A Cooperative MAC protocol for Ad Hoc Wireless Networks

Thanasis Korakis†, Zhifeng Tao◇, Yevgeniy Slutskiy⋆, Shivendra Panwar†

† Department of Electrical and Computer Engineering, Polytechnic University, Brooklyn, NY 11201
◇ Mitsubishi Electric Research Laboratories, Cambridge, MA 02139
⋆ Department of Electrical Engineering, Columbia University, New York, NY 10027

e-mail: korakis@poly.edu, tao@merl.com, ys2146@columbia.edu, panwar@catt.poly.edu,

***Abstract*— *Cooperative* communications fully leverages the broadcast nature of the wireless channel and spatial diversity, thereby achieving tremendous improvements in system capacity and delay. By enabling additional collaboration from stations that otherwise will not directly participate in the transmission, cooperative communications ushers in a new design paradigm for wireless communications. In this paper, we extend a cooperative MAC protocol called *CoopMAC* [1] into the ad hoc network environment[1]. The new protocol is based on the idea of involving in an ongoing communication an intermediate station that is located between the transmitter and the receiver. The intermediate station acts as a helper and forwards to the destination the traffic it receives from the source. Thus, a slow one-hop transmission is transformed into a faster two-hop transmission, thereby decreasing the transmission time for the traffic being handled. Extensive simulations in a large scale wireless ad-hoc network (150 stations) show that CoopMAC significantly improves the ad hoc network performance in terms of throughput and delay, and indicate how such cooperative schemes can boost the performance of traditional solutions (e.g., IEEE 802.11).**

***Index Terms*— Cooperative communications, MAC, 802.11, ad hoc network**

I. Introduction

The notion of *cooperation* takes full advantage of the broadcast nature of the wireless channel and creates spatial diversity, thereby achieving tremendous improvement in system robustness, capacity, delay, a significant reduction in interference, and extension of coverage range. Moreover, by enabling additional collaboration from stations that otherwise will not directly participate in the transmission, cooperative communication unveils a new protocol design paradigm for wireless communications.

The initial attempts for developing cooperative communications focused on physical layer schemes [2]–[4]. These approaches refer to the collaborative processing and retransmission of the overheard information at those stations surrounding the source and the destination. By combining different copies of the same signal transmitted by source and different relay stations, the destination can improve its ability to decode the original packet.

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The innovation of cooperative communications is not confined only to the physical layer. It is available in various forms at different higher protocol layers [5]–[7]. To expose access to physical layer information and adaptability to constant mobility, it is natural to introduce the notion of cooperation into the layer directly above the Physical layer, namely the medium access control (MAC) layer. A MAC protocol called CoopMAC [1] illustrates how the legacy IEEE 802.11 distributed coordination function (DCF) [8] can be enhanced with minimal modifications to maximize the benefit of cooperative diversity.

In this paper we propose and study a cooperative MAC protocol for ad-hoc wireless networks. The protocol is based on CoopMAC functionality [1] and is adapted to work efficiently in the ad-hoc environment. The focus of the protocol is to assist transmitter-receiver pairs that experience poor channel quality. In such a case, a relay station or helper, located somewhere between the transmitter and the receiver, is used to boost the slow communication. The transmitter, instead of sending its packets directly to the receiver at a low rate, uses the helper to transmit the packets in two high-rate hops, thus decreasing the transmission time. In this way, the particular communication lasts less time, resulting not only in the improvement of the throughput of the transmitter but also in the increase of spatial reuse, in the sense that neighboring stations can initiate a new transmission earlier than they otherwise would have.

To familiarize the reader with the Cooperative MAC protocol, its operation is first summarized in Section II. A set of simulation results for a large scale ad-hoc network of 150 stations along with the insights revealed therein are reported in Section III. Section IV completes the paper with our final conclusions and possible future work.

II. Cooperation at the MAC Layer

A. Multirate Capability and Motivation for Cooperation

Before delving into the protocol details, the motivation of cooperation and the multi-rate capability of IEEE 802.11b deserve a brief discussion, as they are crucial to an understanding of the advantage of cooperation at the MAC layer.

In order to deliver acceptable frame error rate (FER), frames in IEEE 802.11 can be transmitted at different bit rates,

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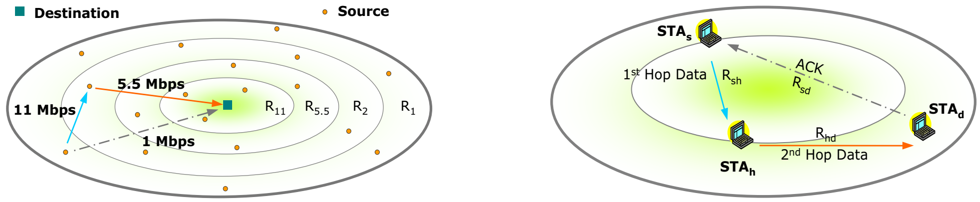

(a) Transmission range versus rate. (b) Data plane operation of CoopMAC.

Fig. 1: Cooperation at MAC layer.

depending on channel quality. In general, the transmission rate is essentially determined by the path loss and instantaneous channel fading conditions. For IEEE 802.11b, in particular, four different rates, 1, 2, 5.5, and 11 Mbps are supported over the corresponding ranges R_1, R_2, $R_{5.5}$ and R_{11}, as depicted in Figure 1(a).

Another key observation conveyed by Figure 1(a) is that a source station that is far away from the destination may persistently experience poor channel quality, resulting in a rate as low as $1Mbps$ for direct transmission over an extended period of time. If there exists some neighbor who in the meantime can sustain higher transmission rates (e.g., $11Mbps$ and $5.5Mbps$ in Figure 1(a)) between itself and both the source and the intended destination, the source station can enlist the neighbor to *cooperate* and forward the traffic on its behalf to the destination, yielding a much higher equivalent rate. With the simple participation of a neighboring station in cooperative forwarding, the aggregate network performance can derive a significant improvement, which motivates the introduction of cooperation into the MAC layer.

B. A Cooperative MAC Protocol for ad-hoc networks

The protocol that is described in this section is based on a MAC protocol that is called CoopMAC and is proposed in [1]. CoopMAC is a cooperative protocol for infrastructure wireless LANs. Its main aim is to support and improve the communication of wireless stations in a cell with the corresponding AP. In this paper we extend the functionality of this protocol, adding new features, in order to design a new cooperative MAC protocol for ad-hoc wireless networks.

The set of new features of cooperative MAC spans both the data plane and control plane of the protocol stack. For ease of explanation, the term *relay* and *helper* will be used interchangeably in the following discussion. As shown in Figure 1(b), STA_s, STA_h and STA_d represent the source, helper and destination station, respectively. R_{sd}, R_{sh} and R_{hd} denote the sustainable rates between STA_s and STA_d, between STA_s and STA_h, and between STA_h and STA_d, respectively.

1) Data Plane: Before the transmission of a packet, station STA_s should access all the rate information in a *cooperation table* (CoopTable) , and compare the equivalent two-hop transmission time with one-hop transmission time to determine whether the two-hop communication via the relay yields a shorter transmission time. If cooperative forwarding is invoked, CoopMAC engages the selected relay station STA_h to receive the traffic from the source STA_s at rate R_{sh} and then forwards it to the corresponding destination STA_d at rate R_{hd} after a SIFS time. In the end, destination STA_d indicates its successful reception of the packet by issuing an acknowledgment packet (i.e., ACK) directly back to STA_s.

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 station STA_s intends to use a helper STA_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 STA_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 station STA_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. Finally, station STA_d sends a CTS indicating that it is ready to receive.

Since station STA_s initiates the cooperative transmission, it does not know beforehand whether the helper STA_h is able to participate. Thus it sets its NAV in the RTS in a conservative way, covering the worst case scenario of a direct transmission of the data packet without cooperation. Once STA_h receives RTS and decides to participate in the communication, it updates the NAV in the HTS frame, based on the two hop fast transmission. STA_d adjusts the NAV in the CTS based on the updated NAV information in HTS.

2) Control Plane: The key enhancement in the control plane at each station is the establishment and maintenance of a special data structure, the *CoopTable*, which contains essential information related to all the potential helpers.

Each entry in the CoopTable, which corresponds to one candidate helper STA_h, is indexed by its MAC address. The values of R_{hd} and R_{sh} associated with STA_h are stored in the third and fourth field 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 STA_h, is held in another field called *Timestamp*. The last field, *Number of Failures*, reflects the reliability of each helper, by recording the number of consecutive unsuccessful transmissions that use STA_h as a helper.

Whenever a packet is overheard from a neighboring station STA_h, if that neighbor has no corresponding entry in the CoopTable, a new entry is created and inserted into the table; otherwise, all the fields associated with STA_h would undergo any necessary updates.

It is worthwhile to note that for STA_s to acquire the

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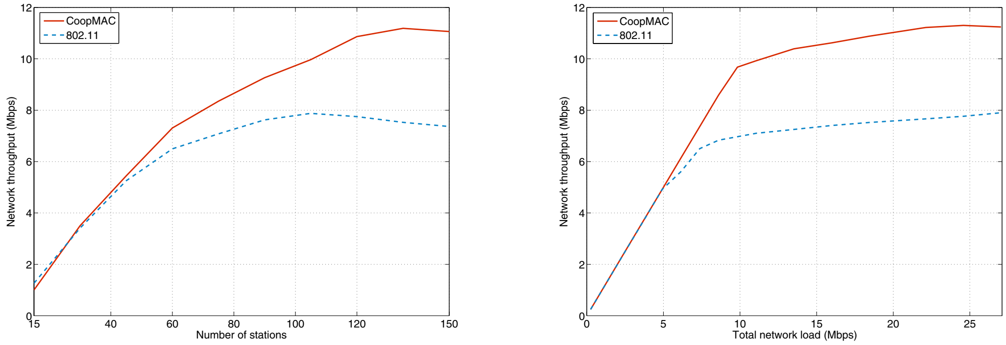

(a) Throughput as the number of stations increases

(b) Throughput as the load increases

Fig. 2: Throughput comparison

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 stations within hearing distance in the network, including STA_s. However, STA_s may not be able to correctly retrieve the MAC address of the transmitter and receiver directly from the corresponding data packet, since such information is contained in the MAC header and is in many instances transmitted at a rate higher than what STA_s can reliably receive. But fortunately, since each data packet is sometimes preceded by a successful handshake of RTS/CTS or succeeded by an acknowledgment, and all these control messages are exchanged at the base rate, STA_s can determine the identity of STA_h and STA_d with which the rate R_{hd} is associated. If there are direct transmissions between STA_s and STA_h, the rate estimation should proceed as prescribed by the adopted rate adaptation algorithm [9]. When no communication between these two stations occurs during an extended period of time, STA_s is still able to derive the highest rate R_{sh} that it can sustain, by estimating the quality of the link between STA_s and STA_h based upon the signal strength of the frames that STA_s overhears from STA_h.

It is worthwhile to note that although the proposed cooperative MAC seemingly bears some superficial resemblance to the conventional network layer ad hoc routing protocols, they are in essence fundamentally different. First and foremost, forwarding in cooperative MAC is the practical means of accomplishing the goal of cooperative diversity, instead of the goal itself. Secondly, all the associated operations occur in the MAC layer, which enjoys a shorter response time and more convenient access to the physical layer information, as compared to the traditional network layer routing. For wireline networks, the adage "switch if you can, route if you must," is often cited. In this paper, we will demonstrate that the same is true for wireless ad hoc networks.

III. 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.

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. Four possible rates, namely 1 Mbps, 2.2 Mbps, 5 Mbps and 11 Mbps, which constitute the permissible set of rates defined in IEEE 802.11b, were used in our simulations. For each simulation, stations were randomly placed in a circle of radius R = 350 m. The number of stations varied from 15 to 150. The coverage areas for different transmission rates are concentric circles of radius 100 m, 82.3 m, 76.7 m and 58.6 m for 1 Mbps, 2 Mbps, 5.5 Mbps and 11 Mbps, respectively.

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

B. Simulation Results

Figure 2(a) reveal the relation between the network throughput and the number of stations deployed. The MSDU packet size is 1024 bytes. To obtain the system capacity, the network is saturated and each station is in a backlogged state. It is apparent that the cooperative MAC significantly outperforms IEEE 802.11b.

Indeed, the Cooperative MAC protocol is anticipated to deliver more throughput than the legacy IEEE 802.11 DCF due to several reasons: First, it accelerates the slow transmissions by replacing them with faster two-hop transmissions. Second, the proposed protocol not only improves the performance of slow stations, but also makes it possible for fast stations to access the channel earlier, as the data transmissions from slow stations take significantly less time.

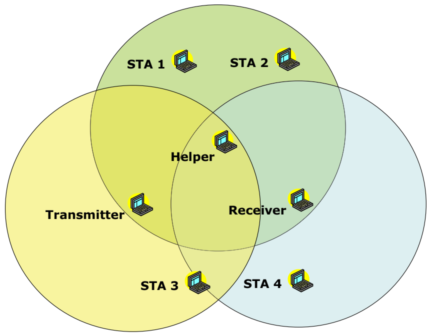

Fig. 3: Spatial reuse on cooperative MAC

An interesting point that needs to be investigated in an environment of a dense ad-hoc network, is whether spatial reuse is benefited or harmed by cooperation. This is not a straightforward issue. On first thought, one would say that the proposed cooperative scheme would reduce spatial reuse. In order to understand this, consider the example in Figure 3. When 802.11 is used, the stations that should be silent during an ongoing communication between $Transmitter$ and $Receiver$ are $STA3$ and $STA4$. On the other hand, when cooperation is used, the HTS frame also forces $STA1$ and $STA2$ to defer their transmissions in order not to collide with the ongoing communication. However, after considering the effect of cooperation on the transmission time, we realize that in the CoopMAC case the four stations are silenced for much less time than the two stations in the IEEE 802.11 case. In a scenario where the transmission rate for the single hop is 1Mbps, and the transmission rates for the two hops during cooperation are both 11Mbps, the time period that the stations will be mute in 802.11 is approximately 4.5 times bigger than the time in the cooperative MAC. In other words, when cooperation is used, more stations may be muted due to the involvement of helper but the mute period will be much smaller. This final statement leads to the conclusion that the overall spatial reuse is increased in the case of cooperation in the sence that the neighboring stations will be free to transmit for a significantly more time than in 802.11. This is one of the main reasons for the increase of throughput seen in Figure 2.

Another interesting observation in Figure 2 is that when the number of stations increases, the throughput of the IEEE 802.11b network decreases since more collisions will occur. In the cooperative MAC scheme, the throughput increases as the number of stations grows. This is because the more stations in the network, the higher possibility that a station can find a helper and transmit at a higher rate. In addition, the higher the number of stations, the higher the spatial reuse as we described above. Both these effects not only offset the throughput decrease caused by collisions, but lead to a continued increase in the total throughput.

Figure 2(b) depicts the network throughput as the total load increases. The network consists of 150 stations and the MPDU size is 1024 bytes. For low load the performance of 802.11 and our cooperative protocol is similar. This is due to the fact that in a low load the transmission of the frames is quite rare and thus the time a station occupies the medium to transmit the frame is not critical for the performance of the network. In other words, in this case there are enough bandwidth resources for transmission of the network traffic even at low link rates.

As the load increases, more and more traffic needs to be transmitted. Now the transmission time plays a significant role. CoopMAC, by reducing the transmission time for the slow transmissions, increases the number of transmitted frames in a given time interval and thus increases the throughput. The more the load on the network, the higher the CoopMAC throughput is. This increase ends once the network reaches saturation.

Figure 4 gives the throughput comparison as the MPDU size increases. We can see that for large MPDUs cooperative MAC outperforms IEEE 802.11. This is something we expect to see and it is explained based on the benefits of cooperation that we mentioned in the previous paragraphs. On the other hand, when the MSDU is quite small (less than 140 bytes) there is no benefit from cooperation. A close look shows that in this case not only there is no benefit from cooperation but the proposed protocol performs exactly the same as 802.11. The explanation to these statements comes from a more careful examination of the protocol details.

The new protocol adds an extra control frame (HTS) to announce the participation of the helper in the cooperation. Thus, it increases the overhead. For small frames, this overhead affects the overall transmission time, canceling the benefits of cooperation. When the packet size exceeds a certain threshold (approximately 140 bytes), the benefits from transmitting the data frame with cooperation cancel the overhead, and we can see an improvement in the throughput. This improvement is higher as the packet size increases. In order to explain the fact that the throughput of cooperative MAC is exactly the same as 802.11 for frames smaller than the mentioned threshold, we should recall that the transmitter decides to use cooperation only if it gains in transmission time. Since it realizes that the use of the cooperative scheme will result in more transmission time for the specific frame (due to the added overhead), it will

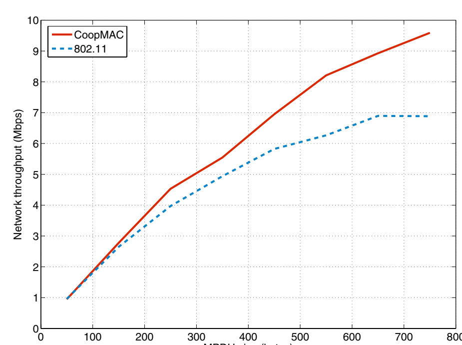

Fig. 4: Throughput comparison as the MPDU size increases

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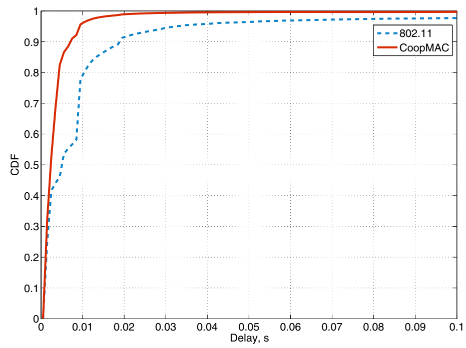
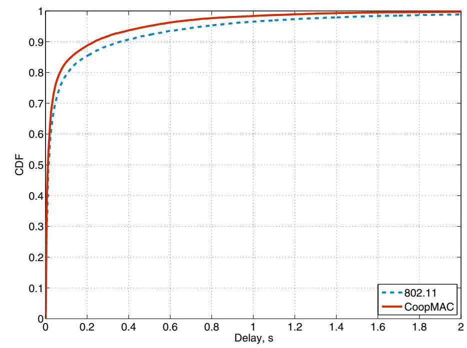


(a) CDF for service delay (light load)



(b) CDF for service delay (heavy load)

Fig. 5: Service delay for a network of 150 stations

revert to using the basic 802.11 protocol.

Delay is another performance metric critical for a wide variety of applications. Figure 5(a) depicts a cumulative distribution for the service delay. The simulation is for a network of 150 stations with a packet size of 1024 bytes and a light network load (3.5 Mbps overall load). Every station has a buffer size of 30 frames. The total delay refers to the time from the moment the packet arrives at the MAC layer till the moment the packet is successfully transmitted.

Figure 5(a) shows a cumulative distribution for the service delay for a network of 150 stations, with a packet size of 1024 bytes and a lightly loaded network traffic. The service delay refers to the time it takes for a packet to be successfully transmitted after it becomes the head-of-the-line (HOL) packet in a buffer of a station. We can see that the delay of our protocol is significantly lower than that of IEEE 802.11 in both cases. This is because the CoopMAC decreases the transmission time of slow rate frames and thus more frames can be transmitted in a given period of time, a fact that decreases the queuing and service time of the frames.

IV. Conclusions and Future Work

In this paper we study a cooperative MAC scheme for adhoc wireless networks. We measure its performance using simulation results from a large scale network of 150 stations. The thorough study shows that the cooperative protocol outperforms IEEE 802.11 in most of the cases and set up a base for considering the use of cooperation at the MAC layer as an answer to the constraints on traditional protocols in dense network environment.

As for future work, cross layer approaches will be considered, combining cooperation in the MAC and the PHY layer. In the proposed protocol, a data frame is transmitted sequentially two times: Once from the transmitter and once from the helper. Since the receiver is able to overhear both transmissions, inherently the protocol can support cooperative schemes in the PHY layer. We are planning to combine several PHY layer schemes with the cooperative MAC to study the further improvements we can gain by such a combination.

It is also worthwhile to develop further understanding about the use of cooperation in ad hoc wireless networks by studying power consumption as well as the effect of mobility. Moreover, an interesting field to be investigated is the possible interference reduction effect that cooperation can cause in dense environments with high spatial reuse.

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