MEMORANDUM OF TRANSMITTAL

U.S. Army Research Office
ATTN: AMSRL-RO-BI (TR)
P.O. Box 12211
Research Triangle Park, NC 27709-2211

☒ Reprint (Orig + 2 copies)

☐ Technical Report (Orig + 2 copies)

☐ Manuscript (1 copy)

☐ Final Progress Report (Orig + 2 copies)

☐ Related Materials, Abstracts, Theses (1 copy)

CONTRACT/GRANT NUMBER: **W911NF0410224 (46637-CI-MUR)**

REPORT TITLE: Andrea Munari, Francesco Rossetto, Michele Zorzi, "A new Cooperative Strategy for Deafness Prevention in Directional Ad Hoc Networks", IEEE International Conference on Communications (ICC), Glasgow, Scotland, UK, June 24 2007 - June 28 2007.

is forwarded for your information.

SUBMITTED FOR PUBLICATION TO (applicable only if report is manuscript):

Sincerely,

Michele Zorzi
University of California, San Diego

Enclosure 3

REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE March 2007	3. REPORT TYPE AND DATES COVERED **Reprint** **01 June 2004 - 31 March 2007**

4. TITLE AND SUBTITLE A new Cooperative Strategy for Deafness Prevention in Directional Ad Hoc Networks	5. FUNDING NUMBERS **W911NF0410224**
6. AUTHOR(S) Andrea Munari, Francesco Rossetto, Michele Zorzi	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of California. San Diego** **9500 Gilman Drive, La Jolla, CA 92093-0407**	8. PERFORMING ORGANIZATION REPORT NUMBER **N/A**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSORING / MONITORING AGENCY REPORT NUMBER **N/A**

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.	12 b. DISTRIBUTION CODE **N/A**

13. ABSTRACT (Maximum 200 words)

We propose the novel concept of cooperation for deafness prevention in directional antenna ad hoc networks, along with a low-complexity multiuser detector specialised for these systems. We call a generic MAC protocol that uses these techniques a Cooperative-MAC (CMAC) and we define an upper and a lower bound on the performance of this class of protocols. Several simulations compare these bounds against the Circular RTS/CTS protocol (CRCM), which is one of the finest deafness-suppression systems proposed so far, and show that our combined techniques achieve significant gains over CRCM in terms of throughput and energy consumption.

14. SUBJECT TERMS	15. NUMBER OF PAGES 7
	16. PRICE CODE **N/A**

17. SECURITY CLASSIFICATION OR REPORT **UNCLASSIFIED**	18. SECURITY CLASSIFICATION ON THIS PAGE **UNCLASSIFIED**	19. SECURITY CLASSIFICATION OF ABSTRACT **UNCLASSIFIED**	20. LIMITATION OF ABSTRACT **UL**

This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the ICC 2007 proceedings.

A new Cooperative Strategy for Deafness Prevention in Directional Ad Hoc Networks

Andrea Munari, Francesco Rossetto, Michele Zorzi
DEI - University of Padova - Via G. Gradenigo, 6/B, I-35131 Padova (PD), Italy
{munari,rossetfm, zorzi}@dei.unipd.it

Abstract— **We propose the novel concept of cooperation for deafness prevention in directional antenna ad hoc networks, along with a low-complexity multiuser detector specialised for these systems. We call a generic MAC protocol that uses these techniques a Cooperative-MAC (CMAC) and we define an upper and a lower bound on the performance of this class of protocols. Several simulations compare these bounds against the Circular RTS/CTS protocol (CRCM), which is one of the finest deafness-suppression systems proposed so far, and show that our combined techniques achieve significant gains over CRCM in terms of throughput and energy consumption.**

I. INTRODUCTION

Wireless ad hoc networks are radio-based systems that do not need an access point or base station to operate. This feature makes them very suitable for scenarios where an established infrastructure cannot be provided (such as disaster relief or battlefield). However, the lack of an element that provides coordination may cause a severe degradation in performance because the channel access must be managed in a fully distributed way. The MAC policy of choice is often random access, which is epitomized by the IEEE 802.11 DCF [1]. In this case, the coordination is achieved by a combination of physical and virtual carrier sense, and a backoff mechanism.

In this context, the usage of antenna arrays has been proposed by quite recent research as a way to improve the network performance, because of the interference suppression and spatial multiplexing capabilities of a MIMO link [2]. However, the introduction of smart antennas at every node in a network can also have drawbacks if not properly managed. One of the most prominent issues is deafness [3], which is defined as the impossibility for a node to reply to incoming packets (see Section III). This may happen because the terminal is busy, being in backoff or exchanging data packets. The main problem is that the sender interprets the missing reply as due to congestion or link failure, whereas the addressee was simply not available and the new communication should have been delayed. This erroneous belief is a consequence of the MAC policies typically used in these types of networks (e.g. [4] and [5]), that directionally send channel negotiation frames just toward the desired destination. On the other hand, this may prevent neighboring nodes from receiving such packets[1]. In this way, these terminals would remain unaware of the impeding transmission and they could unsuccessfully try to contact a busy node.

In summary, the reduction of interference due to directivity is suitable for unicast data transmission (because the communication energy can be focused towards the only recipient), but directional transmission of control packets (like handshake frames) can aggravate the problem of deafness. The consequence is a degradation of the degree of coordination among nodes.

In recent years some deafness reduction techniques have been proposed in the literature. For instance, in [6] the usage of busy tones enables nodes in backoff to correctly deduce that a missing reply is due to deafness and not to congestion. Nonetheless, this mechanism comes at the price of a dedicated channel for the busy tones, which are sent out of band. In [7] the extent of deafness is limited by a more accurate handling of directional receptions to avoid capture due to unwanted packets. Therefore a node can continue to listen to the neighboring communications. Finally, one of the most effective deafness-suppressing systems is the Circular RTS [8], later developed in the CRCM protocol [9]. According to this method, an extended-range broadcast is achieved by successively beamforming to different bearings, until the whole horizon is swept. This technique provides omnidirectionality and a broader reach, increasing the network connectivity, and informing more nodes about the ongoing data exchanges. Yet this delays the packet delivery and causes more interference.

However, these approaches cannot completely eliminate the problem of deafness. In order to cope more systematically with the issue, we propose a new system which is based on the principle of *deafness prevention*. The main cause of deafness, as explained, is a mistaken idea of the network activity. Had a node been aware that the intended receiver was unreachable (for instance because it was engaged in some communication), it would not have tried to reach it at all. Then, each terminal should store information about the duration of its neighbors' ongoing transmissions, by means of a *Communication Register* (CR). The accuracy of this table can be greatly improved by means of circular handshaking and *node collaboration*. We have designed a new protocol (called *Cooperative MAC*, or CMAC) around these ideas.

The main contribution of this paper is the proposal of the collaboration mechanism and a very simple form of multiuser detection that helps prevent deafness. Furthermore, we evaluate by simulation two solutions, called L-CMAC and B-CMAC, which represent respectively a lower and an upper bound for the performance attainable by node collaboration. A comparison with CRCM proves that even in the worst case (L-CMAC) cooperative protocols perform better than deafness reduction strategies proposed in the literature so far.

The rest of the paper is organized as follows: Section II introduces the considered antenna model; Section III analyzes the problem of deafness; Sections IV and V explain the proposed mechanisms and the CMAC protocol; Section VI presents some simulation results and finally Section VII draws the conclusions and delineates our future research in the field.

---

[1] Nonetheless, secondary lobes may enable some close neighbors to decode the packet anyway (e.g. node F in the topology of Fig. 1).

II. ANTENNA MODEL

We consider an antenna system made up of an array of N half-wave dipoles, arranged on a circle of radius $\lambda/2$. In transmission mode we use simple beamforming techniques [10], feeding each element of the array with a phased copy of the signal s that has to be delivered. In particular, letting $\mathbf{t}$ be the input vector for the array, we get $\mathbf{t} = s \cdot \mathbf{w}(\varphi)$, where $\mathbf{w}(\varphi) = [w_1(\varphi),\, w_2(\varphi),\, \ldots,\, w_N(\varphi)]^T$, and $w_i(\varphi)$ are complex values lying on a circle of unit radius. A suitable choice of $\mathbf{w}$ allows to focus most of the energy in the desired direction φ. The beamwidth θ_B of the main lobe is determined by the number of elements that compose the array, yet the circular geometry guarantees that θ_B depends very weakly upon the pointing bearing φ. Furthermore, this technique makes it possible to cover the whole horizon with directional gain by means of a sequence of M transmissions ($M = \lceil 2\pi/\theta_B \rceil$) with main lobes pointed toward bearings $\varphi_1,\, \varphi_2 = \varphi_1 + \theta_B,\, \ldots,\, \varphi_M = \varphi_1 + (M-1) \cdot \theta_B$.

As far as reception is concerned, we suppose that each antenna is connected to a dedicated RF chain. In this way we may simultaneously collect N versions of the incoming signal, $\mathbf{r} = [r_1\, r_2\, \ldots\, r_N]^T$, characterized by phase lags due to the differences in the the path lengths undertaken to reach the array elements. If these copies are weighed using the $\mathbf{w}(\varphi)$ vector, a directional reception pattern is obtained [10], in which the main lobe points toward φ and signals coming from other directions are filtered out. Furthermore, let $\mathbf{W}$ be an $N \times M$ matrix whose columns are the sets of weights $\mathbf{w}(\varphi_i)$, $i = 1, \ldots, M$. A single DSP can easily perform the product $\mathbf{r}^T \cdot \mathbf{W}$, obtaining a vector of received signals that covers with directional gain all the possible bearings. This system is formally identical to a bank of CDMA-matched filters, although here the match is with respect to a spatial signature rather than to a spreading sequence.

Let us refer to a Line of Sight propagation environment (which is the one simulated in our tests). Given that a packet arrives according to a certain Angle of Arrival (AoA), the inner product of the received signal $\mathbf{r}$ and the matrix $\mathbf{W}$ will be maximum for a certain column $\mathbf{w}$, that depends on the AoA. Consider two packets, whose AoAs are spaced by at least one lobe beamwidth and therefore will be detected by different filters. Each of them impinges in the secondary lobes of the filter that detects the other, causing some mutual interference (the larger the array, the smaller the secondary lobes and thus the interference). This makes it feasible to detect both packets[2] and can be regarded as a simple form of MultiUser Detection (MUD) [11].

As a consequence, it is possible for a node to listen to the channel even during an ongoing data reception, as well as to receive with beamforming gain from multiple directions simultaneously. This important fact, while simple to implement and well-known in the PHY community, has surprisingly been overlooked in the design of MAC protocols for MIMO ad hoc networks [3 - 9], making those solutions often suboptimal or unnecessarily complex.

The choice of a circular array over a linear one is due to protocol design reasons. First of all, the maximum power gain (and thus the transmission range) for a circular geometry is almost independent of the aimed bearing. Therefore, a neighbor will be reachable regardless of its orientation with respect to the transmitter. On the contrary, the gain of a linear array depends on this orientation [10]. Secondly, a circular array has a single main lobe. Instead, the radiation pattern of a linear solution (due to the axial symmetry) always has two main lobes. When transmitting, then, two beams are simultaneously covered, with a significant increase in generated interference. In reception mode, on the other hand, signals coming from different directions may not be distinguished.

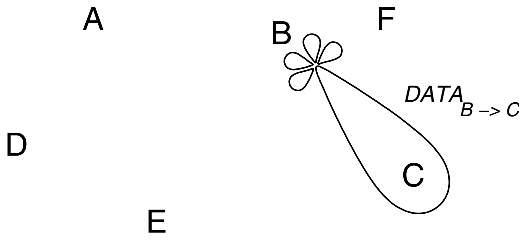

Fig. 1: A simple network topology

III. THE PROBLEM OF DEAFNESS

In the context of 802.11-based Ad Hoc Networks, a terminal is said to be deaf if it does not answer an RTS message addressed to it. In an omni-directional scenario, this condition may typically occur because of a collision. Two terminals, in fact, may simultaneously try to access the medium. The intended destination of the RTS packet, in this case, is not able to decode the frame due to the high level of interference, and cannot reply. The channel contention between the two transmitters, anyway, is solved by the exponential backoff procedure of the 802.11 MAC layer [1], and deafness does not significantly affect the overall network performance.

The impact of this issue, on the contrary, becomes more relevant if antenna arrays are employed. Directional transmissions, in fact, enable a spatial reuse of the channel, as simultaneous communications can be established within a set of neighbors [4], [6]. This result, nevertheless, can only be achieved if a terminal is allowed by the MAC layer to access the medium (i.e., to send an RTS frame) even if other neighboring links are active[3], unless specific alignment conditions are met [5], [12]. Such an approach, as a drawback, makes it possible for a node to try to establish a connection with a busy neighbor. As an example, refer to the situation depicted in Fig. 1, and suppose that node A sends an RTS message to B, which is actually already involved in an ongoing communication with C (i.e., it is sending data). In this case node B is deaf to the RTS (because of its own transmission), and A does not receive any reply. According to the 802.11 policy, node A, with the erroneous belief that a contention with another terminal is taking place, starts a backoff procedure, listening to the channel for a random time. At the end of this period, A tries to contact B again, re-transmitting the RTS. The length of the backoff window is typically shorter than the time required for B to return idle, and thus A's reattempt is likely to be unsuccessful as well.

---

[2] In the most favorable case, the system can decode M packets simultaneously, provided that they come from different directions (i.e., they are received by different lobes). However, the comparison with CDMA systems suggests that this is possible only when the packets have comparable strengths, otherwise the near-far problem (when one strong signal overpowers all the others) could make only one packet detectable.

[3] We remark that the IEEE 802.11 omnidirectional virtual carrier sense policy would not permit nodes to send any packet if a handshake frame has been recently overheard

This brief analysis shows that a terminal which contacts a deaf destination may spend a lot of time in useless backoff procedures, delaying other possible parallel data communications and affecting the efficiency of its medium access strategy. Moreover, had the sender (A) known that the intended destination (B) was busy and had it buffered a packet for a reachable node (say E), A may have tried to contact E instead, thus improving packet delivery latency. This comes at the price of a queueing manager, but the entailed software complexity cost is usually limited. Secondly, the transmission of multiple RTS frames increases the overall interference, potentially damaging other ongoing links. In the worst case, lastly, all the attempts to contact the destination may not succeed. In this condition, the initiating node would report a link failure message to the higher layers [1], falsely believing that the addressee has moved out of range. This information would cause the higher layers to start expensive (in terms of overhead and complexity) and pointless route-recovery procedures [13], significantly affecting the network performance.

Finally, we remark that while all the previous causes of deafness are deeply rooted in any directional antenna system, a suboptimal usage of these arrays may create additional problems. Let us consider, for instance, a terminal that is performing a backoff procedure. According to the IEEE 802.11 DCF, the node omni-directionally listens to the medium, and is thus able to perceive all the signaling on the channel. Instead, some authors [4], [6], who employ smart antennas, require the terminal to perform a directional reception, steering its lobe toward the addressee of its request. On the contrary, had the pattern been kept omni-directional (e.g., using the model of Section II), such a problem would not have occurred. In this way, though, packets coming from directions out of its reception pattern would not be detected. As a reference, consider Fig. 1. Node A, according to [6], during the backoff procedures due to B's unavailability, stays beamformed toward B and actually becomes itself deaf to any request. If in the meantime another terminal, say D, tries to contact it, the frame is not detected and no reply from A is obtained. Then D enters a deafness-induced backoff as well. The chain of nodes stuck in useless attempts may be further extended, potentially leading to a severe degradation of the network performance.

IV. CMAC: A CLASS OF COOPERATION-BASED PROTOCOLS

We propose a new class of MAC protocols for Ad Hoc Networks, collectively called *Cooperative MAC*, or CMAC, which improves the overall network performance by exploiting the advantages offered by directional communications. CMAC, in particular, extends the basic structure of 802.11 medium access policy[4] in order to reduce the impact of deafness.

The analysis of Section III has shown how in a directional scenario the lack of a CTS may be due to the erroneous forwarding of packets addressed to destinations which are actually busy. CMAC tries to avoid this situation by letting each node have an accurate perception of the surrounding network activity. To this aim, every terminal has an internal table, called *Communication Register*, or CR, where all the known ongoing communications are reported. For each of them, the nodes involved, the time left before conclusion[5] and the pointing bearing needed to reach the data transmitter are stored. The last quantity is estimated from the AoA of the RTS frame, while the other fields are inferred from RTS, CTS or ACK packets (unlike IEEE 802.11, in CMAC the CTS includes the ids of source and destination). Every time any of these frames is received, a new entry is created in this table, if necessary. When a frame has to be delivered, the terminal checks its CR in order to determine whether the desired destination is already involved in another activity, preventing useless attempts. The more updated the CR, the more effective this strategy. According to this principle, CMAC employs three solutions to let the nodes have a fair image of their neighbors' state: A) circular delivery of RTS and CTS, as in [8], [9]; B) use of the reception model described in Section II that, although well known in the physical layer community, has not been incorporated in MAC protocols so far; C) cooperation among nodes, which is actually a new proposal.

A) Circular Handshaking. RTS and CTS packets in CMAC are sent in a circular fashion, resembling the strategy proposed in [9]. These frames are broadcast omni-directionally by means of a sequence of directional transmissions, suitably spaced in order to cover the whole horizon. This approach introduces some overhead with respect to protocols that perform simple directional handshaking [4], [14], but nevertheless it turns out to be fundamental in reducing deafness, as all the neighboring nodes that are listening to the channel are informed about the link being established. The simulation results will show how the advantages offered by an omni-directional delivery of handshake frames outweigh the drawbacks and contribute to the overall CMAC performance improvements.

B) Multiple Receptions. The reception model described in Section II allows a node to simultaneously decode up to M packets, provided that they come from different angular sectors. In our protocol, then, unlike the solutions proposed in the literature [4], [6], [8], [9], a terminal is able to listen to the channel and to update its CR even when involved in the reception of a frame. The joint use of circular handshaking and multiple receptions leads to a significant reduction of deafness (see Section VI): when two terminals, say A and B, start a channel negotiation, all the neighbors which are idle or in reception mode become aware of the link under establishment. Hence, transmissions toward A and B are avoided for the period of their communication.

C) Cooperation among nodes. Circular handshaking and multiple receptions, as explained, protect nodes that are listening to the medium at the moment of a channel negotiation, but are not able to completely solve the problem of deafness. If frequency duplexing is not employed, in fact, simultaneous transmissions and receptions are not possible, and a terminal that is sending a frame actually becomes deaf. Suppose that A in Fig. 1 successfully negotiates the channel and starts transmitting a data packet to D. Moreover, assume that during this communication a link between B and C is established. In this case E, supposed idle, and D (i.e., the nodes that are listening to the channel) correctly update their CR and become aware of B→C activity. On the other hand, terminal A cannot decode RTS or CTS for this transmission. It is possible, then, that at the end of its communication with D, A erroneously tries to contact either B or C but fails because they are deaf.

To address this issue, CMAC proposes a cooperation scheme among nodes, trying to inform terminals that go back to idle mode after a transmission about communications that have started in the meantime. Let us refer again to Fig. 1. Nodes informed about both A→D and B→C links are aware that

---

[4] For a detailed description of CMAC procedures please refer to [12]

[5] The *time left* field is suitably decreased by the node. When the counter has reached zero, the registered communication has come to an end, and the CR entry is removed.

the second transmission has been established while A was deaf. Therefore, they know that A has an outdated image of the surrounding activity. In our situation this is the case for terminals E and D. At the end of A's activity (i.e., after the potential reception of an ACK packet from D), these nodes send to A a directional cooperation frame containing information about the ongoing link involving B and C (see Section V for the details of the algorithm). In this way A is able to update its CR and to prevent communication attempts with busy neighbors.

The proposed cooperation method is robust to mobility. Let us refer to Fig. 1 and focus on A→D data exchange. Node D can beamform the cooperation packet very accurately because it has perfect knowledge of A's location (it has just received a data packet from it). The other idle nodes in the network that decide to cooperate had estimated A's bearing when they received A's RTS, which was sent shortly before the transmission of the data packet. Given our data rates, a data packet and its handshake last for about 15ms. Even at relatively high vehicular speeds (120 km/h = 75 mi/h) the maximum displacement is moderate (50 cm = 1ft 8in), and unlikely to significantly affect the nodes' relative positions. Therefore the cached AoA can be considered as reliable and the cooperation packet will be properly delivered.

The additional signaling introduced by cooperation frames increases the overall interference. Nonetheless, our simulations show that there is a net gain in network performance. These benefits are due to two main reasons: firstly, the cooperation packets are short and directionally sent (unlike RTS/CTS), thus limiting interference due to this mechanism. Secondly, a more updated CR may prevent useless and harmful handshake frames sent to nodes otherwise reputed as deaf.

Furthermore, due to the finite size of a collaboration packet, only a limited number of new communications can be reported. This implies that some new transmissions might still be ignored by the node that receives these frames.

From the above discussion, we may conclude that cooperation has three main limits: a) the amount of information that can be delivered is finite, b) some interference is generated, and c) some overhead is introduced in order to deliver collaboration frames.

Let us consider the class of CMAC protocols whose cooperation packet size is no larger than x bits ($x = 120$ bits in our simulations). Once the overhead is bounded, the efficiency of the protocol is proportional to the number of new communications that can be conveyed in a collaboration frame. This quantity may vary between 1 and k, where k is the number of links the packet recipient is unaware of.

In order to evaluate the efficiency of this family of CMAC schemes, we have simulated two systems, called L-CMAC and B-CMAC, that we compare for a fixed value of the overhead (i.e. drawback c) has the same impact on both protocols). The former represents an ideal solution that fully exploits the potential of the collaboration mechanism, and may be regarded as an upper bound for the CMAC protocol family. According to B-CMAC, at the end of each communication the transmitter is informed (at no cost in time or energy) of all the k other links that have been established in the meantime. This simulates the presence of an idle node that transmits a cooperation packet carrying data about all these new communications but generating no interference (i.e., drawbacks a) and b) are not taken into account).

On the other hand, the L-CMAC protocol provides a basic implementation of CMAC structure. In this case, idle nodes actually send collaboration frames and thus generate interference (drawback b)). Moreover, these packets are very short and contain information concerning just one out of k new ongoing communications. In this way, the impact of drawback a) is maximized. It is thus clear, according to the previous discussion, that L-CMAC represents a lower bound to the performance of the CMAC protocols.

V. COOPERATION ALGORITHM

In this section we give a brief description of the cooperation procedure proposed in L-CMAC.

IDLE NODE

If *Time Left* field of a CR entry (entry #1) expires and the RTS for that communication has been received (i.e., the bearing of the transmitter has been cached at the beginning of the data exchange):

A) Check if there is another entry (entry #2) registered after entry #1. If so:
   A1) Create a cooperation packet containing ids of source and destination and time left of entry #2.
   A2) Get the bearing of the data transmitter of the frame registered in entry #1. Beamform towards this node and send the cooperation packet.

RECEIVER NODE[6]

If the data reception is successfully completed:

A) Beamform toward the transmitter and send an ACK packet.
B) Check the CR to determine whether any entry has been scheduled during the data reception. If so:
   A1) Create a cooperation packet containing ids of source and destination and time left of the entry.
   A2) Beamform toward the transmitter of the received data frame and send the cooperation packet.

TRANSMITTER NODE

After the reception of the ACK frame:

A) Listen to the channel waiting for cooperation packets. If any is received:
   A1) Update the CR exploiting information contained in the cooperation frame.
B) Go back to idle mode.

VI. SIMULATION RESULTS

The simulations have compared the CRCM protocol with the bounds on the cooperation performance (L-CMAC and B-CMAC). In order to evaluate the impact of collaboration over multiple receptions on the network behavior, we have also tested a protocol called MUD: this is a simplified version of L-CMAC, which employs the antenna model described in Section II but does not rely on the idea of collaboration; that is, it only employs strategies A and B described in Section IV. All these systems have been evaluated by means of the OPNET modeler (version 11.5). The network was made up by 10 or 15 nodes, uniformly and independently located inside a 1500 m × 1000 m rectangle. The results have been averaged over 30 independent simulations for each network size and packet generation rate. Each simulation lasts 30 s. This duration has been chosen long enough to stabilize the results.

Every node produces Poisson traffic at nominal rates of 8, 16, 25, 50, 100, 150 pk/s, until the throughput metric does not increase anymore or starts decreasing for all the protocols. The destination of each data packet is randomly chosen among the nodes in the network (the destination being different from the

---

[6] With *Receiver Node* we refer to a node that is receiving a data packet, and with *Transmitter Node* to a terminal that is transmitting a data frame.

source). There are five types of packets (Data, ACK/NACK, RTS, CTS and collaboration), whose sizes are equal to 10240, 120, 240, 240 and 120 bits, respectively, in agreement with the IEEE 802.11 specifications [1]. In addition, the bandwidth is equal to 1 MHz, the modulation is BPSK and the final data rate is 1 Mbit/s. All the results for the 10 node networks are reported in this paper, whereas only the most significant metrics for a 15 node configuration are shown, due to space constraints and similarity of trends with the 10 node case.

Each terminal is equipped with a circular array composed by N = 8 antennas. Since this array presents a 3-dB beamdwidth of 44.1^o, we need M = 9 sectors to sweep the horizon. The propagation environment is purely Line of Sight and we have calibrated the transceiver parameters with a 10% target packet error rate. [7] The transmission power is equal to 1 mW, which enables two nodes located at the opposite corners of the deployment area to communicate with each other provided that their main lobes are steered to maximize the gain.

The simulated network is thus single hop and no routing is needed. This choice is meant to highlight the efficiency of the analyzed protocols. The medium access coordination, together with the capability of guaranteeing spatial reuse, in fact, are deeply tested only if all the nodes may simultaneously contend for the channel. Moreover, single hop scenarios are more frequent in directional antenna networks because of the increased communication range and higher connectivity. Finally, the single hop nature of our networks implies that there are no hidden nodes. Therefore all the terminals are in visibility and may heavily interfere with each other. This highlights how the number of terminals in the network (up to 15) is large enough to stress the protocols. Nonetheless, the impact of our solutions on multihop networks and routing is an interesting problem and is part of our future work.

The first two metrics under study are the number of link failures and the number of packets addressed to deaf nodes. These have been chosen because they are directly related to the concept of deafness. Let us consider Fig. 1: given that A tries to contact B (and B is deaf), the latter metric is increased in either of these two situations: 1) all backoff cycles are unsuccessfully undertaken, or 2) A understands that B is actually busy and consequently aborts its attempt. The link failure metric on the contrary accounts only for condition 1). Case 2) happens if the source, while waiting for a CTS reply, overhears a packet (i.e., an RTS, CTS or ACK) coming from or addressed to its destination. Since this is a sign that B is actually busy as it is engaged in some communication, A delays the packet delivery. Therefore A is aware that the link is still active and will not report a link failure to the higher layer. The successful transmission of the packet is probably just postponed, not impossible as the link failure would suggest. In both cases, the impairments are due to deafness.

The results for the percentage of packets sent to deaf nodes is reported in Fig. 2. This metric is depicted against the nominal load (generation rate of the Poisson process). First of all, we note that the CRCM protocol addresses the majority of its packets to nodes that are unable to reply. This can be explained observing that the registers do not faithfully represent the neighbors' status because they cannot be updated during the exchange of data packets (i.e., for [8] and [9], a node cannot listen to the channel while transmitting or receiving data). Therefore, these registers do not provide reliable information on the surrounding network activity, and thus the virtual carrier sense no longer works. Instead, all the proposed systems significantly abate this phenomenon by a factor of at least two. Firstly, the simple MUD scheme is able to halve the extent of the problem, since the receiving nodes can continue decoding other packets. The possibility to receive control packets (such as RTS/CTS) is particularly beneficial as they convey the status of the network. Moreover, an effective usage of the cooperation mechanism (see B-CMAC curve) may further halve this metric, reducing its value to almost 20%. This bound proves that this technique may significantly reduce the impact of deafness. In addition, even in the worst case (L-CMAC) cooperation is able to achieve about 11% of improvement over MUD. Nonetheless the presence of deafness has been strongly diminished. Our research is currently looking for a mechanism that may attain a bigger share of the untapped performance improvements.

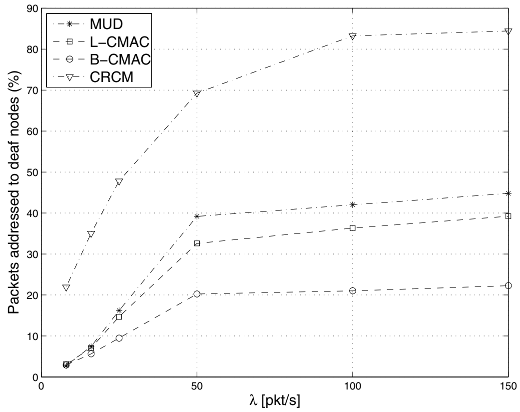

Fig. 2: Deafness vs nominal load for a 10 node network

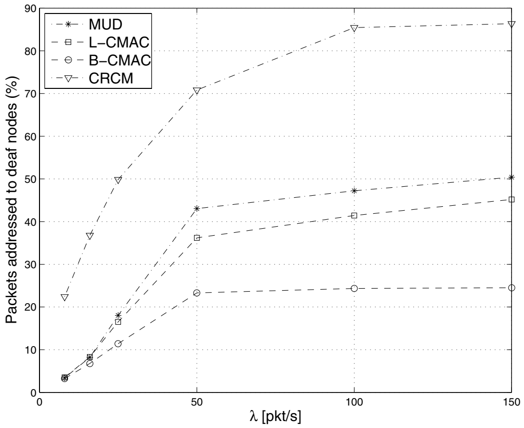

Fig. 3: Deafness vs nominal load for a 15 node network

Fig. 3 shows the behavior of this metric in a 15 node network. The trends are similar, giving further foundation to our previous comments. In addition, all protocol curves rise by about 5% because of the higher interference generated in the larger network. The more numerous collisions beset the

---

[7] Incidentally, the transmission of cooperation packets can be robust to fading. Let us refer to Fig. 1: node A completes a data packet transmission to D, and E collaborates with A to inform it about B-C communication. E→A channel has been estimated from A's RTS, which was decoded no earlier than a data exchange ago (about 15 ms in our simulations). At pedestrian speeds (up to 20 km/h) the channel coherence time is significantly longer, and thus the frame can be correctly beamformed. Robustness for faster user's speed could be guaranteed by higher data rates since the required coherence time would be reduced.

proposed solutions, because the increased level of interference affects the signaling packets (i.e., RTS, CTS). These frames are then corrupted more frequently, and the impact of deafness and link failures is greater. Incidentally, we notice that B-CMAC metric shifts upward by only 2-3%. Thus, a good implementation of cooperation schemes is more robust to interference and collisions.

Tightly correlated with the number of packets addressed to deaf nodes is the number of link failures. Such an event happens when a node tries to contact another terminal but all the backoff cycles fail. Therefore link failures are actually special and detrimental cases of packets for deaf destinations. We remark that our nodes are stationary and the propagation environment is not affected by shadowing. Link failures, then, cannot be ascribed to mobility, but only to protocol inefficiencies. The main reason for this phenomenon is deafness: it is highly likely that a destination is unreachable in all these attempts because it is engaged in one or more data exchanges. The simulation outcome is reported in Fig. 4, where the percentage of transmission attempts that lead to a link failure is shown against the nominal load. The MUD system already brings a remarkable improvement over CRCM, since link failures are cut by a factor of nearly three. In addition, if cooperation is exploited to the utmost (B-CMAC), link failures are reduced to as little as 15%, one sixth of the CRCM value. This highlights again the potential of this technique.

Nonetheless, in the worst case (L-CMAC) cooperation achieves a link failure rate of 25%, while MUD alone had 30%. We want to point out that this difference is the same that we had between the L-CMAC and MUD curves in Fig. 2 (which analyzed the number of packets addressed to deaf nodes). That is to say, these two metrics are reduced by the same quantity when cooperation is included. This could have been expected, and the reason is the following: by the above discussion and bearing in mind that our networks are static, it turns out that a link failure may happen only when a node tries to contact a terminal that is deaf throughout the duration of the backoff cycles. Thus, every link failure always stems from a communication with a deaf terminal and any method (like cooperation) that prevents packet transmissions to deaf nodes also avoids potential link failures. However, collaboration packets are sent only at the end of a data exchange and if afterwards an RTS is transmitted to a deaf node, no further help can be provided by this solution. Therefore, in this condition, the behavior of MUD and L-CMAC protocols is the same (i.e. the node may either succeed in its backoff procedure, recover from it or eventually incur a link failure). This confirms our view that cooperation (at least as we have implemented it) is a proactive rather than reactive mechanism, because it aims to prevent these problems, but not to solve them after their appearance.

Finally, we note that all the curves change slope between 50 and 100 pk/s. At the second packet generation rate, the offered load is at least 100· 10240 bits/node/s. Since the data rate is 1 Mbit/s, the bandwidth is too small to support the traffic and congestion is unavoidable. Our protocols basically degrade more gracefully than CRCM in these situations.

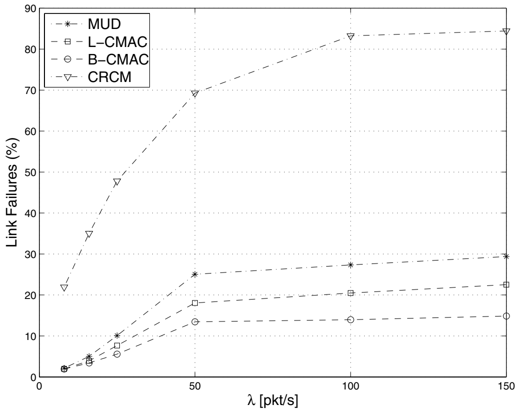

Fig. 4: Link failures vs nominal load for a 10 node network

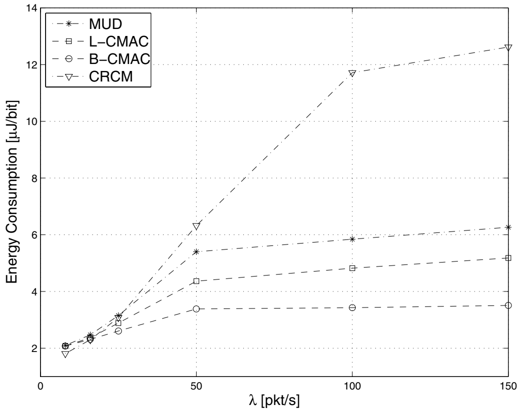

Fig. 5: Power consumption vs nominal load for a 10 node network

The third metric under study is transmit energy consumption, plotted against the nominal load, which is a vital issue for ad hoc networks (that are often battery-constrained). It has been computed as the total energy used by the nodes in transmission divided by the number of bits successfully sent across the channel. Congestion is one of the factors that affect energy consumption, and we expect that our enhancements will provide a significant boost, since they are able to coordinate the transmissions more efficiently and to reduce packets sent to deaf nodes. The simulation results (Fig. 5) prove that savings of up to 52% are achievable with the simple MUD. The inclusion of cooperation packets may reduce the energy consumption between 58% (L-CMAC) and 67% (B-CMAC). This last figure shows that an efficient usage of cooperation can use just a third of the transmit energy needed by [9]. We remark that the better network activity perception implied by the collaboration approach offsets the power drawn by the increased signaling. This is due to the fact that an updated CR reduces the number of packets sent to deaf nodes and therefore useless backoff cycles with the subsequent RTS packets, leaving more time to send data packets or just reducing interference and power consumption. These facts show that the proposed improvements can provide extremely interesting savings at a limited cost. It is acknowledged that these simulations do not include processing consumption, but the MUD scheme under use is extremely simple (it is actually a bank of matched filters), and the collaboration requires power only to examine the communication registers, which are lookup tables. Therefore we do not expect that the benefits would be significantly eroded if the processing power were explicitly taken into account. Finally, while cooperation packets in B-CMAC are sent at no energy cost, we believe that this bound is not exceedingly loose because these packets are short and thus the amount of required energy is limited.

The last metric studied is the aggregate throughput as a function of the aggregate load. The former is defined as the

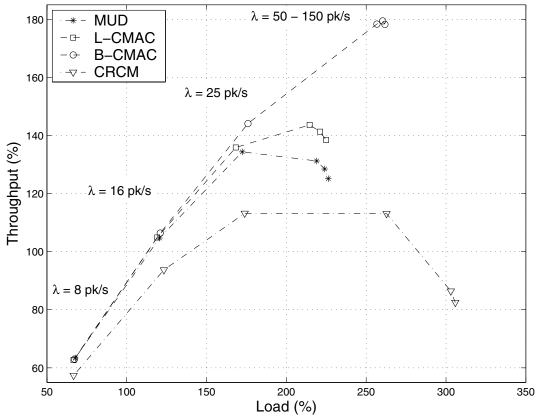

Fig. 6: Throughput vs effective load for a 10 node network. The numbers close to the symbols are the nominal load in pk/s

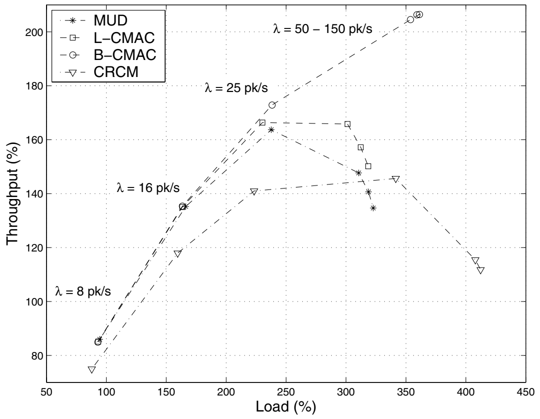

Fig. 7: Throughput vs effective load for a 15 node network. The numbers close to the symbols are the nominal load in pk/s

total amount of data bits successfully delivered and acknowledged normalized by the product of simulation duration and bit-rate, while the latter is measured as the total number of transmitted bits normalized by the same quantity. A percentage above 100% means that on average more than one link was active in any given instant of time, and thus is a proof of spatial re-use. The results are reported in Fig. 6 and Fig. 7, for a 10 and 15 node network respectively. The relative improvements are significant close to saturation loads, and they range between 21% and 61%, the latter being achieved by B-CMAC against CRCM for the 10 node scenario. This is a consequence of the increased coordination: the time wasted because of collisions, transmissions to deaf nodes and other protocol inefficiencies is extremely limited. This leaves more time to carry data packets and it reduces the interference due to unsuccessful packets (the RTS sent in backoff state). This performance gap is extremely significant and proves that cooperation, along with the other mechanisms, is a very promising way to abate deafness and its performance drawbacks. In the 15 node network throughput gains by our protocols are slightly more contained (between 14% and 41%), because of the harsher interference. In addition, there is some gain also at low loads. This actually highlights the value of the protocol, because in such conditions (very low congestion) we would expect all the protocols to deliver comparable performance. Instead, the increased coordination enables to get close to optimal performance (troughput/load > 90%). This is still an effect of the improved network coordination and collision avoidance due to deafness reduction.

As a final note, we stress that also a weak use of collaboration (L-CMAC) is able to enhance the overall performance with respect to the CRCM solution. This testifies once again how the deafness reduction achieved by cooperative protocols leads to a more efficient and better coordinated medium access.

VII. CONCLUSIONS AND FUTURE WORK

The problem of deafness in ad hoc networks has been analyzed, along with its causes and effects. The idea of cooperation has been introduced as a possible way to combat the deafness experienced by a node when engaged in data transmission. We have compared two bounds on the performance of this approach with CRCM [9], which provides relatively good performance with respect to many directive antenna ad hoc network protocols and can suppress deafness to some extent. The outcome has been a significant reduction of deafness related problems (link failures and packets addressed to busy nodes), with positive consequences for other important metrics (e.g., power consumption and throughput). The upper bound on the CMAC performance shows that cooperation can offer very significant performance improvements for several metrics of interest. In addition, the protocol operates in a much smoother way than CRCM, because the impact of link failures and their subsequent recoveries is very much reduced.

Our future work will pursue techniques to improve deafness resistance and bridge the gap between the proposed practical scheme and the performance of the ideal case. In addition, our current work includes the characterization of the protocol behavior in a multihop scenario as well as the design of a mobility-aware version of it.

REFERENCES

[1] IEEE 802.11 WG, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification, 1999.

[2] A. Paulraj, R. Nabar, D. Gore, *Introduction to space-time wireless communications*, Cambridge press, Cambridge (UK), 2003.

[3] R. R. Choudhury, N. H. Vaidya, "Impact of Directional Antennas on Ad Hoc Routing"; *IFIP Personal and Wireless Comms (PWC)*, 2003.

[4] M. Takai, J. Martin, A. Ren, R. Bagrodia, "Directional virtual carrier sensing for directional antennas in mobile ad hoc networks"; *ACM MOBIHOC '02*, Lausanne, Switzerland, June 9-11 2002.

[5] T. ElBatt, T. Anderson and B. Ryu; "Performance Evaluation of Multiple Access Protocols for Ad hoc Networks Using Directional Antennas", *IEEE WCNC*, 2003.

[6] R. R. Choudhury, N. H. Vaidya, "Deafness, a MAC problem in ad-hoc networks when using directional antennas"; *10th IEEE International Conference on Network Protocols (ICNP)*, Berlin, Oct. 2004.

[7] H. Gossain, C. Cordeiro, D. Cavalcanti, D. P. Agrawal, "The Deafness Problems and Solutions in Wireless Ad Hoc Networks using Directional Antennas", *GLOBECOM 2004*, November 2004, Dallas (TX, USA).

[8] T. Korakis, G. Jakllari, L. Tassiulas, "A MAC protocol for full exploitation of Directional Antennas in Ad-hoc Wireless Networks"; *ACM MobiHoc 2003*, Annapolis (MA, USA), pp. 98-107.

[9] G. Jakllari, I. Broustis, T. Korakis, S.V. Krishnamurthy and L. Tassiulas; "Handling Asymmetry in Gain in Directional Antenna Equipped Ad hoc Networks", *IEEE PIMRC 2005*, Berlin (Germany).

[10] C. A. Balanis, *Antenna theory, Analysis and Design*; 3rd edition, John Wiley, New York (NY, USA), 2005.

[11] S. Verdù, *Multiuser detection*, Cambridge University Press, New York (NY, USA), 1998.

[12] A. Munari, *A New Cooperative MAC Protocol for Mobile Ad Hoc Networks Exploiting Directional Antennas*; Università degli Studi di Padova, 2006 (MSc Thesis).

[13] E. Royer, C-K.Toh, "A review of current routing protocols for ad hoc wireless networks", *IEEE Personal Communications Magazine*, vol. 6, no. 2, April 1999, pp. 46-55.

[14] R.Ramanathan, "On the performance of ad hoc networks with beamforming antennas", *ACM MOBIHOC 01*, Long Beach (CA), pp.95-105.