshold, then h uses the highest of them, boosting in such a way the rate of the second transmission. Otherwise h uses R_{hd}. The boost in the rate in the second transmission results in significant performance improvement, compared to CoopMAC without receiver combining, as will be shown by the simulation results.

As an option, the RTS/CTS signaling defined in IEEE 802.11 can be extended to a 3-way handshake in CoopMAC to further facilitate the ensuing cooperative data exchange. Under this option, when a node s intends to use a helper h for its transmission, it initializes the whole procedure by sending an RTS frame. This frame is an extension of the regular RTS frame and includes also the MAC address of the potential helper h, as well as the proposed rate information R_{sh} and R_{hd}. In this way, the candidate helper as well as the receiver are informed for the intention of the transmitter to use cooperation. The helper node h, upon receiving the RTS, should send a Helper-Ready-to-Send (HTS), if it is *able* and also *willing* to participate in the cooperative transmission. Station h is said to be able to help, if it can support rates R_{sh} and R_{hd}, and if its participation in the cooperation does not interrupt any other ongoing communication. Finally, node d sends a CTS indicating that it is ready to receive. The new three-way handshake for control information exchange is depicted in Figure 1(a).

2) Collection and Maintenance of Helper Information: A critical issue of the new cooperative scheme is for a node to be aware about available helpers in the neighborhood as well as about their capabilities to help. For this reason each node establishes and maintains a special data structure called *CoopTable*, which contains essential information related to all the potential helpers.

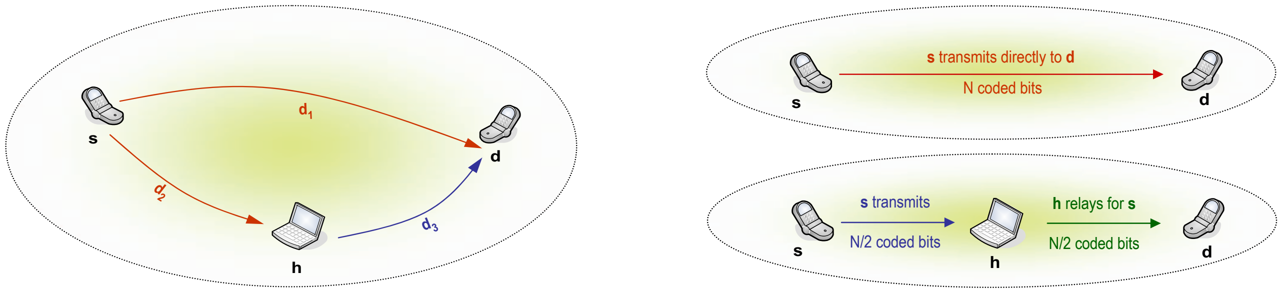
Each entry in the CoopTable, which corresponds to one candidate helper h, is indexed by its MAC address. The values of R_{hd} and R_{sh} associated with h are stored in two fields of the CoopTable, respectively. The main indication of the freshness of the learned information, namely the time at which the most recent packet is overheard from h, is held in another field called *Timestamp*. The last field, *Number of Failures*, which reflects the reliability of each helper, is a record of the number of consecutive unsuccessful transmissions that use h as a helper.

It is worthwhile to note that for s to acquire the value of R_{hd} and R_{sh}, a passive eavesdropping approach is followed, so that the overhead of additional control message exchange can be kept to a minimum. More specifically, since the physical layer header of any 802.11 data packet is always transmitted at the base rate, it can be decoded and understood by all other nodes within hearing distance in the network, including s. Another way for s to derive the highest rate R_{sh} that it can sustain is by estimating the quality of the link between s and h based upon the signal strength of the frames that s overhears from h.

Following this approach, s can learn about the rate R_{hd} that corresponds to the direct transmission between h and d. However, since s does not know in advance whether the selected h can boost the rate or not for the second hop transmission, it cannot take the possible rate increase on the second hop into consideration when choosing the helper. Therefore, although the protocol defined above is applicable for a receiver with diversity combining capability, it is not guaranteed that an optimal relay will be used with receiver combining. Nevertheless, the suboptimality of helper selection in our protocol is not anticipated to have major negative impact on the performance of cooperation, as the likelihood of ending up with such suboptimal relay is not significant.

C. Cooperation in the PHY Layer

In order to illustrate the idea of coded cooperation and cooperative diversity at the physical layer, we consider the



(a) Cooperative system for an isolated link.

(b) Time division in cooperative coding.

Fig. 2: Illustration of cooperative coding

cooperative coding scheme used in [10] and [11]. Let's consider an isolated source s who wants to communicate with a destination d with the help of a cooperative relay that we call helper h as illustrated in Figure 2(a). Here d_i's denote the distances between the nodes.

For direct transmission (that is if the helper h is not utilized) each channel block, or packet, contains B data bits and r parity bits for forward error correction (FEC), leading to a total of $N = B + r$ *coded* bits as shown at the top of Figure 2(b). For ease of exposition we have $r \geq B$. We assume cyclic redundancy check (CRC) is employed for error detection. In order to cooperate, s divides its channel block into two and only transmits in the first half as shown at the bottom of Figure 2(b). Hence in the cooperative mode s ends up sending only half of its coded bits. These bits are received both by the destination and by the helper h. The helper observes a higher coding rate, and hence a weaker FEC. Nevertheless, it attempts to decode the underlying B data bits. If h has the correct information (which can be checked using the CRC), it re-encodes and sends the remaining $N/2$ parity bits in the second half of S's time slot. Otherwise, h informs s that there was a failure in decoding, and s continues transmission. Thus when h decodes correctly, the destination will receive half of the coded bits from s and the remaining from h, creating spatial diversity. The question is how often this happens and how it affects the overall error performance. We now present the details about the cooperative scheme we used in our mechanism.

In coded cooperation, we assume that during the first hop, s transmits the coded bits with a certain coding rate R_{c1} and modulation mode. The helper h attempts to decode the information bits and re-encodes the information bits to get the additional coded symbols which were not originally transmitted by s with another coding rate R_{c2} and modulation mode. Hence, the destination observes part of the coded symbols ($\frac{B}{R_{c1}}$ coded bits) through s-d link, the another part ($\frac{B}{R_{c2}}$ coded bits) through h-d link. To optimize the performance, the number of coded bits from these two links may not be necessarily the same [11]. Then, the effective coding rate the destination observes is $\frac{1}{\frac{1}{R_{c1}}+\frac{1}{R_{c2}}}$. Different modulation modes may be used for these two coded parts as well. At the destination, it firstly de-modulates the different modulated symbols separately and then sends all demodulated soft-bits to a Viterbi decoder the decoded information bits. These links were assumed to obtain independent quasi-static fading, leading to an overall block-fading channel from the perspective of the destination. This provides additional diversity, obtained through the helper's link toward the destination. Please note that the averaged error rate is determined by the averaged received SNR, coding rate and modulation mode. Given the averaged SNR, the transmitter can simply select the coding rate and modulation mode to meet the average error rate requirement. Therefore, to improve the overall throughput of the system, the data rate R_{sd} and R_{hd}, which are determined by the coding rate and modulation mode between the transmitter and the receiver, may be chosen as high as possible such that the resulting average error rate at the destination is not larger than the one required by the system. The chosen data rate R_{sd} determines the sustainable data rate between s and h, R_{sh}.

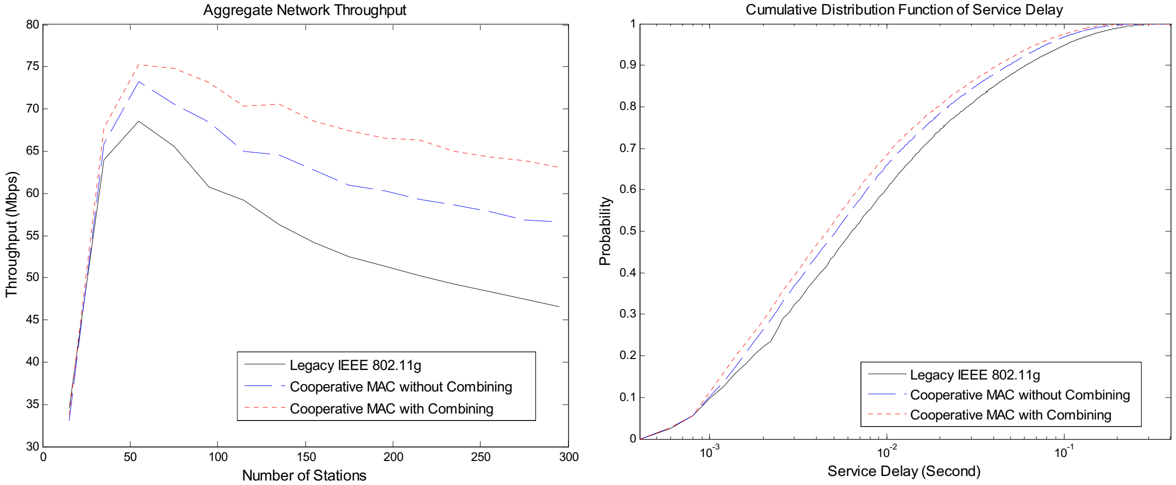
When receiver combining is enabled at physical layer, the helper can now forward packets at a rate equal to or greater than in CoopMAC where combining is not possible. The transmission rate on the second hop is the highest one that meets a predetermined average error rate at the destination, once the destination combines the source and relay signals. Thus, the diversity combining capability allows the new cooperative mechanism to leverage both the spatial diversity and the coding gain, thereby resulting in even better performance than the protocol without receiver combining. Using the coded cooperation framework described above, the helper provides different coded bits than the source, leading to a better error performance than repetition coding.

IV. PERFORMANCE EVALUATION

In order to evaluate the performance of our protocol and gain deeper understanding of the protocol behavior in a large scale ad hoc network, extensive simulations have been conducted. The results of these simulations provide a performance comparison of our protocol with IEEE 802.11. In order to get insights on the value added to our scheme by leveraging receiver combining in the PHY layer, we also compare it with CoopMAC withouut combining [1] [2].

A. Simulation Settings

To quantify the performance of our proposed MAC, and to assure a fair comparison with IEEE 802.11, we have developed an event-driven simulator. Eight possible rates, namely 6 Mbps, 9 Mbps, 12 Mbps, 18 Mbps, 24 Mbps, 36 Mbps, 48 Mbps and 54 Mbps, which constitute the permissible set of rates defined in IEEE 802.11g, have been used in our simulations. For each simulation, nodes are randomly placed in a circle of radius R = 350 m. The coverage areas for different



(a) Throughput as the number of nodes increases

(b) Service delay for 300 nodes

Fig. 3: Throughput and delay comparison for different number of nodes (up to 300 nodes)

TABLE I: Maximum range for each data rate

Data Rate (Mbps)	6	9	12	18	24	36	48	54
Maximum Range (Meter)	100	84	77	63	51	39	34	26

transmission rates are concentric circles with the radius of 100 m, 84 m and so on. The details are listed in Table I.

In the simulations, the destination of each packet was chosen randomly from all of the neighbors that could be reached directly by a source node. For each scenario we collected three types of statistics: the aggregate network throughput, service delay and total delay. The data presented hereafter was averaged over hundreds of runs, each of which was with a different random initial seed and ran for a period of time that was long enough to get stabilized results.

B. Simulation Results

Figure 3(a) reveals the relation between the network throughput and the number of nodes deployed. The MSDU packet size is 1500 bytes. To obtain the system capacity, the network is saturated and each node is in a backlogged state. It is apparent that the cooperative MAC with combining significantly outperforms CoopMAC (without combining), which in turn outperforms the legacy IEEE 802.11g.

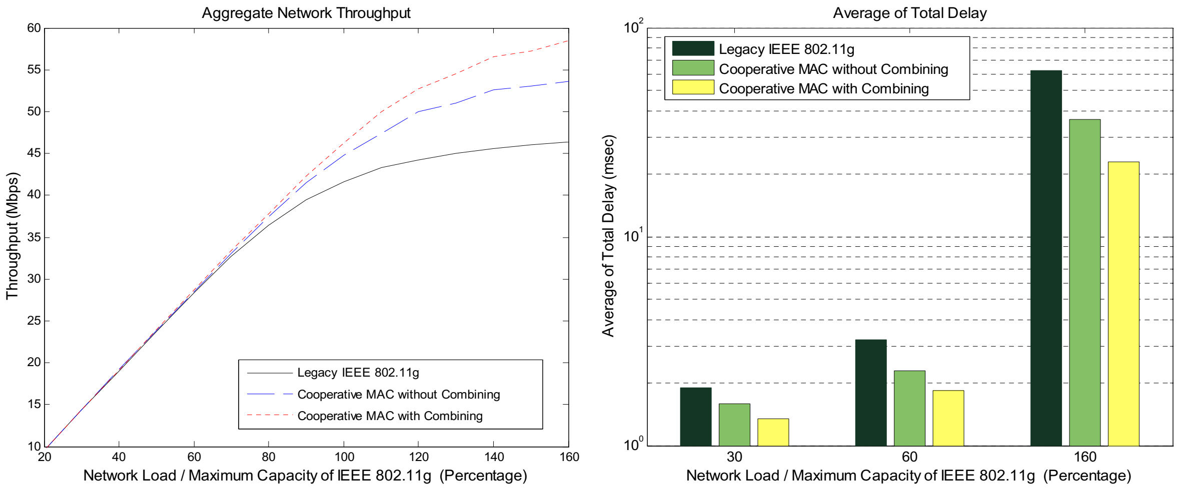
The fact that both our proposed access method and the CoopMAC protocol deliver more throughput than the legacy IEEE 802.11 DCF is due to several reasons [2]: Firstly, the protocol accelerates the slow transmissions by replacing them with faster two-hop transmissions. Secondly, since slow transmissions are accelerated, wireless channel could be released earlier and thus the source nodes of fast transmissions could access channels earlier, which improves the performance of the source nodes of fast transmissions.

As we can see in the same figure, our proposed access method performs better than CoopMAC (without combining). This is because the second hop data rate is boosted in the new protocol, so a transmission can finish in an even shorter time. Another interesting fact is that the performance of both cooperative MAC protocols are comparable to legacy IEEE 802.11g when there are less than 50 nodes in the network. This is because the network is too sparse and thus the chance for a source to find a helper is very limited. On the other hand, relative improvement of the cooperative protocols (with and without combining) increases as the nodal density of the network increases.

Note that the throughput gain our proposed access method can achieve becomes lower, when the MSDU size is smaller. Similar phenomenon has been observed in CoopMAC as well. Due to the space limitation, however, the simulation results will not be presented here.

Figure 3(b) depicts the simulation results for the cumulative distribution of service delay for a network with 300 nodes. Service delay is the duration from the time a packet becomes the head-of-line (HOL) packet until the time the packet is successfully received by the destination. Service delay essentially is the sum of channel contention time and packet transmission time. Since channel contention time is independent of transmission data rate, it is almost the same for the cooperative protocols and legacy IEEE 802.11g. Thus it is transmission time that makes a difference for service delay: The cooperative MAC protocols significantly reduces the transmission time for slow transmissions.

Besides the experiments above, we also conducted experiments with a fixed number of nodes while increasing the load on each node. Figure 4(a) depicts the relationship between network throughput and network load in an ad-hoc network with 200 nodes, which were randomly placed in a circle with radius R = 350 m. In the experiment, the load increases from 20% to 160% of the maximum network capacity of IEEE 802.11g in an ad-hoc network with 200 nodes. From the figure we can see that when network load is not heavy (less than 80% of the maximum network capacity of IEEE 802.11g), both cooperative protocols do not improve throughput significantly. However, as network load increases, we observe significant improvement of throughput when we use cooperation. The more the increase of the load, the more the benefits from



(a) Network throughput

(b) Total delay

Fig. 4: Throughput and delay comparison as the load increases (for a network of 200 nodes)

cooperation are apparent. Additionally, the cooperative MAC with combining does even better than CoopMAC.

With a light or medium network load, there are few throughput benefits from cooperation, as shown in Figure 4(a). However, in such conditions we observe great benefits from cooperation when we look at the delay statistics. Figure 4(b) shows the average of total delay for light, medium and heavy load conditions. As we can see, even with light network load (30% of the maximum capacity of IEEE 802.11g), both cooperative MAC protocols significantly reduce the total delay for a packet, as compared to the non-cooperative IEEE 802.11g. The total delay here is the total delay time a packet experiences, which is measured as the time interval from the arrival of a packet into the transmission queue of a source node until the successful decoding of the packet at the destination node. From Figure 4(b), we see that in any load condition, the cooperative protocol with combining always outperforms CoopMAC, which in turn always outperforms IEEE 802.11g. Apart from the 200 nodes experiment discussed above, we also did experiments for other fixed number of nodes and got similar results, which are not presented here.

Regarding the suboptimality issue, we have taken a closer examination of the simulation results and discovered that most of the transmissions on the second hop are conducted at a very high rate (e.g., 54 Mbps). This finding further corroborates that it is unlikely to find the selected helper to be suboptimal by using the protocol proposed in this paper.

V. CONCLUSIONS

In this paper we propose and study a MAC-PHY cross layer cooperative mechanism for ad-hoc wireless networks. The new protocol consists of a realistic model of a cooperative framework that takes advantage of receiver combining and provides the access scheme for cooperative communication among stations. We measure the performance of the proposed scheme using simulation results from a large scale network of up to 300 nodes. We compare the new mechanism with a similar MAC protocol without receiver combining (CoopMAC) and legacy IEEE 802.11g. The study shows that the new cooperative mechanism significantly outperforms CoopMAC and IEEE 802.11 due to the fact that it leverages both spatial diversity and coding gain. Based on the promising results we believe that the new scheme illustrates a new design paradigm for realistic cross-layer cooperative mechanisms for next generation wireless ad-hoc networks.

VI. ACKNOWLEDGMENTS

The authors would like to thank Zinan Lin for her help with the design and simulation of the PHY layer cooperative schemes.

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