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Research Article

On Wireless Ad Hoc Networks with Directional Antennas: Efficient Collision and Deafness Avoidance Mechanisms

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Wireless ad hoc networks allow anywhere, anytime network connectivity with complete lack of central control, ownership, and regulatory influence. Medium access control (MAC) in such networks poses extremely timely as well as important research and development challenges. Utilizing directional antennas in wireless ad hoc networks is anticipated to significantly improve the network performance due to the increased spatial reuse and the extended transmission range. Nevertheless, using directional antennas in wireless ad hoc networks introduces some serious challenges, the most critical of which are the deafness and hidden terminal problems. This paper thoroughly explores these problems, one of which is discovered and reported for the first time in this paper. This paper also proposes a new MAC scheme, namely, directional MAC with deafness avoidance and collision avoidance (DMAC-DACA), to address both problems. To study the performance of the proposed scheme, a complete directional communication extension to layers 1, 2, and 3 is incorporated in the ns2 simulator. The simulation results show that DMAC-DACA significantly enhances the performance and increases the network throughput. This paper also reveals that deafness has a greater impact on network performance than the hidden terminal problem.

1. INTRODUCTION

Unlike conventional infrastructure-based wireless networks, such as cellular networks, a wireless ad hoc network is an autonomous system consisting of wireless hosts that do not rely on any fixed network infrastructure or central administration [1, 2]. A node communicates directly with nodes within its wireless range and indirectly with other nodes using a dynamically computed, multihop route.

In wireless ad hoc networks, the nonexistence of a centralized authority complicates the problem of medium access regulation. The centralized medium access control (MAC) procedures, undertaken by a base station in cellular networks, have to be enforced in a distributed and collaborative fashion by the nodes in wireless ad hoc networks [3, 4]. Numerous MAC schemes have been proposed for wireless ad hoc networks, while IEEE 802.11 distributed coordination function (DCF) [5] has been utilized as the underlying MAC sublayer for WLANs as well as wireless ad hoc networks. IEEE 802.11 is based on MACA [6] and MACAW [7]. Nevertheless, IEEE 802.11 is designed for WLANs and wireless ad hoc networks with omnidirectional antennas. Although IEEE 802.11 achieves reasonable performance in WLANs, in terms of throughput at least, as shown in [8, 9], the omnidirectional transmission mode is a fundamental capacity limitation in such networks. This is due to the tradeoff between the number of end-to-end hops and the spatial reuse. To decrease the number of hops, so as to reduce the traffic demand from relaying packets, the omnidirectional transmission range must be increased accordingly. These results in more interference to other nodes and a reduction in the number of simultaneous transmissions, and hence degrades spatial reuse. On the other hand, reducing the omnidirectional transmission range results in more hops and more network traffic. This is a nontrivial problem and it has been extensively studied in [10, 11].

In addition, omnidirectional transmissions also limit the nodes' ability to achieve a longer transmission range. In omnidirectional mode, the energy of the transmitted signal is spread over a large region, while only a small portion is received by the intended receiver. This not only causes unnecessary interference to other nodes, but also reduces the range.

To address these serious capacity and performance limitations, directional antennas have been recently identified as a means for increasing the network throughput and enhancing spatial reuse in wireless ad hoc networks [12]. Poor spatial reuse and short transmission range are efficiently addressed using directional antennas. Spatial reuse is improved due to the reduced interference resulting from the narrower beamwidth, and the transmission range is extended due to the greater signal-to-noise ratio.

Nevertheless, some serious problems, such as the deafness and hidden terminal problems, arise when directional antennas are used in wireless ad hoc networks. These problems can cause packet dropping at the MAC sublayer and greatly limit the potential performance improvement due to using directional antennas. This paper thoroughly studies these two problems and proposes a new MAC scheme that addresses these problems and improves network performance.

The remainder of this paper is organized as follows. In Section 2, we provide a literature review. In addition to the IEEE 802.11 DCF and the problems and limitations of omnidirectional antennas, the proposed schemes for directional MAC are also presented in Section 2. An overview of the challenges pertaining to directional communication is presented in Section 3. Our new MAC scheme is proposed in Section 4. This is followed by the simulation and performance evaluation study in Section 5. Finally, in Section 6, we present the conclusions drawn from the paper.

2. RELATED WORK

2.1. IEEE 802.11 DCF

IEEE 802.11 provides two medium access mechanisms: distributed coordination function (DCF) and point coordination function (PCF). The DCF is the fundamental contention-based mechanism and will be briefly introduced below.

In DCF, the default scheme is a two-way handshake technique called basic access. This mechanism is characterized by the transmission of a positive acknowledgement (ACK) by the receiver to confirm the successful reception of a data frame. If the sender does not receive the ACK frame, it regards the transmission as a failure.

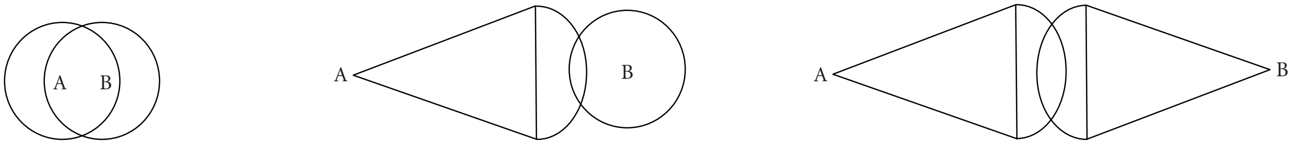
DCF is a random access protocol, based on carrier sense multiple access with collision avoidance (CSMA/CA). In DCF, a node has to sense the channel idle for a distributed interframe space (DIFS) before transmitting. If several nodes transmit simultaneously after they sense the channel idle for a DIFS, collisions will take place. To address this problem, DCF uses a collision avoidance (CA) mechanism on top of the CSMA scheme. DCF uses an exponential backoff interval as the CA mechanism to resolve channel contention. Before initiating a transmission, a node S chooses a random backoff interval from a range [0, CW-1], where CW is the contention window. Node S then decrements the backoff counter by 1 after every idle time slot. This is called counting down. When the backoff counter reaches zero, node S transmits the frame. If the transmission from node S collides with other transmissions (detected by means of the absence of an ACK after a predetermined timeout period), node S doubles its current CW, chooses a new backoff interval, and then retransmits. The value of CW is doubled after each collision until it reaches a maximum value. During the backoff interval, if node S senses the channel as busy, it freezes the backoff counter and will only resume counting down from the last frozen backoff counter value if it senses the channel as idle again for a DIFS period.

DCF works well when all the nodes can hear each other within a single hop. Nevertheless, if the nodes are not fully connected, collisions may be caused by some nodes that have not heard the ongoing transmission. This is called the hidden terminal problem [13, 14]. To avoid the hidden terminal problem, DCF defines an optional four-way handshake consisting of the exchange of a ready-to-send (RTS) frame and a clear-to-send (CTS) frame preceding DATA and ACK transmissions. A short interframe space (SIFS) is inserted between each portion of the handshake to allow the wireless transceiver to switch between receiving and transmission modes. Both RTS and CTS frames carry the remaining length of the duration required for the upcoming transmission. Nodes located in the vicinity of a communicating pair and that overhear either or both of the RTS and CTS frames have to defer their own transmissions until the conclusion of the ongoing transmission. This is called virtual carrier sense (VCS). To enable VCS, each node maintains a variable called a network allocation vector (NAV). A node updates its NAV according to the duration field in each overheard RTS or CTS frames. Therefore, the area where nodes could interfere with the current sender and receiver is considered reserved. The nodes in this area must remain silent for the duration of the current transmission.

2.2. Directional antennas

In wireless communication networks, the antenna model is often classified as omnidirectional or directional. Omnidirectional antennas radiate and receive equally well in all directions. A directional antenna concentrates more energy in one direction compared to the other directions when transmitting or receiving. The gain of an antenna is an important term and is measured by comparing the relative power in one direction of an antenna to a model antenna, typically the omnidirectional or, equivalently, the isotropic antenna. The gain of an antenna is measured in the direction in which it radiates the best and is also called the peak gain. For the same transmission power, directional antennas can achieve longer transmission ranges than omnidirectional antennas. Moreover, with beamforming, the receiver's antenna can also achieve a larger receiver gain and is able to receive the signal from a greater distance than omnidirectional antennas.

In addition to the main lobe of the peak gain, there are also side lobes and back lobes with a smaller gain. The desired



(a) OO neighbors with the shortest transmission range (b) DO/OD neighbors with the extended transmission range (c) DD neighbors with the longest transmission range

Figure 1: OO, DO, OD, and DD neighbors.

design for directional antennas is to maximize the gain of the main lobe, while minimizing the gain of the other lobes.

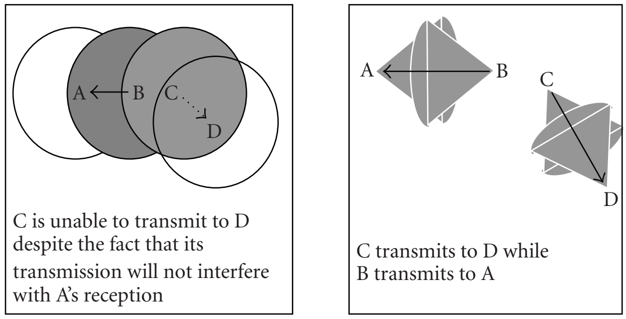
Another related concept is the antenna beamwidth. It is usually referred to as the "3 dB beamwidth" and is defined as the angle, where the signal strength drops off by at most 3 dB from the peak gain.

Typically, two types of directional antenna models are used: switched-beam antennas and steered-beam antennas. The switched-beam system is composed of predetermined beams, and the beam with the best signal strength is selected for the transmission or reception. In this type of directional antenna system, the node controls the RF and switches the connections to many fixed antenna beams. The antenna beams may be labeled with predefined numbers to identify each of them.

In a steered-beam system, the main lobe can be pointed virtually in any direction, often automatically through the received signal from the target using direction of arrival (DOA) techniques. However, the steered-beam system requires the beamforming algorithm to steer the main lobe to enhance the radio link quality and is much more complex and expensive to deploy and operate than the switched-beam system.

Due to space limitations, we are only providing a brief introduction to directional antennas in this section. More information about directional antenna models is found in [15–18].

In wireless ad hoc networks with omnidirectional antennas, there is only one type of neighborhood relationship between nodes. With the beamforming of directional antennas, however, four types of neighborhood relationships arise depending on whether the nodes are in the directional mode or omnidirectional mode. Node pairs can be categorized as omni-omni (OO) neighbors, directional-omni (DO) neighbors, omni-directional (OD) neighbors, and directional-directional (DD) neighbors. When directional antennas are involved, the transmission range not only depends on the type of antenna used by the sender, but also on the receiver's antenna. In this case, the conventional use of a single circle to illustrate a node's transmission range is not sufficient. As far as the figures in this paper are concerned, the transmission range depends on the sender and the receiver. If the two circles are intersecting, the two corresponding nodes are considered within the transmission range of each other, as shown in Figures 1(b) and 1(c). If only omnidirectional antennas are involved, the convention of using a single circle still applies, as shown in Figure 1(a).



(a) Omnidirectional antennas (b) Directional antennas

Figure 2: The exposed terminal problem.

2.3. *Main benefits of directional antennas*

IEEE 802.11 is considerably limited by omnidirectional transmissions. With directional antennas, such limitations may be overcome to not only enhance spatial reuse, but also to increase throughput and minimize end-to-end delay.

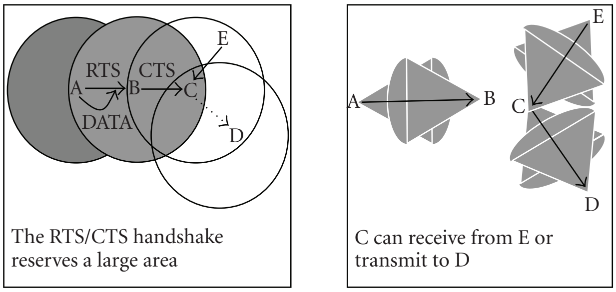
2.3.1. *Spatial reuse*

First, the conventional exposed terminal problem [19] reveals one scenario of such limitation. For example, in Figure 2(a), node B is transmitting to node A. Although node C's transmission cannot collide with node A's reception, node C may not start its transmission to node D because it is blocked by node B's omnidirectional transmission. As shown in Figure 2(b), however, by node B's beamforming to A, node C will not hear node B's transmission and can, therefore, transmit to D simultaneously.

Secondly, although VCS avoids the hidden terminal problem via RTS/CTS handshakes, it achieves this at the expense of reduced spatial reuse. A large area, as shown in Figure 3(a), is reserved by the RTS and the CTS. Node C won't respond to an RTS from node E or transmit an RTS to node D. As shown in Figure 3(b), however, by beamforming to node A, node B's reception will not block node C's transmission. Therefore, node C can receive packets from node E or transmit to D simultaneously with the transmission from node A to node B.

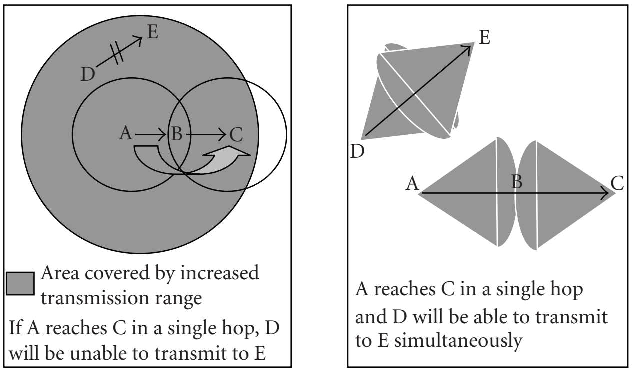
2.3.2. *Number of hops*

In multihop wireless ad hoc networks, shorter routes are preferred. Generally, the longer the transmission range,



(a) With omni antennas (b) With directional antennas

Figure 3: The hidden terminal problem.



(a) Omnidirectional antennas (b) Directional antennas

Figure 4: Number of hops in a route.

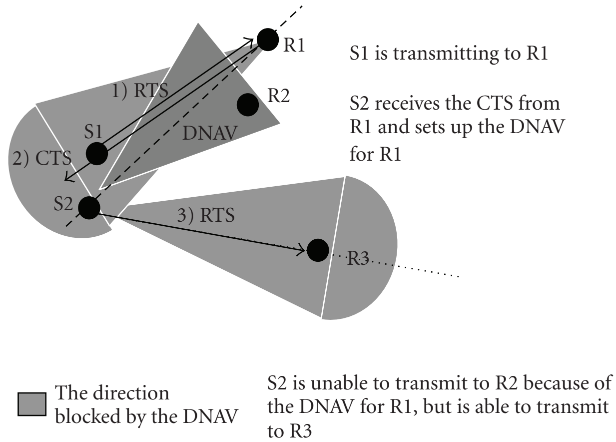


Figure 5: A DNAV example.

the fewer the number of hops. Nevertheless, the longer transmission range also results in a larger interference area, which, in turn, reduces the number of simultaneous transmissions, as shown in Figure 4(a). By beamforming, node A and node C become DO or DD neighbors and are able to reach each other in a single hop. The transmission from node D to node E is safely performed simultaneously, as shown in Figure 4(b).

2.4. Overview of directional antenna-compliant MAC schemes

Some MAC schemes have been proposed for wireless ad hoc networks with directional antennas. In principle, most of the proposed MAC protocols [11, 20–30] for ad hoc networks with directional antennas are based on the IEEE 802.11 four-way handshake, with some adaptations to take advantage of directional communications. Such adaptations include, but are not limited to, directional virtual carrier sense (DVCS) and directional network allocation vector (DNAV) [22–24]. In IEEE 802.11, a NAV is set in a node whenever it overhears any non-ACK unicast frame that is not intended for it. DNAV is a directional version of NAV and is a very important method to efficiently manage the directional transmission, avoiding collisions, and enabling spatial reuse as well. The DNAV is a table that keeps track of the directions and the corresponding periods during which a node must not initiate a transmission. If a node receives an RTS or a CTS frame from a certain direction, it defers only the transmissions associated with that direction. A transmission intended toward some other direction may be initiated. Figure 5 illustrates the operation of DNAV.

Some proposals focus on scheduling when using directional antennas [28–30]. Among them, [28, 29] investigate the potential of using TDMA, and [30] investigates the so-called space scheduling that is enabled by space division multiple access (SDMA). To utilize the benefits of directional antennas, in almost all of the proposed schemes, the DATA and ACK frames are transmitted directionally, while the transmission of RTS/CTS frames varies.

Among the first proposals in this area are [20, 21]. The directional antenna models used in both papers assume directional transmission only, but not directional reception. Since reception is carried out omnidirectionally, interference could result from any direction. Consequently, in [20, 21], both RTS and CTS frames are transmitted omnidirectionally, while DATA and ACK frames are transmitted directionally. Because of the omnidirectional transmissions of RTS/CTS frames, the benefits associated with the longer transmission range of the directional antennas cannot be realized.

In [11], the author provides a broad examination of many factors that affect network performance in wireless ad hoc networks with directional antennas, such as channel access, link power control, neighbor discovery, and multihop routing. Some abstract models are used in the simulation, which only examined the relative performance improvement associated with the different factors studied. Recently, an extension to [11] was proposed in [22], in which the authors implemented and simulated a directional power-controlled MAC with a modified backoff procedure.

In [23], DVCS is proposed. In this protocol, RTS/CTS frames are transmitted directionally. It is assumed that the transmitter knows the direction associated with the receiver before it starts to transmit. Instead of the NAV used in IEEE 802.11, DNAV is used in conjunction with DVCS. Each DNAV is associated with a direction and a width, and multiple DNAVs can be set for a node. The DNAVs are updated each time a node receives the RTS or CTS frames. For directional transmission, DVCS determines that the channel is available for a specific direction when is not covered by a DNAV.

Directional MAC (DMAC) is proposed in [24]. DMAC utilizes directional physical as well as virtual carrier sensing. In DMAC, it is assumed that an upper layer, usually the network layer, is aware of the node's neighbors and is capable of supplying the transceiver profiles required to directionally communicate to each of these neighbors. DMAC receives these transceiver profiles from upper layers along with the packet to be transmitted. This is a reasonable assumption for multihop wireless ad hoc networks and can be carried out by the network layer during route discovery. A discussion of the problems arising from the use of directional antennas is also presented in [24]. However, no solid solution is provided to address these problems. Instead, a multihop RTS MAC (MMAC) is proposed. It exploits the extended transmission range of directional antennas by enabling DD communication. The challenge is that the receiver cannot receive the RTS frame from its DD neighbor when the former is idle and in the omnidirectional mode. Via the established route to the DD neighbor, the sender node uses a multihop RTS frame through several DO transmissions to inform the intended DD neighbor to beamform to the sender. The CTS, DATA, and ACK frames will be transmitted through this DD link directly over a single hop. The authors assume that the sender knows its DD neighbors before initiating the multihop RTS frame.

ToneDMAC is proposed in [25] to address the deafness problem caused by a wireless node that is unaware of its neighbor's unavailability and, as a result, keeps transmitting RTS frames needlessly to that neighbor. The so-called tones are not transmitted simultaneously with the data frame like a "busy tone." The protocol assumes a single transceiver with the capability to transmit or receive over multiple channels. A tone is transmitted each time a node successfully transmits or receives a data frame to implicitly notify neighbors of its activity. These tones are transmitted omnidirectionally through control channels, and multiple tones are required to identify each node that initiated the tone. The complicated tone assignment mechanism makes ToneDMAC hard to implement. Moreover, [25] only addresses one type of deafness problem, but does not investigate the other more important and more serious type of deafness.

An approach to address the hidden terminal problem is proposed in [26]. Circular directional RTS frames are used to notify all the DO neighbors of the upcoming transmission through several consecutive directional transmissions. In addition, a node maintains a location table for each neighbor that includes a pair of beam labels with which it and the corresponding neighbor can communicate with each other. The frame header in an RTS or a CTS frame contains the corresponding beam pair retrieved from the sender's location table. Similar to [25], this protocol also requires that the node knows its DD neighbors in advance to utilize the proposed mechanisms. In addition, in the implementation, an idle node is required to hear the channel for a duration of $M\times$ RTS instead of DIFS, where M is the number of antenna beams. This long delay degrades the performance of the proposed protocol significantly.

While a few of the proposed schemes [24–26] discuss the deafness and hidden terminal problems associated with using directional antennas in wireless as hoc networks, our paper is the first to thoroughly investigate these two problems and propose a solution to jointly address them.

3. DIRECTIONAL COMMUNICATION CHALLENGES

Utilizing directional antennas can improve the performance of ad hoc networks. However, it introduces serious challenges, such as the deafness and hidden terminal problems. In this section, we will discuss these two problems in the context of DMAC.

3.1. DF—deafness problems

The problem of deafness arises when the intended receiver is unable to respond with a CTS frame, while the sender continues to retransmit its RTS frame. The receiver is thus denoted as "deaf." Since the sender is unaware of the fact that the receiver is "deaf," the sender will continue to retransmit the RTS frames and will finally drop the data packets, for which the RTS frames are being transmitted, when it reaches the RTS-ret-limit. The packets dropped due to the deafness problem will adversely affect the network utilization. There are two scenarios in which the intended receiver may be designated deaf.

3.1.1. DF1—deafness due to being a transmitter or a receiver

In this scenario, the intended receiver (the deaf node) is itself a transmitter or a receiver in an ongoing transmission, such as nodes A and C in Figure 6. This type of deafness problem was shown in [24] and has been extensively studied in [25].

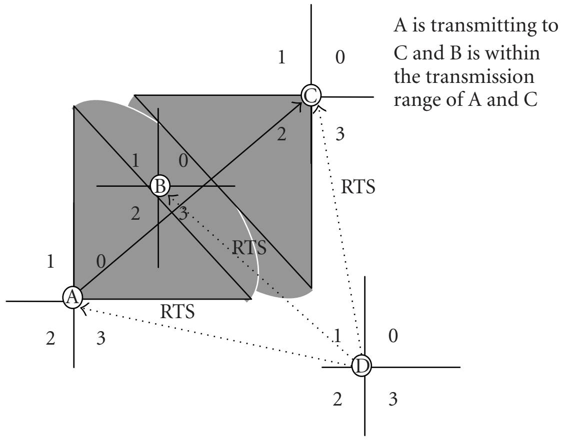
3.1.2. DF2—deafness due to being in a deaf zone

In this scenario, the intended receiver, such as node B in Figure 6, lies in the deaf zone, which is the coverage area of another ongoing transmission, and is thus unable to receive the RTS frame and respond with a CTS frame. To our best knowledge, we are the first to discover this type of deafness problem, which is discussed for the first time in this paper.

DF2 is more common and more important than DF1 since DF2 blocks the nodes in a whole area, while DF1 only blocks two nodes: the transmitter and the receiver of a transmission.

3.2. HT—hidden terminal problems

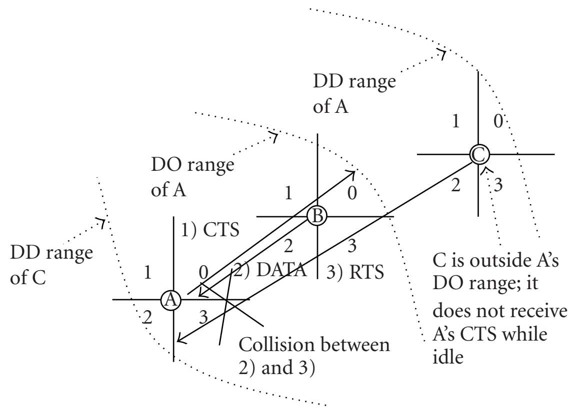
The hidden terminal problem is a well-known problem in wireless networks in general and in ad hoc networks in particular. IEEE 802.11 and most directional MAC protocols use VCS or DVCS to address this problem, which requires the transmission of RTS/CTS and assumes that the nodes that can interfere with the ongoing transmission will receive



The area blocked by A and C's transmission

If D transmits a RTS to A or C, DF1 takes place; if the RTS is transmitted to B, DF2 takes place

Figure 6: Illustration of the two types of deafness problems.



C's transmission will collide with B's transmission to A while A is beamforming for reception

Figure 7: Illustration of first type of hidden terminal problems.

the RTS/CTS frame successfully. This is true in most cases in ad hoc networks with omnidirectional transmissions, if RTS/CTS frames do not collide with other transmissions; with the directional transmission of RTS/CTS frames, this assumption does not hold, and two new hidden terminal problems arise.

3.2.1. HT1—due to asymmetry in gain

HT1 is caused by the DD neighbors. In omnidirectional mode, DD neighbors may not receive the RTS/CTS frame that reaches the DO range. However, these nodes can interfere with the current transmission if they beamform to the direction of the receiver and start to transmit. Figure 7 illustrates the first type of hidden terminal problems.

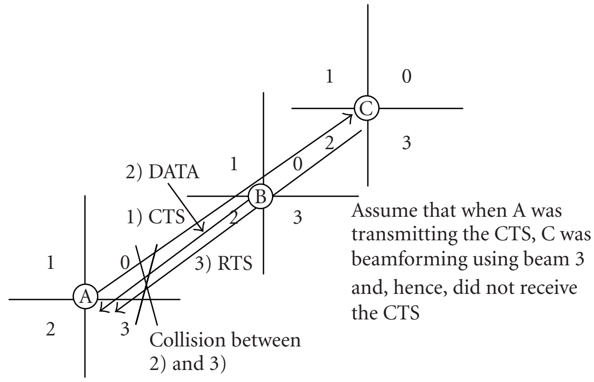


Figure 8: Illustration of second type of hidden terminal problem.

3.2.2. HT2—due to unheard RTS/CTS

HT2 is caused by the DO neighbors that are beamforming to other directions when the RTS/CTS frames are transmitted. Therefore, these nodes do not receive the RTS/CTS frames. Figure 8 illustrates the second type of hidden terminal problem.

As a result, both DF and HT cause packet dropping at the MAC sublayer: at the sender node due to DF and at the receiver node due to HT.

4. A NEW SCHEME: DMAC-DACA

A new scheme, namely, directional MAC with deafness avoidance and collision avoidance (DMAC-DACA), is proposed herein. Switched-beam antennas are used in DMAC-DACA, and the area around a node is covered by M nonoverlapping antenna beams, numbered from 0 to $M-1$. A node can beamform to any of the M beams to transmit or receive the signals. In idle mode, a node hears omnidirectionally. Similar to other directional MAC schemes, DMAC-DACA also uses DNAV to perform DVCS. DMAC-DACA uses omnidirectional backoff and sweeping RTS/CTS frames. Based on the information acquired by these two techniques, several mechanisms are proposed to address the deafness and hidden terminal problems.

4.1. Omnidirectional backoff

In DMAC-DACA, a node switches back to the omnidirectional mode when performing backoff. In omnidirectional backoff, a node senses the channel as busy only when there is a signal from the direction in which this node intends to transmit the packet (for which the backoff is being performed). In omnidirectional backoff, a node can receive an RTS frame and respond with a CTS frame.

4.2. Sweeping RTS/CTS

A mechanism called sweeping RTS/CTS is used herein. Using this mechanism, a node transmits several consecutive sweeping directional RTS/CTS frames counterclockwise to inform all its DO neighbors of its upcoming transmission/reception.

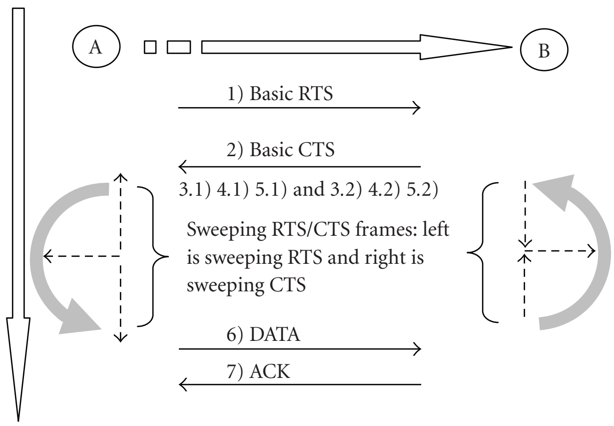


Figure 9: DMAC-DACA handshakes.

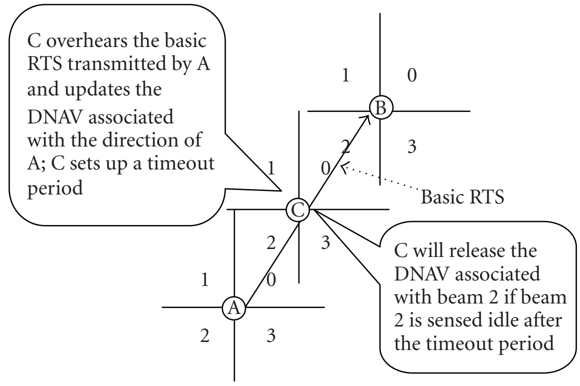


Figure 10: An example of DMAC-DACA reservation release.

To distinguish the original RTS/CTS from the sweeping ones, the original RTS/CTS is referred to as basic RTS/CTS. The different handshakes adopted in DMAC-DACA are illustrated in Figure 9. The arrows in Figure 9 represent the transmission direction. There is no per beam backoff associated with the sweeping RTS/CTS and if a beam is not allowed to transmit, a node will be silent for an l_{RTS} duration and will then switch to the next beam and start transmission in that direction, and the same procedure is repeated.

In IEEE 802.11, a CTS frame does not include the address of the source (of the CTS frame) since it is mainly used to confirm the reception of an RTS frame. Including the receiver address suffices for this purpose. However, unlike 802.11, a sweeping CTS frame is used to inform the neighbors of the upcoming transmission; both the transmitter and the receiver addresses of the upcoming transmission are useful and thus are included in the sweeping CTS frames. This also implies that the sweeping RTS and sweeping CTS have the same length.

The duration information carried in the basic RTS/CTS frames must include the extra duration required for the sweeping transmissions as follows:

$$\begin{aligned}&\text{Duration}_{\text{Basic-RTS}}\\&\quad= l_{\text{SIFS}}+l_{\text{CTS}}+(M-1)(l_{\text{SIFS}}+l_{\text{RTS}})+l_{\text{SIFS}}+l_{\text{DATA}}+l_{\text{SIFS}}+l_{\text{ACK}},\\&\text{Duration}_{\text{Basic-CTS}}\\&\quad= (M-1)(l_{\text{SIFS}}+l_{\text{RTS}})+l_{\text{SIFS}}+l_{\text{DATA}}+l_{\text{SIFS}}+l_{\text{ACK}}.\end{aligned}\tag{1}$$

Similarly, the duration information in the sweeping RTS/CTS is decremented by an $l_{\text{RTS}} + l_{\text{SIFS}}$ after each RTS transmission. For the kth sweeping RTS/CTS frame,

$$\begin{aligned}&\text{Duration}_{k\text{th Sweeping-RTS/CTS}}\\&\quad= (M-1-k)(l_{\text{SIFS}}+l_{\text{RTS}})+l_{\text{SIFS}}+l_{\text{DATA}}+l_{\text{SIFS}}+l_{\text{ACK}}.\end{aligned}\tag{2}$$

A problem arises if the basic CTS frame is not received. In this case, the node that sent the basic RTS will not send the DATA frame, but the nodes that overheard the basic RTS will still regard the channel as busy and remain silent for the duration advertised in the basic RTS frame. This will decrease the network utilization. We call this problem overreservation by a failed basic RTS/CTS handshake. This problem exists in all the RTS/CTS reservation-based schemes, including IEEE 802.11 DCF. Nevertheless, it is more serious in DMAC-DACA since the time advertised in the basic RTS frame also includes the time a node needs to send the sweeping RTS frames. To address this problem, we develop a method called DMAC-DACA reservation release, which is shown in Figure 10.

In Figure 10, node A sends a basic RTS to node B. Node C sets up the DNAV linked to beam 2 after it overhears this basic RTS frame. To enable reservation release, node C also sets up a timer to signify when the data transmission is expected to start. Therefore, if node C does not sense the channel as busy with respect to beam 2 after the timeout, node C determines that the data frame transmission will not take place (possibly due to the failure of the basic RTS/CTS handshakes). Thus, node C safely releases its DNAV associated with beam 2. The aforementioned timeout period is equal to the time from receiving the last bit of the basic RTS until the node hears the first bit of the data frame transmitted by the sender node:

$$\text{Timeout} = l_{\text{SIFS}}+l_{\text{CTS}}+\tau+(M-1)(l_{\text{SIFS}}+l_{\text{RTS}})+l_{\text{SIFS}}+\tau,\tag{3}$$

where τ is the maximum propagation delay.

4.3. DA1—deafness avoidance for DF1

In DA1, two techniques are designed to attain deafness avoidance: deaf neighbors table (DNT) and deafness vector (DV).

Every node maintains a DNT that includes a set of deaf neighbors, and the corresponding durations until the deaf neighbors are once again available for receiving. Each time a node receives a sweeping RTS/CTS frame, it updates its DNT by adding the nodes included in the sweeping RTS/CTS frame or modifying the duration field if the neighbors are already stored in the DNT.

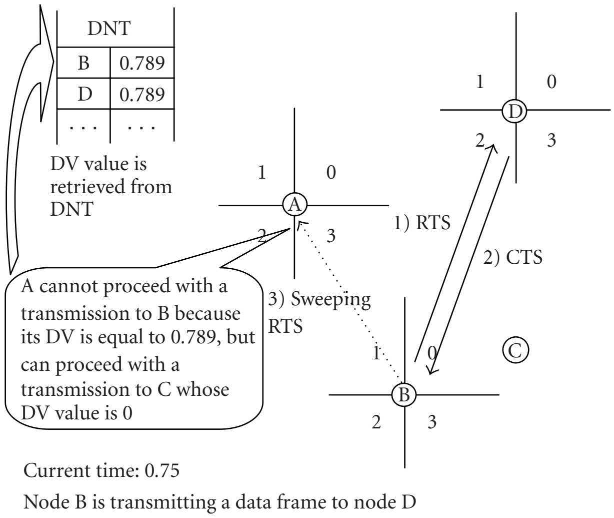


Figure 11: Illustration of the DA1 mechanism.

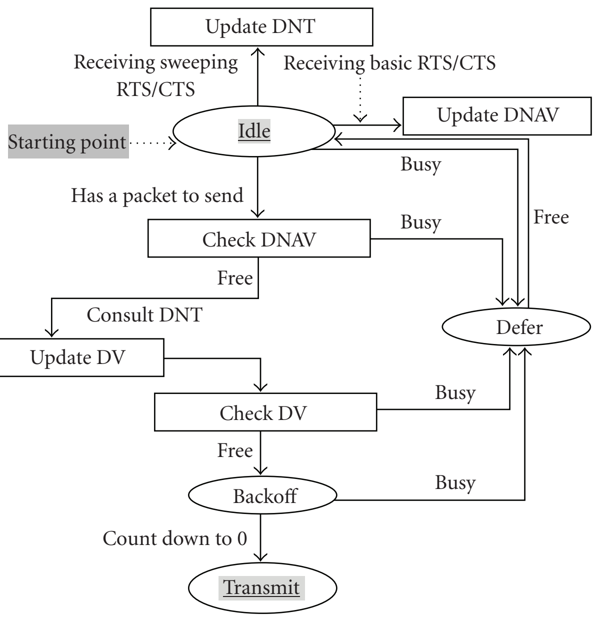


Figure 12: DNT and DV flowchart.

Every node also maintains a DV, which is a variable related to the destination of the packet to be transmitted. Each time a packet at the head of the queue is awaiting transmission, the node sets up its DV by copying the duration field from the corresponding record in the DNT. The DV indicates the time at which the destination will be available, and the node has to defer its transmission attempt until then. Figure 11 illustrates how the DNT and DV are set up in DA1.

Figure 12 shows the decision-making process when a node receives a basic or sweeping RTS/CTS frame. Table 1 shows a comparison between DV and DNAV.

Table 1: DNT/DV versus DNAV

DNT/DV	DNAV
For deafness avoidance	For collision avoidance
Indicates the availability of a specific node	Indicates the availability of a specific direction
Every node has a single DV, related to the packet at the head of the waiting queue; the updating of the DV is performed with the help of the DNT	Every node has several DNAVs, one for each direction; each DNAV is maintained separately

4.4. DA2—deafness avoidance for DF2

DA1 does not resolve DF2 since the sweeping RTS/CTS only carries the address of the transmitter and the receiver of the upcoming transmission. DA2 is designed to solve DF2. DA2 requires utilizing location information retrieved by GPS. The location information will be added to the basic RTS/CTS as well as the sweeping RTS/CTS frames. A node maintains a neighbors' location table and it updates it every time it receives a basic or a sweeping RTS/CTS. When a node receives a sweeping RTS/CTS frame, it will search its neighbors' location table and update the record in the DNT if any of its neighbors lies within the coverage area (i.e., the deaf zone) of the upcoming transmission. Afterwards, the DV-related procedure will be performed in a similar fashion to DA1.

We define the deaf zone as the area covered by the upcoming transmission of the transmitter only, but not including the area covered by the upcoming transmission of the receiver. Otherwise, the spatial reuse will be greatly decreased. Although the receiver also causes the deafness problem when transmitting a CTS or an ACK, these frames are much shorter than the DATA frame and do not cause as many RTS retransmissions and as much packet dropping.

Figure 13 illustrates the usefulness of DA2. If node E has a packet to transmit to node C, it defers its transmission because node C lies within the deaf zone (i.e., the coverage area of node A). However, if node E has a packet to transmit to node D, the transmission from node E to node D can be started during the transmission from node A to node B, and both transmissions will be completed successfully using DMAC-DACA.

4.5. Collision avoidance (CA)

Utilizing the CA mechanism, receiving sweeping RTS/CTS frames may also trigger a node to update its DNAV depending on the direction and the distance between this node and the transmitter or receiver node. This distance is called DD neighbor threshold (DDNT) and is assumed to be the nominal wireless communication range for DD neighbors. The proposed CA mechanism is illustrated in Figure 14. As shown in Figure 14, each node calculates the beam pairs and distances to the upcoming transmitter and receiver upon receiving the sweeping RTS/CTS with the embedded location information. For example, node C calculates the beam pair (C : 0, A : 2), indicating that it will use beam 0 to

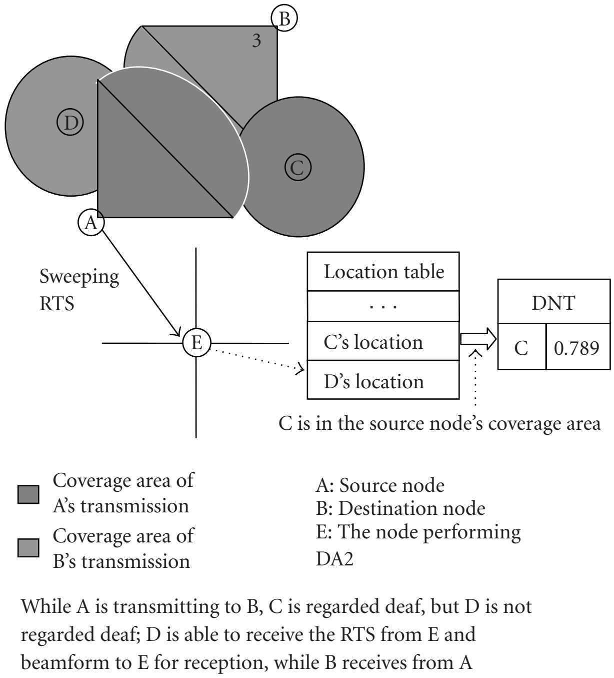


Figure 13: Illustration of the DA2 mechanism.

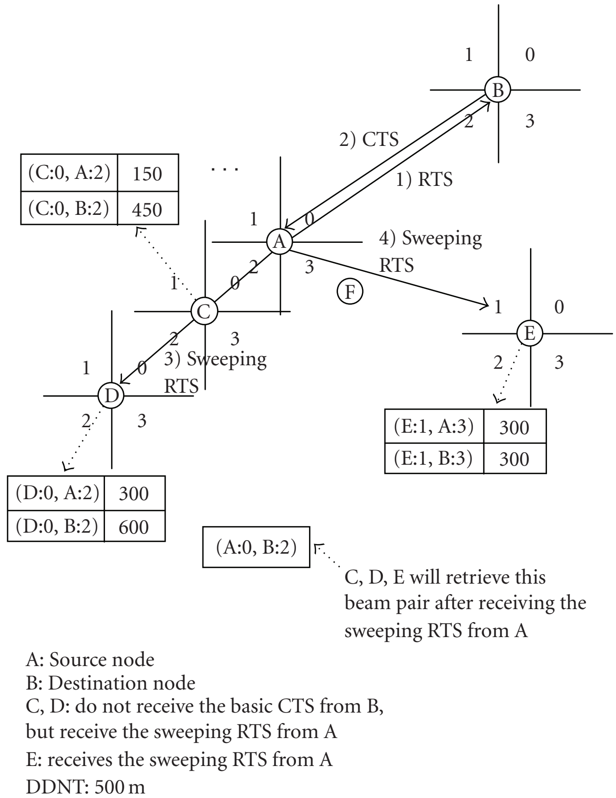


Figure 14: Illustration of the CA mechanism.

communicate with the source, node A, through A's beam 2 and 150 m, representing the distance to node A. Node C also calculates the beam pair (C : 0, B : 2) and a distance of 450 m to the destination, node B. Moreover, each node also finds out the beam pair for the upcoming transmitter and receiver, (A : 0, B : 2). Node C finds out that node B will use the same beam (i.e., beam 2) to communicate with the source (and with itself), and that the distance between node B and itself (which is equal to 450 m) is less than DDNT (which is equal to 500 m). This means that node C would interfere with B's reception from A if node C were to transmit using beam 0. Therefore, node C updates its DNAV for beam 0. Hence, HT1 is avoided.

Node D discovers that it is 600 m (i.e., more than DDNT) away from node B. Being more than DDNT away from node B, node D's transmission will not interfere with node B's reception and, hence, it does not update its DNAV. Finally, node E finds out that it will neither interfere with the source node A nor the destination node B and, as a result, it does not update its DNAV.

In addition, HT2 is also avoided in a similar fashion. As shown in Figure 14, node F is a DO neighbor of node B, but does not receive the CTS from node B. It still, however, receives the sweeping RTS from node A and updates its DNAV for beam 0 accordingly.

4.6. DMAC-DACA versus directional antenna-compliant protocols

Table 2 lists the main features of the proposed directional MAC protocols as well as DMAC-DACA. Evidently, as shown in the last row in Table 2, DMAC-DACA is the only scheme that jointly addresses all types of deafness and hidden terminal problems.

It is also worthy to compare DMAC-DACA to circular RTS [26], since both of them transmit multiple RTS/CTS packets around a node. There are several key differences between these two schemes.

Despite utilizing several RTS/CTS frames around a node, the sweeping RTS/CTS mechanism devised for DMAC-DACA is fundamentally different from the circular RTS mechanism proposed in [26]. As shown in Figure 9 (Section 4.2), the order of the handshakes associated with the sweeping RTS/CTS mechanism is different from circular RTS. In case of the sweeping RTS mechanism, the first RTS is transmitted in the direction pertaining to the intended receiver, while in the circular RTS mechanism, the first RTS is transmitted to a predefined direction. A long delay equal to $M\times$ RTS, where M is the number of antenna beams, is caused by the latter approach. This long delay is required to protect the RTS transmission to the intended receiver (which may be reached by the antenna, i.e., the last RTS transmission). In addition, in DMAC-DACA, the sweeping RTS/CTS frames are transmitted after the successful handshakes related to the basic RTS/CTS frames, whereas in [26], the circular RTS frames are transmitted within the RTS/CTS handshakes. The latter approach will cause serious problems if the RTS/CTS handshakes are not successful, since the nodes overhearing the circular RTS frames will be unnecessarily prohibited from reserving

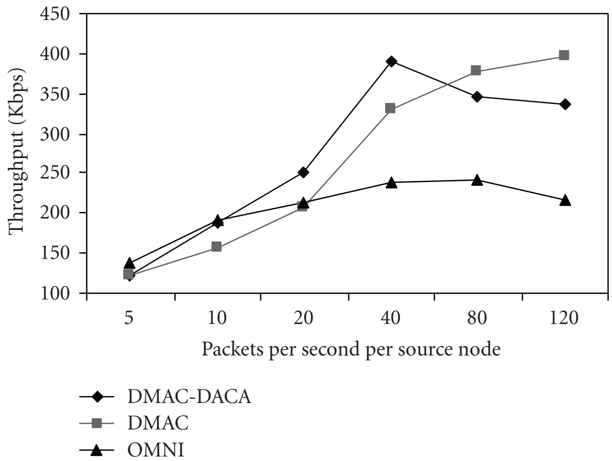


Figure 15: Throughput of OMNI IEEE 802.11, DMAC, and DMAC-DACA.

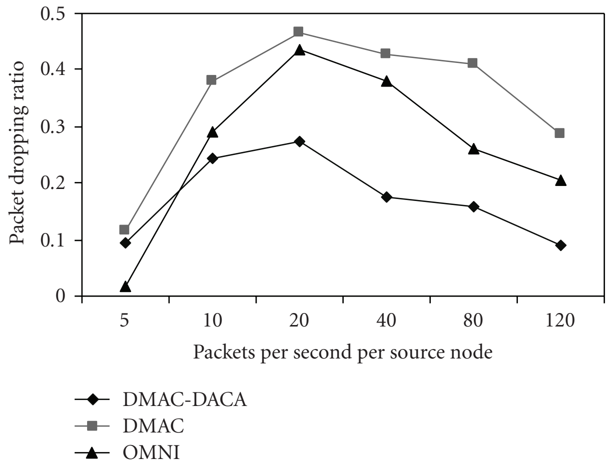


Figure 16: Effect of DMAC-DACA's DA mechanism.

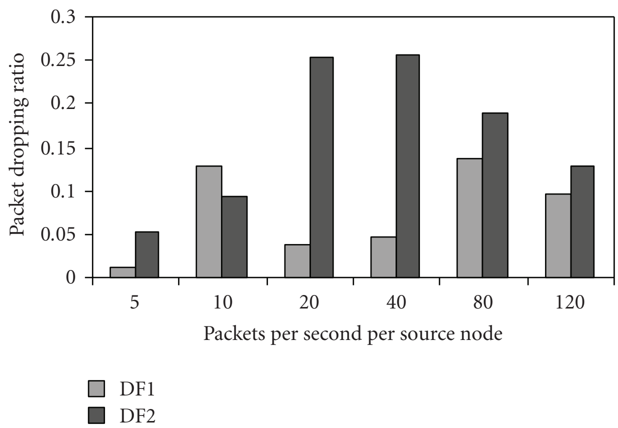


Figure 17: DF1 versus DF2 in DMAC.

the medium, an issue similar to the overreservation problem discussed in Section 4.2. Moreover, DMAC-DACA is designed to solve the two types of hidden terminal as well as the two types of deafness problems, while [26] only address the first type of hidden terminal problems (which is due to the asymmetry in gain). Thus, DMAC-DACA provides a novel integrated solution to solve both the deafness and hidden terminal problems. In Section 5, the performance of DMAC-DACA is thoroughly evaluated by means of simulation and is shown to outperform existing schemes.

5. PERFORMANCE EVALUATION

Computer simulations are conducted using the ns2 network simulator with our complete directional communication extension for layers 1, 2, and 3. We also modified the ad hoc on-demand distance vector (AODV) [31] routing protocol to facilitate directional communication and named the modified version directional AODV (DAODV). In DAODV, the beam to the next hop is discovered together with the next hop neighbor. Table 3 lists the parameters used in the simulations.

5.1. Throughput

As shown in Figure 15, both DMAC and DMAC-DACA achieve much higher throughput than OMNI IEEE 802.11. For most traffic loads, DMAC-DACA achieves a higher throughput than DMAC; however, when the traffic load is high, DMAC-DACA achieves a lower throughput.

The DA and CA mechanisms highly rely on the reception of sweeping RTS/CTS frames. Under heavy load, the probability of successful reception of sweeping RTS/CTS will be lower. As a result, the deafness and collision avoidance will be ineffective and cannot offset the overhead associated with sweeping RTS/CTS transmissions.

5.2. Effectiveness of DMAC-DACA's DA mechanism

As shown in Figure 16, DMAC suffers severely from the deafness problem to the extent that its packet dropping ratio exceeds that of OMNI 802.11. DMAC-DACA efficiently addresses the deafness problem, and the percentage of packets dropped due to the deafness problem is significantly reduced. In many cases, the packet dropping probability of DMAC-DACA is only 50% and 30% of that of OMNI IEEE 802.11 and DMAC, respectively.

5.3. DF1 versus DF2

Figure 17 shows that most of the packets dropped as a result of deafness are attributed to the second type of deafness, which is discovered and reported in this paper. Thus, the second type of deafness is more serious than the first type of deafness problems.

5.4. Effectiveness of DMAC-DACA's CA mechanism

Figure 18 shows that DMAC-DACA has a higher percentage of dropped packets due to collisions compared to DMAC and OMNI IEEE 802.11. This is because the increased traffic

Table 2: Comparison between directional schemes, including the newly proposed DMAC-DACA.

Directional MAC Scheme	Carrier sensing	VCS	RTS	CTS	DATA/ ACK	Backoff	Sweeping RTS/CTS	Separate CTRL, DATA Channels	Resolves DF1	Resolves DF2	Resolves HT1	Resolves HT2	Nominal wireless communication range
D-MAC [21]	Y	Y	Dir/ Omni	Omni	Dir	BEB	N	N	N	N	N	N	OO
DMAC [24]	Y	Y	Dir	Dir	Dir	BEB	N	N	N	N	N	N	DO
MMAC [24]	Y	Y	Dir	Dir	Dir	BEB	N	N	N	N	N	N	DD
Tone DMAC [25]	Y	Y	Dir	Dir	Dir	BEB	N	Y	Y	N	N	N	DO
DVCS [23]	N	Y	Dir	Dir	Dir	BEB	N	N	N	N	N	N	DO
Power-Controlled D-MAC [22]	Y	Y	Dir	Dir	Dir	Flexible	N	N	N	N	N	N	DD
Circular [26]	Y	Y	Dir	Dir	Dir	BEB	Y	N	N	N	N	Y	DO
DMAC-DACA	Y	Y	Dir	Dir	Dir	BEB	Y	N	Y	Y	Y	Y	DO

Table 3: Simulation parameters.

Parameter	Value/description
Number of nodes	50
Network grid	1000 m × 1000 m
Traffic sources	CBR UDP
Traffic rate per source (packets/second)	5, 10, 20, 40, 80, 120
Length of IFQ	50
Data frame size	512 bytes
Data rate	2 Mbps
RTS-retry-limit	7
Number of beams for directional communication	8
Antenna gain when beamforming	16 dBi
DDNT	500 m

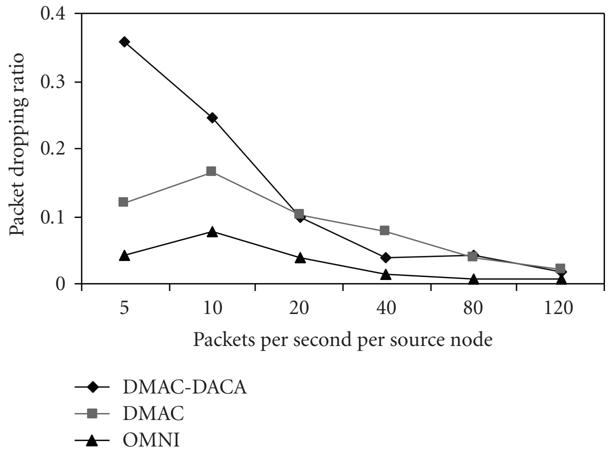


Figure 18: Effect of DMAC-DACA's CA mechanism.

load attributed to the sweeping RTS/CTS causes more hidden terminal problems, which offsets the benefit of the CA mechanism. This is not a serious limitation since most of the frame dropping is attributed to deafness rather than hidden terminals, as will be pointed out in Section 5.5. In addition, the results reported in Figure 16 indicate that DMAC-DACA outperforms both DMAC and OMNI 802.11 with respect to the overall packet dropping probability (by achieving a significantly lower packet dropping ratio).

5.5. *DF versus HT*

As shown in Figures 19, 20, and 21, the deafness problem is far more serious than the hidden terminal problem and is the dominant factor causing packet dropping, especially at traffic loads exceeding 5 packets/second. At 40 packets/second, for example, more than 80% of the dropped packets are due to deafness in all three-directional MAC schemes.

5.6. *Effect of DDNT*

The effect of DDNT on the performance of DMAC-DACA is illustrated in Figures 22, 23, and 24. The performance of DMAC-DACA remains practically the same for different values of DDNT. This is a desirable feature since different transceivers may have different nominal OO and DO ranges.

5.7. *Effect of antenna gain*

Figures 25–27 illustrate the effect of different antenna gains on the throughput of DMAC-DACA, DMAC, and OMNI 802.11, respectively. Figures 25 and 26 show that the throughput improves for DMAC-DACA and DMAC when

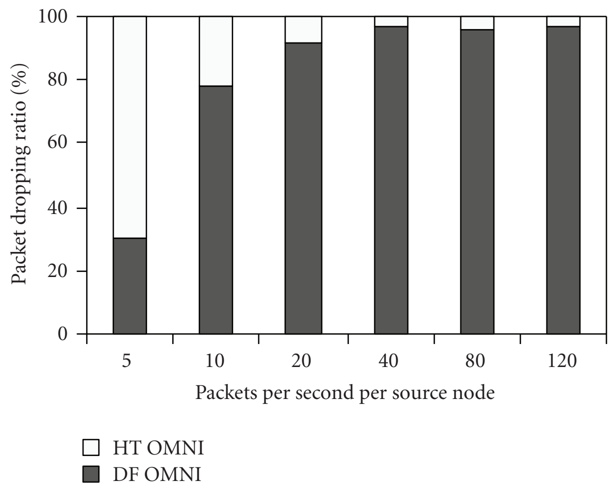


Figure 19: OMNI IEEE 802.11: deafness versus hidden terminals.

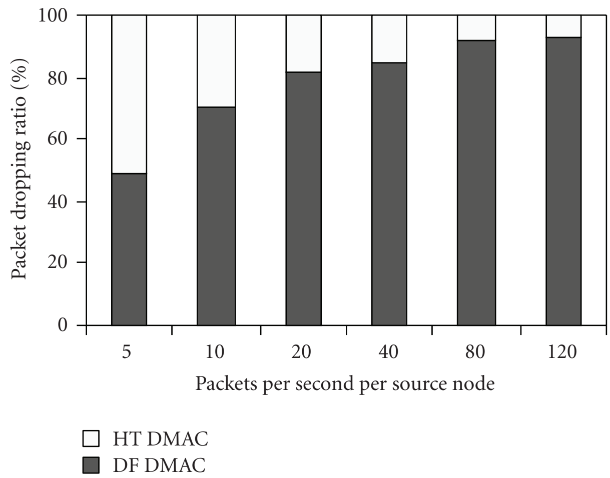


Figure 20: DMAC: deafness versus hidden terminals.

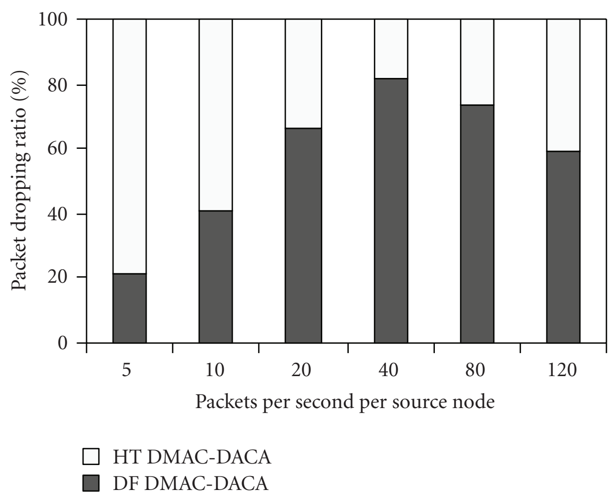


Figure 21: DMAC-DACA: deafness versus hidden terminals.

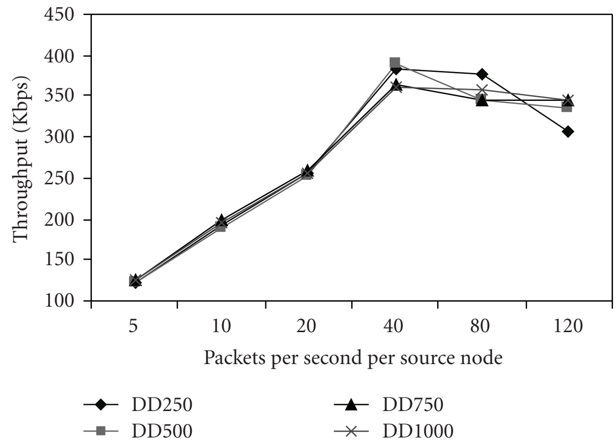


Figure 22: Throughput of DMAC-DACA with different DDNTs.

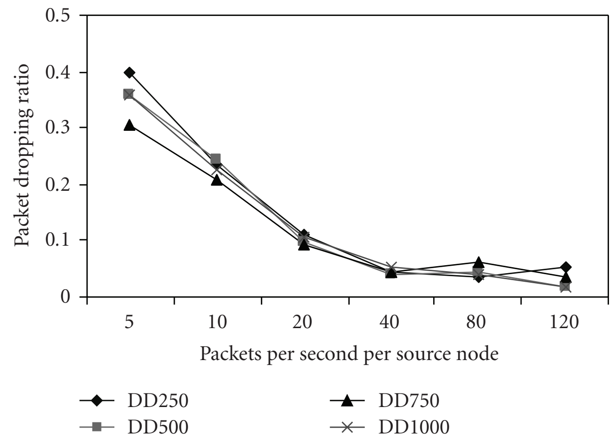


Figure 23: Effect of different DDNTs on the CA mechanism.

the antenna gain is increased. In OMNI 802.11, the effect is negligible, except under large offered loads.

6. CONCLUSION

In this paper, we thoroughly investigated the deafness and hidden terminal problems arising from utilizing directional antennas in wireless ad hoc networks. We also discovered a new type of deafness problems, which happens to be the one to which the majority of the packets dropped are attributed. Moreover, a new directional MAC scheme, namely, DMAC-DACA, is proposed to jointly address the deafness and hidden terminal problems. The ns2 network simulator was extended at layers 1, 2, and 3 to accommodate directional communications. Our simulation experiments revealed that DMAC-DACA significantly enhances the performance and greatly increases the throughput. The simulation experiments showed that DMAC-DACA outperforms DMAC and OMNI 802.11 with respect to throughput, especially with light and moderate traffic loads. With respect to packet dropping, a 70% reduction in packet dropping is reported for DMAC-DACA for some offered loads. The simulation results also revealed that deafness is much more serious

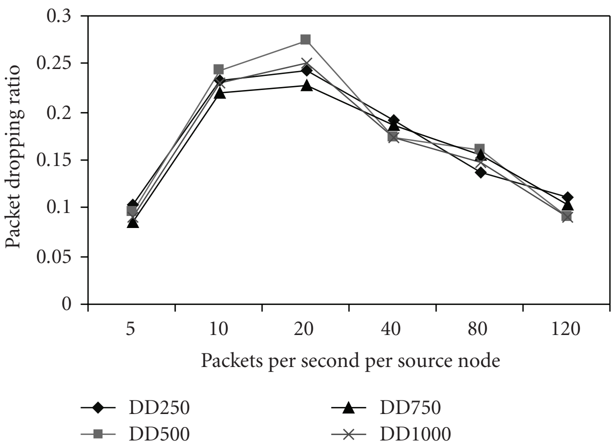


Figure 24: Effect of different DDNTs on the DA mechanism.

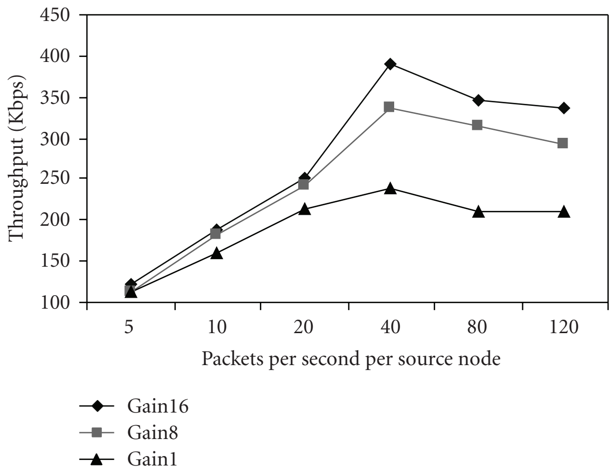


Figure 25: Throughput of DMAC-DACA with different antenna gains.

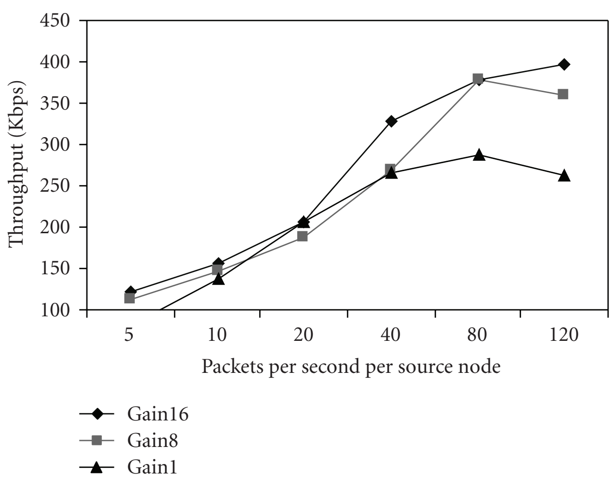


Figure 26: Throughput of DMAC with different antenna gains.

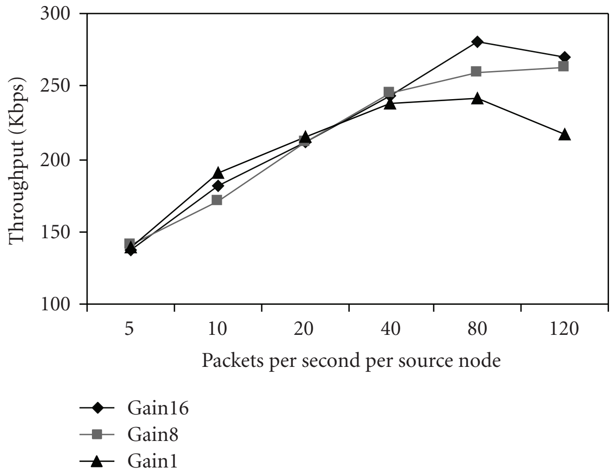


Figure 27: Throughput of OMNI IEEE 802.11 with different antenna gains.

than the hidden terminal problem and that the second type of deafness is more serious than the first. Additionally, we thoroughly investigated the effects of DDNT as well as the antenna gain on the network performance.

Finally, due to the directional mode of transmissions, the channel around a node can be regarded as several subchannels rather than a single channel. While a node may not be allowed to transmit in one direction, it may be allowed to transmit in other directions. The DNT proposed and implemented in DMAC-DACA can be further extended to schedule packet transmissions among different directions (subchannels). This will further increase spatial reuse and enable more simultaneous transmissions and is a topic of current and future research. Using directional antennas in conjunction with advanced wireless network architectures, such as A-Cell [32], is also an important research topic.

ACKNOWLEDGMENTS

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