Cooperation and Directionality: Friends or Foes?

Zhifeng Tao[◇], Thanasis Korakis[†], Feilu Liu[†], Shivendra Panwar[†], Jinyun Zhang[◇], Leandros Tassiulas‡
◇ Mitsubishi Electric Research Laboratories (MERL), 201 Broadway, Cambridge, MA 02139
⋆ Department of Electrical and Computer Engineering, Polytechnic University
‡ Computer Engineering and Telecommunications Department, University of Thessaly, Volos, Greece 38221

***Abstract*— As the two key technologies that have the potential to reshape the landscape of next-generation wireless network, cooperative communications and directional antenna system so far have been developed in parallel, if not in isolation from each other. In order to establish a thorough comparison between the relative system performance of cooperative diversity and directional transmission in an adhoc environment, we design and quantitatively evaluate three medium access control protocols, namely O-CoopMAC, D-NoopMAC and D-CoopMAC. The study yields the unexpected yet crucial observation that cooperative forwarding significantly *limits* the spatial reuse created by transmission directionality, and therefore can appreciably *degrade* the performance of a directional system with a sufficiently narrow antenna beam. To the best knowledge of the authors, this is the *first* paper to systematically compare the performance of these two technologies in an adhoc environment and reveal the key fact that *cooperation and directionality are rather foes than friends*!**

I. Introduction

Directional antenna [1] and cooperative communications [2] are two advanced wireless technologies that have recently gained significant momentum in not only academia but also industry. For example, the notion of beamforming and directional transmission has already been entertained in the latest wireless standards ranging from IEEE 802.15.3 for personal area network (PAN) to IEEE 802.16e for metropolitan area network (MAN) [3] [4], whilst the concept of cooperative communication will be incorporated in such multihop relay standards as IEEE 802.16j [5].

By concentrating energy only in the intended direction, directional antennas can increase the potential for *spatial reuse* and provide longer transmission and reception ranges with the same amount of power, ultimately leading to higher network capacity, less interference, and fewer transmission hops.

Meanwhile, cooperative communications leverage *spatial diversity* by intelligently enlisting relay stations and letting them forward the information overheard from the source to the intended destination fully or in part. The destination receives multiple versions of the message from the source and one or more relays, and combines these to achieve higher capacity, reliability and extended coverage.

Although both can achieve significant performance gain in similar perspectives, directional antenna and cooperative communications derive the improvement from two distinct sources. More specifically, directional antenna relies on *directional* transmission of wireless signal, whilst cooperative communications depend on the *broadcast* nature of wireless channel. Given the merely diametrically *opposite* relation between directionality and broadcast, a natural question to contemplate is: ***are cooperative communications and directional antenna friends or foes?***

To seek an answer, a comparative approach has been pursued in this paper to quantitatively evaluate the system performance of directional antenna, cooperative communications and a combination thereof. In order to establish a more thorough understanding of real system performance, the overhead incurred by the protocols that enable the system to operate shall be taken into consideration in the study. Meanwhile, involving too much higher layer protocol complexity may risk blurring the view and losing the grip of the essence. To strike a balance, therefore, the evaluation in this paper will be conducted at medium access control (MAC) level, which is directly on top of the physical (PHY) layer where directional antenna and cooperative communications reside.

Although a handful of MAC protocols have already been proposed to support either directional antenna [6]–[8] or cooperative communications [9] [10], nothing exists that can exploit both simultaneously. Inspired by [8] and [10], we propose in this paper a directional non-cooperative MAC (D-NoopMAC) and an omnidirectional cooperative MAC (O-CoopMAC) as the reference protocols to evaluate the system performance of directional antenna and cooperative communications, respectively. Furthermore, a novel directional cooperative MAC (D-CoopMAC) that taps into the combined potential of both transmission directionality and cooperation diversity (a.k.a. *co-opdirectionality*) is designed in this paper in order to study the joint impact of the two technologies. Note that since the spatial reuse effect of directional antenna is best captured in an adhoc environment, all the evaluation and discussion here are in the context of an adhoc network so that cooperative communications and directional antenna can be compared on an equal footing.

The rest of this paper is organized as follows. Essential background on directional antenna and cooperative communications is first provided in section II-A and II-B. The set of proposed MAC protocols, namely O-CoopMAC, D-NoopMAC and D-CoopMAC, are then elaborated in sections III, IV and V. The performance results are then compared and key insights highlighted in section VI. Finally, the conclusions and discussion of future work are presented in section VII.

II. Background

A. Directional Antenna

A directional antenna consists of multiple element arrays [1]. By sophisticated combining of the transmitted/received signals in the elements, the electromagnetic waves are enhanced in certain directions while attenuated in others, resulting in an amplified signal that is directed to or received by certain directions. Thus, the transmission/reception is beamformed toward certain preferred transmission and reception directions.

Based on the signal possessing method for the element's signal combination, the implementation of directional antenna can be roughly categorized in two different types, namely switched beam and steerable beam [1].

Directional antenna is a key lower-layer technology that holds the promise of extending the coverage range and delivering higher capacity for the next generation wireless networks. However, directionality of communication poses numerous challenges across multiple protocol layers, without the resolution of which the full power of directional antennas cannot be fully harnessed and unleashed. Several sophisticated MAC protocols have been recently proposed in [6]–[8] to address the issues of destination positioning, effective channel reservation, as well as the deafness problem, among others.

B. Cooperative Communications

Fundamentally speaking, cooperative techniques utilize the broadcast nature of wireless propagation by observing that a source signal intended for a particular destination can be "overheard" at neighboring stations. These relay stations process the signals they overhear and transmit towards the destination. The destination combines the signals coming from the source and the relays, enabling higher transmission rates and robustness against channel fading [2].

Akin to directional antenna, cooperative communications require support at different protocol layers and introduce many opportunities for cross-layer design and optimization [9] [11]. Interested readers are encouraged to refer to [10] for more details.

III. Cooperative MAC with Omni-Directional Antenna (O-CoopMAC)

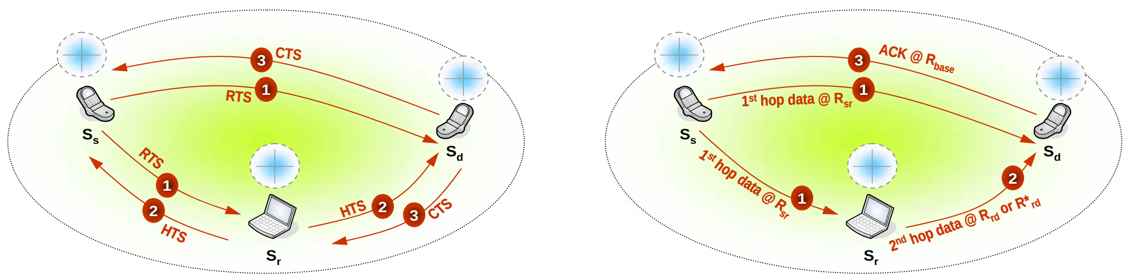
The cooperative MAC with omni-directional antenna (O-CoopMAC) to be introduced in this section is based upon the CoopMAC protocol that was designed for infrastructure-based wireless networks [10]. In this paper, we extend CoopMAC into the adhoc environment, and further leverage the PHY cooperation capability that was not fully exploited in the original CoopMAC [10].

A. Basic Protocol

When a source station S_s starts to handle a new packet, it shall follow a binary exponential backoff scheme similar to that defined in IEEE 802.11. After S_s counts down to zero, it shall look up a local data structure called cooperation table (CoopTable) to identify a candidate relay S_r, through which a two-hop forwarding will consume less time than a one-hop transmission directly from S_s to destiation S_d. The table lookup will also yield such information as the estimated physical transmission rate R_{sr} on link between station S_s and S_r (i.e., L_{sr}), and rate R_{rd} on link between station S_r and the intended destination station S_d (i.e., L_{rd}). The operation of the CoopTable will be further elaborated later in this section.

If a potential relay station S_r is found, S_s broadcasts a RTS message that contains the MAC address of S_r and the proposed rate information R_{sr} and R_{rd}, as illustrated in Figure 1(a). If no relay can improve the efficiency of the transmission, the legacy RTS message defined in IEEE 802.11shall be sent by S_s directly to S_d, instead. Once S_r receives the broadcast RTS message from S_s, it shall reply with a helper-ready-to-send (HTS) message, provided that S_r is able and willing to participate in the cooperation. To complete this three-way handshake, station S_d transmits a CTS message, indicating to both S_s and S_r that it is ready to receive. Similar to IEEE 802.11, note that all the signaling messages, namely RTS, HTS and CTS, shall be transmitted at the base rate (i.e., 6 Mbps for IEEE 802.11g), given their importance in the protocol.

If cooperative forwarding is invoked, CoopMAC engages S_r to receive the traffic from the source S_s at



(a) Handshake (b) Data transmission

Fig. 1: Illustration of the proposed cooperative MAC with omnidirectional antenna (O-CoopMAC).

rate R_{sr} and then to forward it to the corresponding destination S_d at rate R_{rd} after a SIFS time. In the end, destination R_d signals its successful reception of data by issuing an acknowledgment (i.e., ACK) directly back to S_s, as shown in Figure 1(b).

B. Receiver Combining and Adaptive Rate Boost

Thanks to the broadcast nature of wireless channel, the destination S_d will receive the signals transmitted by both the source S_s and the relay S_r. If the destination is capable of combining these two copies to decode the original information, then the diversity can be fully exploited. O-CoopMAC introduces an adaptive rate boost mechanism to further leverage the channel diversity using receiver combining.

When source S_s tranmits the data packet on the first hop to S_r, it includes an additional field in the packet, which contains the average channel estimate (i.e., SNR) associated with the link between S_s and S_d (i.e., L_{sd}). Given this channel estimate, relay station S_r can determine whether or not it can boost the transmission rate on link L_{rd}.

More specifically, suppose the link adaptation algorithm adopted yields a rate R_{rd} that can sustain a certain bit error rate (BER) on link L_{rd}. With receiver combining capability, relay S_r now can forward packet at a rate R^*_{rd} that is equal to or even greater than R_{rd}, as long as a desired post-combining average error rate can be maintained at S_d. Although S_d can completely understand neither the packet on the first hop from S_s to S_r, nor the one on the second hop from S_r to S_d, it will be able to decode the information S_s originally intended to convey. Therefore, the R^*_{rd} essentially should be the highest rate that can result in a target post-combining average error rate at destination S_d.

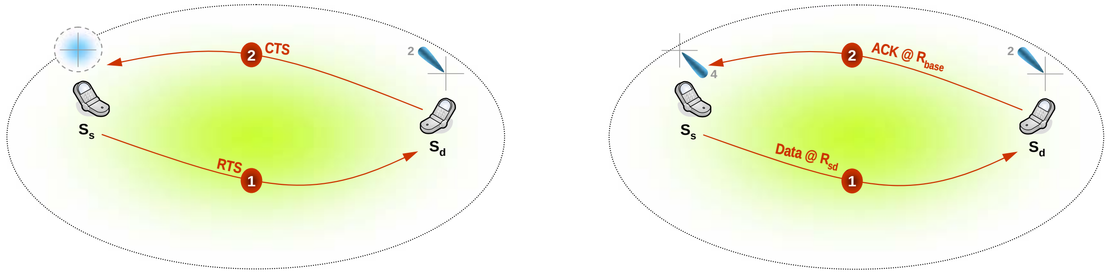
C. Cooperation Table

After a station enters the network, it shall establish and maintain a CoopTable that contains essential information related to all the potential relays. Each entry in the CoopTable, which corresponds to one candidate relay S_r, is indexed by its MAC address. The values of R_{sr} and R_{rd} associated with S_r are stored in the CoopTable.

For rate R_{sd}, S_s can easily determine it by using any of the rate adaptation algorithms proposed for IEEE 802.11 [12]. In the meantime, since the physical layer header of any 802.11 data packet is always transmitted at the base rate, it can be understood by all other stations within hearing distance in the network, including S_s. However, S_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 S_s can reliably receive. But fortunately, since each data packet is preceded by a successful handshake of RTS/CTS or succeeded by an acknowledgment, and all these control messages are exchanged at the base rate, S_s can learn the identity of S_r and S_d with which the rate R_{rd} is associated. Finally, the rate R_{sr} can be estimated by S_s based on the signal-to-noise-ratio (SNR) of the packets S_s overhears from S_r.

D. Discussion

Since S_s does not know in advance whether the selected S_r can boost the rate or not, it cannot take the possible rate increase on the second hop into consideration when choosing the relay. Therefore, although the same O-CoopMAC defined above is applicable for receiver both with and without diversity combining capability, it is not guaranteed that an optimal relay will be used with receiver combining. Nevertheless, the suboptimality of relay selection in O-CoopMAC 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. Therefore, it is still reasonable to use O-CoopMAC protocol for performance comparison purpose in Section VI.



(a) Handshake (b) Data transmission

Fig. 2: Illustration of the proposed directional non-cooperative MAC (D-NoopMAC).

IV. Non-Cooperative MAC with Directional Antenna (D-NoopMAC)

The non-cooperative MAC with directional antenna (D-NoopMAC) described in this paper is similar to the legacy DCF protocol in IEEE 802.11, except that directional antenna will be used in some of the transmissions. More specifically, upon the completion of proper backoff, source S_s broadcasts a RTS message to destination S_d to reserve the channel. Since S_d becomes aware of S_s's relative location based upon the direction it receives the RTS message, it can respond with a CTS message using directional transmission, indicating that it is ready to receive the data. A successful RTS and CTS exchange will then be followed by the data communication and associated acknowledgement, both of which will be conducted using directional transmission. Figure 2(a) and 2(b) depict the handshake and data exchange process of the D-NoopMAC protocol, respectively.

Note that D-NoopMAC is not intended to be a sophisicated protocol that addresses all the MAC layer design issues inherent in directional systems [6]–[8]. In fact, simple as it is, D-NoopMAC by no means has fully exploited the potential of directional transmission. Nonetheless, as it will become evident in Section VI, it is adequate for the purpose of comparison with cooperative system to use D-NoopMAC to provide a lower performance bound of a directional protocol.

V. Cooperative MAC with Directional Antenna (D-CoopMAC)

Advances in cooperative communications and directional antenna design so far have taken place in parallel, if not in isolation from each other. Inspired by the protocols presented in [10] and [8], we propose a new co-opdirectional MAC called D-CoopMAC in order to evaluate the joint effect of cooperation and directionality.

A. Basic Protocol

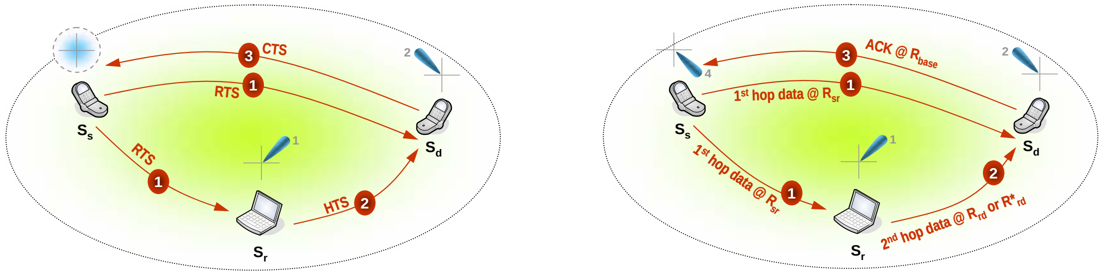
As illustrated in Figure 3(a), the source S_s sends out a RTS message omni-directionally, after finishing a binary exponential backoff. S_s shall also look up the CoopTable to identify a candidate relay S_r, and the estimated physical transmission rate R_{sh} on the link L_{sr}, and R_{rd} on the link L_{rd}. The CoopTable in D-CoopMAC protocol is similar to that introduced in O-CoopMAC in Section III, and will be further explained in Section V-B. If a potential relay station S_r is found, S_s inserts the MAC address of the selected S_r and the proposed rate R_{sr} and R_{rd} into the RTS message so that the selected relay S_r can be properly informed. Station S_r, if it decides to engage in cooperative forwarding, and if it can find destination station S_d in a local data structure called location table (*LocTable*), then transmits an HTS message directionally to S_d a SIFS time after it receives the RTS message. A CTS message is finally sent by the S_d in the direction from which a RTS was received to signal its willingness to join the dialog. Again, the HTS and CTS message shall be seperated by a $SIFS$ interval.

If this three-way handshake is successfully completed, the data exchange can start, which is shown in Figure 3(b). Otherwise, a failure to receive any feedback (i.e., CTS or HTS) would result in a timeout at S_s, which should treat it as a transmission failure and thus return to a new backoff, as it should have in legacy 802.11 DCF protocol.

The data exchange procedure is relatively straightforward, wherein S_s first transmits data at the rate R_{sr} to S_r, which after a $SIFS$ time forwards the received packet(s) to the intended destination S_d. Whether a rate on the second hop can be boosted or not is at the discretion of relay station S_r. To confirm a successful reception, S_d shall transmit an ACK message to the source S_s. Otherwise, a timeout will result at S_s, which then again enters a new backoff process, as long as the retransmission limit has not been exceeded.

B. Key Tables

It is evident from the preceding description that two special data structures, namely the $CoopTable$ and the



(a) Handshake

(b) Data transmission

Fig. 3: Illustration of the proposed directional cooperative MAC (D-CoopMAC).

$LocTable$ play a critical role in enabling cooperation and directional transmission.

- **LocTable**
  When a station initially joins a directional network, it can only transmit directly to a destination using the D-NoopMAC protocol. Once a destination S_d receives a RTS, it can then learn through which direction it can reach the source S_s. Similarly, S_s is able to tell the relative positon of S_d only after it hears a directional CTS. Thus, every wireless station in the end can establish a LocTable, which records the relative direction via which each of the station's neighbors can be reached.
- **CoopTable**
  A station can follow a similar approach described for O-CoopMAC to fill out the field associated with each neighboring station in the CoopTable. The only difference is that S_s cannot learn the rate R_{rd} on link L_{rd}, since S_s may not be able to overhear the directional data transmission between S_r and S_d. As a solution, S_r shall include in its broadcast RTS message the value of rate R_{rd} associated with the data packets that subsequently will be directly transmitted from S_r to R_d.

VI. Performance Evaluation and Comparison

In order to evaluate cooperative communications, directional antenna and co-opdirectionality, we have further extended the simulation platform developed in [8] [10], and implemented the O-CoopMAC, D-NoopMAC and D-CoopMAC protocols. Extensive simulations are then conducted to compare the performance of these three protocols.

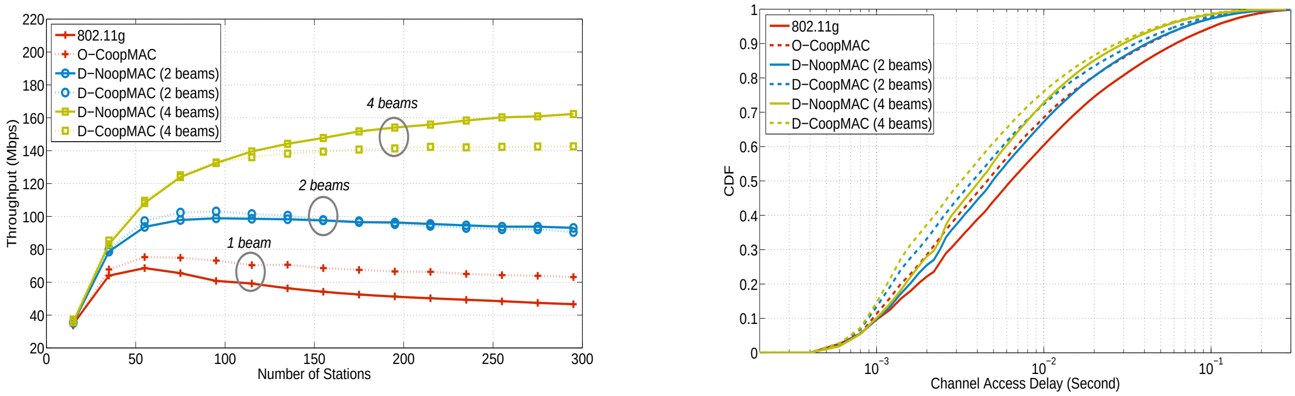
A. Simulation Settings

Given its popularity, legacy IEEE 802.11g is used as a baseline in the simulation. In order to assure a fair comparison, the eight possible rates that constitute the permissible set of rates defined in IEEE 802.11g, are used in our simulations of O-CoopMAC, D-NoopMAC and D-CoopMAC. For each simulation, stations are randomly placed in a circle with a radius of $350m$. The coverage area of an omnidirectional antenna is a circle of radius r_{omni} = 100 m, while that of a directional antenna is a lobe of radius $r_{directional}$ = $100 \times F_{RE}$ m. The F_{RE} here is the range extension factor, which have value of 1.19 and 1.41 for directional antenna with 2 beams and 4 beams, respectively. In our simulations, we have implemented an antenna array model that produces N non-overlapping lobes of $\frac{360}{N}$ degrees each. The destination of each packet has been chosen randomly from all of the neighbors that are within the direct transmission range of a source station. Every piece of simulation result discussed hereafter has been averaged over 10 runs, each of which has a different random initial seed and runs for a period of time that is long enough to ensure convergence.

B. Simulation Results

Figures 4(a) and 4(b) plot the the system throughput and channel access delay versus the number of stations deployed in the network, respectively, when the respective saturation load is applied and each station is always in a backlogged state. It is readily demonstrated in Figure 4(a) that the network throughput of both legacy IEEE 802.11g and O-CoopMAC first increase as the number of stations grows, and then decline when the network becomes too crowded. This trend is similar to that repeatedly observed for 802.11 system in the infrastructure-based environment and has been well explained in [10].

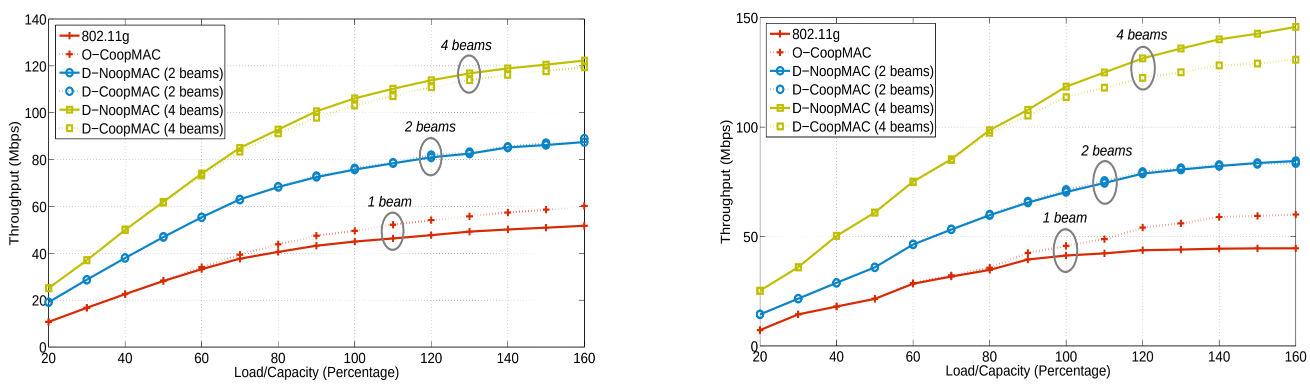
Due to the diversity gain and coding gain facilitated by cooperative communications, moreover, the O-CoopMAC protocol substantially outperforms 802.11g in terms of throughput and channel access delay, as confirmed in Figure 4(a) and 4(b), respectively. Note that this finding is also consistent with that made in [10] for omni-directional transmission. As compared to the single hop scenario, however, note that the absolute



(a) Throughput

(b) Channel access delay

Fig. 4: Performance as a function of the number of stations (MPDU = 1500 bytes)



(a) A network of 100 stations

(b) A network of 300 stations

Fig. 5: Throughput versus traffic load (MPDU = 1500 bytes)

value of network throughput for both IEEE 802.11g and O-CoopMAC are significantly higher in the ad hoc environment, thanks to *spatial reuse*.

When each station is equipped with directional antenna, the D-NoopMAC and D-CoopMAC protocol are simulated for communication without and with cooperation. It is evident in Figure 4(a) that as the number of beams at each station grows from one to four, network throughput witnesses a dramatic increase. Basically, the directional antenna enables each station to take full advantage of *spatial reuse*, whereby multiple transmissions can occur in parallel now, even when all the parties involved are in a direct transmission range of each other and would cause unacceptable interference to each other, were they operating in an omni-directional mode.

One phenomenon that is particularly interesting in Figures 4(a) is that the throughput performance of directional system with four antenna beams is unexpectedly *better* when *no* cooperation exists, which is completely opposite to the observation made in an omni-directional system. In fact, cooperative relaying can still help expedite the transmission of each individual packet, as clearly demonstrated in Figure 4(b) and explained in [10]. A closer examination of the simulation trace reveals that cooperation is at the cost of reduced spatial reuse, as the enlisted relay station has to silence its neighbors and thus prevent potential parellel transmissions from occuring. In addition, the probability of finding a qualified relay for cooperative forwarding is also decreased, as the transmission becomes more directional. As a result, cooperative forwarding and directional transmission appear to work *against* each other, rather than with each other.

In Figure 5, we further evaluate the protocol performance under a wide variety of loading conditions. Under light load, since none of the four protocols have reached their capacity, they deliver similar throughputs. The throughput of each protocol continues climbing and then remains relatively flat on a plateau, as the load enters the corresponding saturation region. Figure 5 also confirms that the *conflict* between cooperative forwarding and directional transmission is perserved across all the loading conditions being investigated.

VII. Conclusions

In this paper we have presented three new medium access control protocol for ad-hoc networks, namely O-CoopMAC, D-NoopMAC and D-CoopMAC, in order to leverage cooperative diversity, exploit transmission directionality and take advantage of the capability of tapping into the combined potential of both, respectively. More importantly, we evaluate these three protocols and establish a deeper understanding of the relative performance of cooperative communications and directional transmission. The key observation made in the study indicates that cooperative forwarding can significantly *limit* the spatial reuse enabled by transmission directionality, and therefore appreciably degrade the performance of a directional system with a sufficiently narrow antenna beam. To the best knowledge of the authors, this is the *first* paper to systematically compare the performance of these technologies in an adhoc environment and reveal the key fact that *cooperation and directionality are rather foes than friends*!

As for the future work, alternative approaches to incorporating cooperative communications and directional antenna in wireless networks will be further explored and compared. Also, it is worthwhile to further investigate the system performance in an ad-hoc environment with proper routing protocol.

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