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Deafness Resilient MAC Protocol for Directional Communications

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SUMMARY It is known that wireless ad hoc networks employing omnidirectional communications suffer from poor network throughput due to inefficient spatial reuse. Although the use of directional communications is expected to provide significant improvements in this regard, the lack of efficient mechanisms to deal with deafness and hidden terminal problems makes it difficult to fully explore its benefits. The main contribution of this work is to propose a Medium Access Control (MAC) scheme which aims to lessen the effects of deafness and hidden terminal problems in directional communications without precluding spatial reuse. The simulation results have shown that the proposed directional MAC provides significant throughput improvement over both the IEEE802.11DCF MAC protocol and other prominent directional MAC protocols in both linear and grid topologies.

key words: *MAC protocols, directional communication, deafness, hidden terminal problems*

1. Introduction

The past decade witnessed enormous advances in wireless communication technologies. These advances have fostered the research in ad hoc networks, which are envisioned as rapidly demployable, infrastructureless networks where each node is equipped with wireless capabilities and act as a mobile router. These characteristics make ad hoc networks suitable to support communications in urgent and temporary tasks, such as business meetings, disaster-and-relief, search-and-rescue, law enforcement, among other special applications.

In an ad hoc wireless network, the nodes are usually assumed to share a common channel and to operate with omnidirectional antennas. Since nodes sufficiently apart from each other can communicate simultaneously, one could expect the throughput to improve with the area they cover. However, the relay load imposed by distant nodes and the inefficient spatial reuse provided by omnidirectional antennas results in poor network throughput [7], [12]. Aiming to provide better spatial reuse to increase network capacity, the research community has begun considering ad hoc networks where the nodes are empowered with directional antennas. The key benefits provided by directional antennas include reduced co-channel interference, transmission range extension, better spatial reuse and signal quality as compared to their omnidirectional counterparts [16].

Despite of its advantages, developing efficient directional Medium Access Control (MAC) protocols in the context of ad hoc networks is a challenging task, particularly due to the lack of efficient means to deal with deafness and hidden terminal problems. In what follows, we briefly review some of the most significant results which are related to our work. The MAC protocol proposed by Ko *et. al.* [10] assumes that each node knows its physical location (perhaps with the aid of a GPS). Two schemes were proposed: (*i*) *Request To Send* (RTS) packets are sent directionally; (*ii*) RTS packets are send in omnidirectional mode if none of its antenna elements are blocked. In both schemes, *Clear To Send* (CTS) packets are sent in omnidirectional mode. In the MAC protocol proposed in [14], source and destination identify the location of each other during the omnidirectional RTS/CTS exchange. In order to obtain location information without the aid of a GPS, the MAC protocol proposed in [1] associates each neighboring node with an antenna element. RTS/CTS packets are sent directionally or selective multi-directional. The MAC protocol in [1] was refined in [20], where the number of control messages to obtain location information is significantly reduced. The works proposed in [2]–[4] aimed to explore the higher gain provided by directional antennas. The works presented in [5], [6] focus on means to attenuate deafness. In [11], the use of circular (directional) RTS has been proposed as an attempt to reduce deafness and hidden terminal problems. A similar approach is used latter in [19], where special frames are sent to neighboring nodes informing the node's unavailability. Despite the above efforts, the lack of efficient means to overcome/minimize the effects of deafness and hidden terminal problems is still a major obstacle when trying to leverage the network performance through directional communications. Obviously, it would be desirable to surmount the aforementioned problems with little overhead and without precluding spatial reuse.

The major contribution of this work is to propose a MAC scheme that attempts to minimize deafness and hidden terminal problems in the context of ad hoc networks. Unlike other proposals that focus in exploring the characteristics of the physical layer, the proposed MAC protocol relies on simple mechanisms that can be easily coupled with a directional antenna without requiring major modifications to the current MAC standard.

The remainder of this paper is organized as follows:

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Section 2 presents the antenna model considered in this work. The motivation of this work is presented in Sect. 3, which discusses some problems associated with directional communications and Sect. 4 presents some preliminary results which are latter used in developing a directional MAC protocol. The main contribution of this work is presented in Sect. 5, which shows the details of the proposed MAC protocol. Section 6 presents the evaluation results and Sect. 7 concludes this work.

2. Antenna Model

There are basically two types of directional antennas: *Switched Beam*, and *Adaptive Arrays*. Switched beam antennas are relatively simple to implement, comprising a number of antenna elements, a basic Radio Frequency (RF) switching function, and a control logic to select a particular beam. The antenna elements are deployed into a number of fixed sectors, among which the one experiencing the highest signal level is selected to collect the incoming signals. Adaptive array antennas rely on sophisticated digital signal processing algorithms to direct the beam towards the intended user and simultaneously suppress interfering signals (by setting nulls in the direction of interferences). Although adaptive antennas can provide better performance than a switched beam antenna, the engineering cost associated with it is a limiting factor. On the other hand, switched beam antennas are expected to be produced at a much lower cost while being able to provide most of the benefits of a more sophisticated system [13]. Hence, switched beam antennas seems to be a feasible option as a first generation technology to be used in ad hoc networks. Indeed, efforts aiming to enhance mobile devices with directional antennas already exist, an example is the ESPAR (Electronically Steerable Passive Array Radiator) antenna currently being developed at ATR (ACR) [15]. In this work we assume that each mobile terminal is equipped with a switched beam antenna, such as ESPAR, and to have similar characteristics as those assumed in [1], [3], [14].

3. Motivation

Despite the efforts to leverage the capacity of ad hoc networks trough the use of directional communications, a number of problems still remain or need optimized solutions. Indeed, hidden terminals and *deafness* can have a major impact in the network performance [5]. When using directional communications, the following problems arise:

- **Deafness:** Occurs when the destination node is locked away from the transmitter (either sensing, sending or receiving). In this case, the transmitter cannot judge whether the transmitted packet has been lost due to collision, or because the destination node is unreachable, forcing the transmitter to increase its *contention window*.
- **Directional Hidden Terminal Problems:** Due to asymmetric gain, deafness, and missed RTS/CTS packets, directional hidden terminal problems may arise.
- **Staled Location Information:** Without a robust location information scheme, transmitting nodes may attempt to reach the desired receiver through a sector that does not include the intended receiver. Note that this situation may arise due to a number of reasons, including node mobility.
- **Staled DNAV Information:** When a node misses an RTS/CTS it may not know about its neighboring communication activity. That is, its DNAV information does not reflect the current communication status. Thus, when such node attempts to engage in communication, it might disrupt ongoing dialogs. Note that staled DNAV *Directional Network Allocation Vector* is a side effect of deafness as well [18].

To the best of our knowledge, no efficient MAC protocol capable of coping with both deafness and hidden terminals problems has been proposed in the literature. Obviously, it would be desirable to avoid, or at least minimize, the effects of the aforementioned problems with little overhead and without precluding spatial reuse. Furthermore, it would be interesting to design a MAC protocol having the following additional properties: (*i*) Single transceiver, i.e., no simultaneous transmission and reception; (*ii*) Simple scheme to associate neighboring nodes to each sector. The MAC layer should be able to handle location information without relying on external equipments, such as GPS; (*iii*) No cross-layer interfaces; and (*iv*) Little modifications to the current standard.

In this work we propose a MAC scheme that attempts to minimize deafness and hidden terminal problem in the context of ad hoc networks with the properties mentioned above.

4. Preliminaries

This section provides some preliminary results that will be used in the subsequent sections. To begin with, suppose that two neighboring nodes are communicating in omnidirectional mode. The area in which the omnidirectional communication overlaps can be thought as the intersecting area of two circles. Such intersecting area forms a two equal and symmetrically placed circular arcs, known as *lens*. Figure 1 depicts the lens area formed by the omnidirectional communication between nodes N_1 and N_2 (gray area).

An interesting fact relating to the lens is that any directional communication, whose beamwidth is less than or equal to 60°, is completely enclosed by lens area. Let d $(= r)$ be the separation between nodes N_1 and N_2, where r is the transmission range. In this case, the lens area formed by the omnidirectional communication of nodes N_1 and N_2 intersect at two distinct points p_1 and p_2 (see Fig. 1). The distance of node N_1 (or N_2) to each of these two points is exactly r. Connecting nodes N_1 and N_2 to either of these points creates a triangle whose sides are of equal length r. Since each of the internal angles of an equilateral triangle

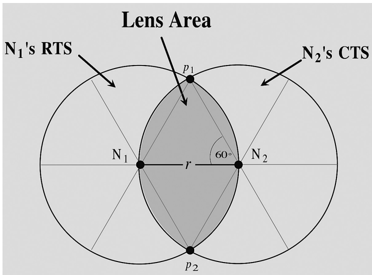


Fig. 1 Directional beam enclosed by the lens area.

is exactly 60°, the lens area should indeed enclose a directional beam with aperture ≤ 60°. Now, suppose that nodes N_1 and N_2 are equipped with a directional antenna whose beamwidth is 60°. Then, if nodes N_1 and N_2 wish to talk directionally, they will select the beam which better captures each other. As we have shown above, such beam should be enclosed by the lens area. For latter reference we summarize the above discussion in the following lemma:

Lemma 1: If the beamwidth of the directional antenna is less than or equal to 60°, then the directional communication between a source and destination nodes is fully enclosed by the lens area.

Our next step is to find the expected area of the lens. For this purpose, let us consider a single-hop ad hoc network where the receiver is randomly distributed, i.e., uniformly and independently, across a two-dimensional area having the geometry of a circle with unit radius. Let the transmitter be located at the center of the network (i.e., circle). The distance between the transmitter and receiver is subject to the *probability density function* (pdf)

$$f(\ell) = \begin{cases} 2\ell, & \text{if } 0 < \ell < 1, \\ 0, & \text{otherwise.} \end{cases}$$

The probability that the destination node is located at distance ℓ, $a \le \ell \le b$, from the source (center of the circle) is given by

$$Pr\{\ell \in [a, b]\} = \int_a^b 2\ell d\ell = b^2 - a^2,$$

and the occurrence of an event $\ell \in [x, x + dx]$, where dx is small, is approximated given by $Pr\{\ell \in [x, x + dx]\} \approx f(x)dx$. The lens area can be computed by the following expression:

$$L(d, r) = r^2 * [\rho - \sin(\rho)], \quad (\rho \text{ in radians}),$$

where $\rho = 2 * \arccos(d/2r)$, r is the common radius and d, $0 \le d \le r$, is the distance between the centers. The average area of the lens in the case where a source node randomly selects its *talking-partner* within its transmission range can computed as follows:

$$\begin{aligned} L_{av} &= \int_0^1 L(x, 1) \cdot f(x)dx \\ &= \pi - \frac{3\sqrt{3}}{4} \\ &= 1.8425. \end{aligned}$$

Thus, the average area outside the lens is $2\pi - 2 \cdot 1.8425 = 2.598$, for $r = 1$, which represents ≈ 42% of the total area enclosed. For latter reference we state the following simple result.

Lemma 2: When a source node randomly selects its talking partner within its communication radius, the average area of the lens is approximated ≈ 58% of the total area enclosed by the omnidirectional communication.

5. Proposed MAC Scheme

Our goal in this section is to use the notion of the lens in order to reduce the effects of deafness and collisions due to hidden terminals while being able to provide spatial reuse. We begin by presenting a simple directional MAC protocol (SD-MAC, for short) which lays the building blocks for presenting the main contribution of this article, a Dual Channel Directional MAC Protocol (DC-MAC, for short).

5.1 Simple Directional MAC Protocol

Our Simple Directional MAC protocol (SD-MAC) uses two separated channels namely: a *Control channel* and a *Data channel*. The Control channel is used for exchanging RTS and CTS packets while the Data Channel is reserved for transferring Data and Ack packets. Note that our protocol does not rely on concurrent transmission and reception. Channel reservation is performed through omnidirectional RTS/CTS exchange between the sender and the receiver as in the IEEE802.11 standard.

By using *Angle of Arrival* (AoA) techniques [8], [11], [14], [21], or the mechanisms to associate each neighboring node to a particular beam proposed in [1], [3], source and destination nodes are able to identify the beam that maximizes the signal strength towards each other during the RTS/CTS exchange. After a successful RTS/CTS exchange, source and destination nodes will leave the Control channel and switch to the Data channel. At this point, sender and receiver will beamform towards each other in order to send/receive Data and Ack packets directionally.

Neighboring nodes, on overhearing the RTS and/or the CTS packets, will set their Directional Network Allocation Vector [18] (DNAV) – which is a directional version of the NAV – towards the direction of the detected signals. Such nodes will defer their own transmissions towards sectors that have set DNAV for the proposed duration of the transfer. However, nodes that have set DNAV are allowed to engage in communication through other sectors, as long as the desired direction of communication does not interfere with any ongoing transfer.

5.1.1 SD-MAC Shortcomings

As the SD-MAC scheme relies on omnidirectional RTS and

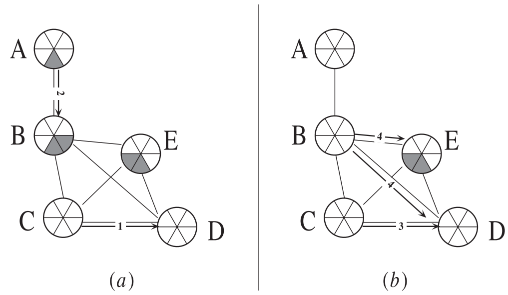


Fig. 2 An example scenario.

CTS exchanges, it might be able to reduce the effects of deafness. Likewise, SD-MAC might reduce collisions as two separated channels are used. Furthermore, the implementation of the above protocol is straightforward. However, SD-MAC cannot prevent collisions from happening at the Data channel as hidden terminal problems are likely to arise.

Figure 2 exhibits a scenario in which collisions at the Data channel are likely to occur. The figure shows a scenario in which two communications have been initiated: the first communication (arrow #1 in Fig. 2 (a) is between nodes *C* and *D* and the second (arrow #2) is between nodes *A* and *B*. While nodes *C* and *D* exchange RTS/CTS packets, neighboring nodes set their DNAV (shown in dark gray) to the direction from which the control packets have been received. As the DNAV of node *B* does not capture node *A*, these nodes are allowed to communicate. Note that the RTS/CTS exchange between *A* and *B* is performed through the Control channel and will not interfere with the communication of nodes *C* and *D*.

While the Data transfer is being carried out between nodes *A* and *B*, nodes *C* and *D* start a new communication (arrow #3 in Fig. 2 (b)). Suppose that node *B* misses the RTS/CTS exchange between nodes *C* and *D*. When the communication of nodes *A* and *B* finishes, the previously blocked sectors of node *B*, which was set towards *C* and *D* would have expired. Now, suppose that node *B* attempts to communicate with node *E* (arrow #4). As the sector that captures *B* is not blocked, node *E* is able to accept the request. When node *B* starts sending Data over the Data Channel, the directional transfer of node *B* might interfere with the directional transfer of node *C*, causing node *D* to drop the packet.

As described in the example above, even though node *E* was idle for a long period and its DNAV was accurate, collisions can still occur. Clearly, the traditional DNAV scheme is not enough to prevent collisions at the Data channel. A possible way to limit the occurrence of collisions at the Data channel is to block additional sectors. However, such mechanisms will reduce spatial division which, in turn, might have a negative impact in throughput. The challenge is to devise a mechanism that limits the occurrence of collisions at the Data channel while still being able to provide spatial division.

5.2 An Efficient Directional MAC Protocol

The main purpose of this section is to present a directional MAC protocol whose main goal is to address the shortcoming of the SD-MAC. The proposed scheme is termed Dual Channel Directional MAC protocol, or DC-MAC for short.

We begin by presenting a scheme to reduce collisions at the data channel. For this purpose, a few constraints are imposed to those nodes located within the lens area. It is assumed that each node has two timers: an *idle timer* T_i and a *lens timer* T_l. The T_i timer indicates the amount of time slots a node has been listening to the Control channel, starting from zero up to T_{max}, where T_{max} is maximum duration of a communication. The T_i timer is set to zero whenever a node returns to the Control channel (that is, after a Data transfer). A node will start the T_l timer whenever it finds itself within the lens area, and will reset it at the end of the communication. Let T_l^S, T_i^S, T_l^R and T_i^R denote the sender (S) and receiver (R) timers, respectively. The RTS packet is modified to accommodate the T_i^S and T_l^S timers. Upon receiving an RTS, the receiving node performs the following verification when the source node is not in a blocked (DNAV) sector:

Rule #1**.** The receiving node is within a lens area. The node will check whether the transmitting node is aware of the communication that created the lens. If $T_i^S \geq T_l^R$ holds, then a CTS can be granted. Clearly, no collision with the communication that created the lens will occur.

Rule #2**.** The receiving node is outside lens area of the transmitting node. If $T_l^S \neq 0$ then check if $T_i^R \geq T_l^S$. If true, then the receiving node is aware of the communication that created the lens around the transmitter. The receiving node can safely reply with a CTS.

Rule #3**.** The lens timer of both transmitting and receiving nodes are non-zero. The case where $T_l^S = T_l^R$ is already covered above since $T_i^S \geq T_l^R$ should hold as source and destination must be within the same lens area. If $T_l^S \neq T_l^R$, then the destination has to make sure that the above two conditions are satisfied.

In what follows, we will show that the above rules can effectively reduce packet disruption. In order to show the effectiveness of the above rules, let us revisit the scenario shown in Fig. 2 (b). As can be seen in the figure, node *E* has set its DNAV towards nodes *C* and *D* on overhearing the control frames necessary to establish the third communication exchange (arrow #3). When node *B* sends an RTS as an attempt to establish the forth communication (arrow #4), node *E* checks whether it is safe to engage in communication or not by applying the above rules. As node *E* lays within the lens created by nodes *C* and *D*, Rule #1 applies. Thus, node *E* checks whether $T_i^B \geq T_l^E$ holds, before replying to an RTS issued by node *B*. That is, node *E* checks whether node *B* is aware of the communication that created the lens, so as to prevent collisions at node D. Clearly, as node B is unaware of the communication between C and D, T_i^B cannot be larger than T_l^E. Note that, if node B was aware of the communication between C and D, the DNAV of node B would have been set towards them. In the latter case, the communication with node E would not be possible as nodes D and E are captured by the antenna sector. Rule #2 applies to those cases where the source node is within the lens and the receiving is outside while Rule #3 applies to the special case where source and destinations nodes are within different lens areas.

By applying the above rules, whenever a node is within the lens (source, destination, or both), the receiving node will be able to decide whether it is safe to accept the request or not. It should be noted that we allow nodes to communicate when the lens timer of both source and destination is zero. As a result, collisions at the Data channel might eventually occur. To further limit the occurrence of collisions at the Data channel, before transmitting a control packet (RTS and/or CTS), the transmitting node could carrier sense the Data channel towards the direction of the intended receiver. Should a Data packet disruption occur, the node at which the collision occurred will not accept to resume the previous communication until the Data channel has become free once again. This scheme aims to give enough time for those nodes that caused the collision to finish their communication and return to the Control channel. At this point, those nodes which had their communication disrupted, as well as those which caused the disruption, will have to compete for the channel once again, thus limiting further collisions at the Data channel.

As stated in Lemma 2, the expected area in which nodes will be setting the lens is ≈ 58% of the area enclosed by the omnidirectional RTS/CTS. Note that these nodes may still be able to communicate when the above rules are satisfied. Indeed, as we will show in the next section, DC-MAC protocol is be able to provide significant improvements in terms of spatial reuse as compared to a traditional omnidirectional protocol.

6. Performance Evaluation

6.1 Environment

The simulations are conduced in QualNet [17], which supports the IEEE802.11 MAC (omnidirectional communication) as well as directional communications. The support for directional communications is based on the protocol proposed in [18]. These two protocols, along with the MAC protocol proposed by Takada et al. [19], which is a Directional MAC protocol designed for Deafness Avoidance (DMAC/DA), will be used as benchmark in comparing the results with DC-MAC. For latter reference, we denoted the above protocols as *Omni*, *Directional*, and DMAC/DA protocols, respectively.

The beam patterns of the ESPAR antenna has been used in the simulations. The ESPAR antenna is a directional antenna which has been developed at ATR-ACR labs [3]. Figure 3 shows the ESPAR antenna beam patterns at 0° and 60° degrees. The transmission power used in the simulations is 10 dBm and a 2 Mbps communication channel is assumed. For DC-MAC we assume that both control and Data channels have similar characteristics. Node mobility is not consider in this work. The averaged results are drawn from twenty runs using different seeds with each run lasting for five minutes. As a directional antenna receives/transmits more power towards a specific direction, the *gain* of a directional antenna (G_d) is usually greater than the gain of an omnidirectional antenna (G_o), that is, $G_d \geq G_o$. In this work, however, we do not focus on range extension capabilities of the directional antennas. Thus, like the works proposed in [1], [10], [14], when transmitting in directional mode, the transmitting node is requested to reduce its transmission power so as to have the same transmission range of an omnidirectional communication.

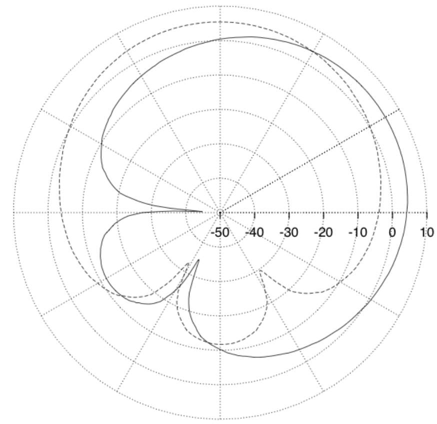


Fig. 3 ESPAR antenna beam at 0° and 60°.

As the proposed protocol (DC-MAC) uses two channels, the reader may find the comparison unfair, which is not the case. First, it should be pointed out that the proposed protocol uses a singe transceiver, which makes it impossible for a node to use both channels concurrently. Also, the control and data channels used in DC-MAC do not need to have the same bandwidth. Indeed, the control channel is used to exchange control frames only, which are 20 and 14 bytes long, corresponding to the RTS and CTS, respectively. The Data frames, on the other hand, are usually much larger than that. Clearly, the DC-MAC could work with two subchannels of a larger channel, where one sub-channel would be responsible of carrying data frames and the other would be responsible for carrying controls frames.

6.2 Reducing Collisions at the Data Channel

We begin by showing that the mechanisms proposed in Sect. 5.2 can effectively reduce collisions at the Data Channel. For this purpose, we define the *Data Packet Disruption Rate* (DPDR) as the ratio of Ack packets received over the number of Data packets sent by the source node. Ad-

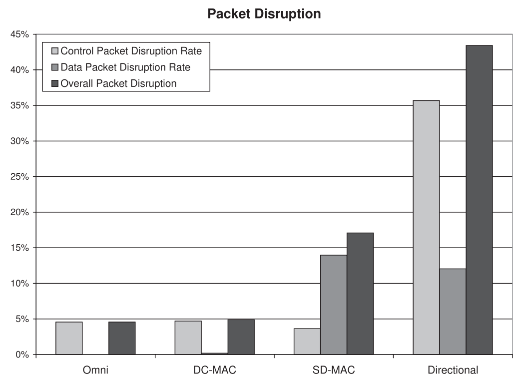
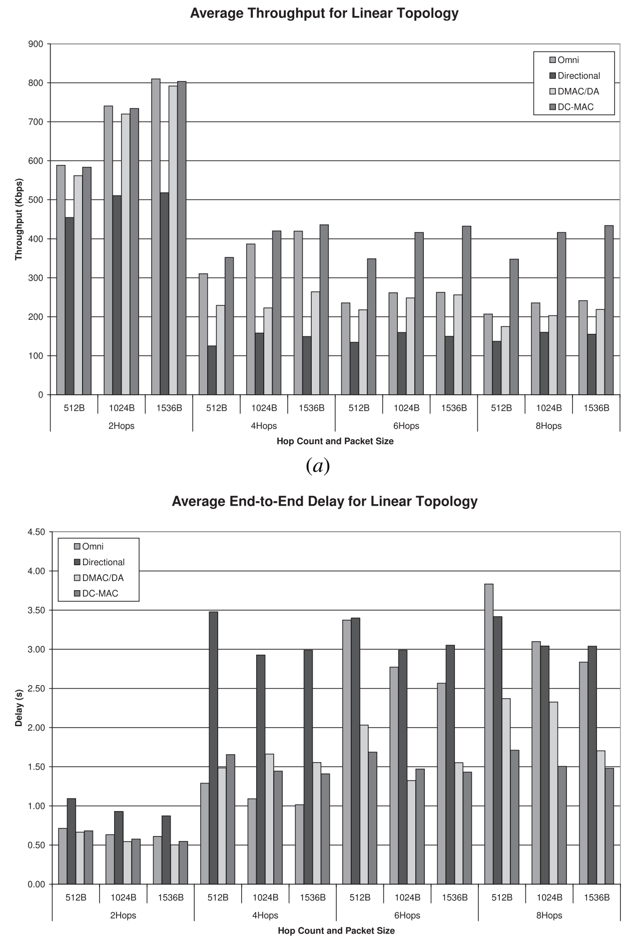


Fig. 4 Average packet disruption for DC-MAC and SD-MAC.



(*b*)

Fig. 5 Average throughput (*a*) and delay (*b*) for a string topology at different hop count and data packet size.

ditionally, we define the *Control Packet Loss Ratio* (CPLR) as the ratio of Data packets sent over the number of RTS packets issued for a particular source node. In other words, the CPLR accounts for the unsuccessful RTS/CTS exchange while the DPDR shows the percentage of Data packet disruption after a successful RTS/CTS exchange.

In what follows, we utilize the example scenario shown in Fig. 2, where nodes *A* and *C* are selected as the source nodes for nodes *E* and *D*, respectively, with node *B* serving as relay for node *A*. The application layer at nodes *A* and *C* are set to generate CBR traffic at the rate of 340 Kbps and 680 Kbps, respectively. Figure 4 shows the results in terms of DPDR and CPLR, for DC-MAC, SD-MAC, Omni and Directional protocols. The figure shows that nearly 14% of the Data packets sent by node *C* are dropped with SD-MAC. This is consistent with the DPDR of the Directional protocol in which more than 12% of the Data packets issued by node *C* are lost. That is, even after a successful RTS/CTS exchange between nodes *C* and *D*, the Directional and SD-MAC protocols cannot guarantee that the Data packets will be safely delivered. On the other hand, DC-MAC can significantly reduce collisions at the Data channel. Although collisions still arise, the DPDR for DC-MAC is comparable to that of the Omni protocol. Due to hidden terminal problems, the CPDR for the Directional protocol surpasses 35%, which is more than 7 times higher than the Omni protocol. The figure shows that more than 43% of the packets issued by node *C* are lost when using the Directional protocol and $\approx$ 17% for SD-MAC. For Omni and DC-MAC, this value is less than 5% with the majority ($\approx$ 99.8%) of the packet loss occurring during the RTS/CTS exchange.

6.3 Deafness and Hidden Terminal in Linear/Grid Network Topologies.

It is well known that directional communications perform poorly in string and grid topologies due to deafness and hidden terminal problems [5]. As the proposed protocol aims to reduce their effects, our goal in this subsection is to verify the performance in such topologies. Two topologies are considered here, linear and grid. In the linear topology nine nodes are arranged in a 1×9 array. The grid topology consists of twenty seven nodes are arranged in 3×9 grid. The transmitting nodes are located at the first column of the grid/ array. Nodal separation set to 260 meters and average throughput and delay performance is verified at every two hops from the source node, that is, at 2, 4, 6, and 8 hops from the transmitting node. Other parameters are the same as discussed before.

Linear Topology: We begin by evaluating the performance of DC-MAC in a linear topology. Figure 5 (a) shows the throughput results for DC-MAC, Omni, Directional and DMAC/DA. The figures shows three different packet sizes: 512, 1024 and 1536 Bytes of CBR traffic, generated at a rate of 2, 4, and 6 *ms*, respectively. As anticipated, the Directional protocol attains a poor throughput performance in a linear topology. At 2 hops and with a Data packet size of 1536 Bytes, the throughput for the Directional protocol is $\approx$ 36% less than the throughput obtained by the Omni and DC-MAC. With a Data packet size of 1024 Bytes, the throughput of the Directional protocol falls bellow 130 Kbps at 4 hops, which is less than 40% of the throughput obtained by the Omni protocol. The poor performance of the Directional MAC protocol comes primarily from its inability to know the status of its neighboring nodes, which exacerbates the occurrence of deafness and hidden terminal problems.

The DMAC/DA, on the other hand, has been designed to overcome deafness. For that purpose, the DMAC/DA uses a special packet, termed WTS (*Wait To Send*), which is similar to an RTS. On DMAC/DA, those nodes that have successfully exchanged an RTS/CTS packets are requested to issue the WTS frame to notify the on-going communication to potential transmitters. In other words, the DMAC/DA requests the transmission of additional packets to every successful RTS/CTS exchange. Also, the WTS frames are sent to directions to which the transmitting node may have little or no knowledge of the channel status, causing collisions and retransmissions. For these reasons, with the increase on the number of hops, the amount of time spent issuing WTS frames has its impact on throughput. Indeed, at eight hops, the DMAC/DA throughput is lower than that provided by the Omni protocol and just a little better than the Directional. When compared with the DC-MAC, at eight hops, the performance of the Omni, Directional and DMAC/DA are just a little above half of the throughput delivered by DC-MAC.

While most of the throughput degradation for the Directional protocol already occurs at 4 hops, the Omni protocol decays gradually as the number of hops increases. At 8 hops, and with a Data packet size of 1536 Bytes, the throughput degrades ≈ 70% for the Omni and DMAC/DA protocols and ≈ 46% for DC-MAC as compared with the results at obtained at 2 hops.

The average end-to-end delay for DC-MAC at 2 hop is comparable to that of the Omni and DMAC/DA protocols (see Fig. 5 (b)), while the Directional protocol is nearly twice as high. Beyond 4 hops, the average end-to-end delay for the Omni protocol increases sharply, nearly as high as the Directional protocol. DC-MAC and DMAC/DA, on the other hand, have a much lower end-to-end delay as compared to the Directional and Omni protocols.

Grid Topology - Effects of Side Lobes and Carrier Sensing: Figure 6 shows the average throughput results for three parallel lines for the Omni, Directional, DMAC/DA and DC-MAC protocols. Compared to the results obtained in a single-line, the throughput for the Omni protocol drops nearly 1/3 at 2 hops. This was expected since the Omni protocol cannot allow for concurrent communications due to the large carrier sensing range. The reduced carrier sensing area provided by directional communications facilitates the Directional protocol to deliver a better performance than the Omni protocol. As the number of hops increases, the effects of neighboring activity make the performance of the Directional and DMAC/DA protocols to deteriorate.

Although carrier sensing also has a negative impact on the performance of DC-MAC and DMAC/DA, this impact, however, is not as severe as in the Omni and Directional protocols. The throughput difference, as compared to the results for single line, is at most 25% for DC-MAC, but can be as high as 37% for DMAC/DA and over 50% in the worst

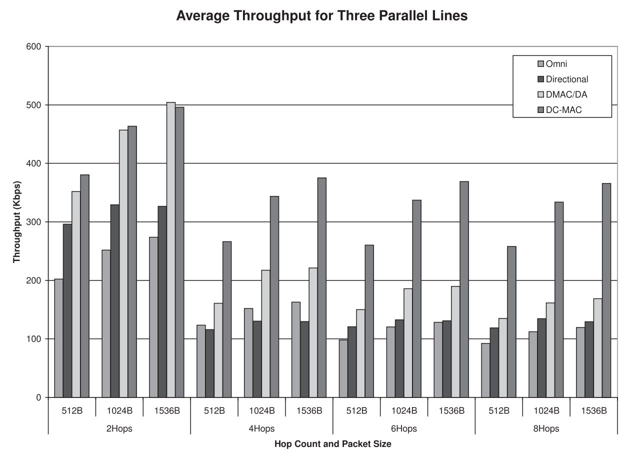


Fig. 6 Average throughput for three parallel lines at different hop count and Data packet size.

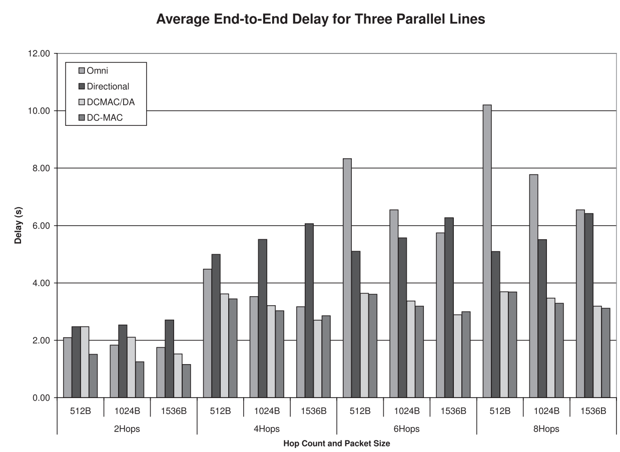


Fig. 7 Average end-to-end delay for three parallel lines at different hop count and Data packet size.

cases for Omni and Directional protocols. As DC-MAC relies on simple mechanisms to avoid deafness, without resorting to additional frame transmissions, DC-MAC is able to achieve a much better performance than DMAC/DA and the Directional protocol. At eight hops, DC-MAC attains nearly twice the throughput obtained by DMAC/DA, which is consistent to the results obtained for single line.

The average end-to-end delay is shown in Fig. 7. Despite the wider beamwidth and protuberant side and back lobes of ESPAR antenna, both DC-MAC and DC/MAC have been able to attain a much lower average end-to-end delay, as compared to the Omni and Directional protocols – less than 50% at 6–8 hops. When compared with the results for single line, both DC-MAC and DMAC/DA have nearly doubled the average end-to-end delay for 4–8 hops. As expected, the end-to-end delay for the Omni protocol is nearly tree times as high, as the communication in a line impacts in at least one adjacent line.

7. Conclusions

The main contribution of this work was to present a directional MAC protocol scheme which focused on reducing the effects of deafness and hidden terminal problems. The proposed MAC protocol relies on two-separated channels which are used for control and Data packets exchange. The simulation results have shown that the proposed directional MAC provides significant throughput improvement over both the IEEE802.11DCF MAC protocol and other prominent directional MAC protocols in both linear and grid topologies. The simulation results also show that the proposed scheme attains a reduced average packet disruption after a successful RTS/CTS exchange.

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