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Addressing deafness and hidden terminal problem in directional antenna based wireless multi-hop networks

Anand Prabhu Subramanian · Samir R. Das

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Abstract We address *deafness* and *directional hidden terminal problem* that occur when MAC protocols are designed for directional antenna based wireless multi-hop networks. Deafness occurs when the transmitter fails to communicate to its intended receiver, because the receiver's antenna is oriented in a different direction. The directional hidden terminal problem occurs when the transmitter fails to hear a prior RTS/CTS exchange between another pair of nodes and cause collision by initiating a transmission to the receiver of the ongoing communication. Though directional antennas offer better spatial reuse, these problems can have a serious impact on network performance. In this paper, we study various scenarios in which these problems can occur and design a MAC protocol that solves them comprehensively using only a *single channel* and *single radio interface*. Current solutions in literature either do not address these issues comprehensively or use more than one radio/channel to solve them. We evaluate our protocol using detailed simulation studies. Simulation results indicate that our protocol can effectively address deafness and directional hidden terminal problem and increase network performance.

Keywords Deafness · Hidden terminal problem · Directional antenna · MAC protocol

A. P. Subramanian (✉) · S. R. Das
Computer Science Department, Stony Brook University, Stony Brook, NY 11794-4400, USA
e-mail: anandps@cs.sunysb.edu

S. R. Das
e-mail: samir@cs.sunysb.edu

1 Introduction

Directional antennas can concentrate radio signal energy in a particular direction, instead of radiating it in all directions like their omni-directional counterpart. So the transmission on a directional antenna can potentially cause much lesser interference, thereby giving a significant capacity advantage in multi-hop wireless networks. Similarly, reception on directional antenna is subject to lesser interference. Thus, advances in directional antenna technology have motivated researchers to revisit the design of medium access control (MAC) protocols to fully exploit their advantages. Recently many approaches [4, 5, 7, 9, 11–13, 15, 17] have been proposed that aim to benefit from the ability to communicate in a desired direction.

Though directional antennas offer many benefits such as better spatial reuse, increased coverage and better link reliability, they also present new problems. *Deafness* and *directional hidden terminal problem* are two such problems. These problems if left unaddressed can have a serious effect on network performance. Deafness occurs when the transmitter fails to communicate to its intended receiver, because the receiver's antenna is oriented in a different direction. Directional hidden terminal problem occurs when a transmitter is unaware of the state of the channel when it orients its antenna to a new direction. This occurs when a potential transmitter fails to hear the RTS/CTS exchange[1] between another pair of nodes (because of its antenna orientation) and then initiates a transmission to the receiver of the ongoing communication. This can cause a collision.

[1] As in all related literature, we will use the IEEE Standard 802.11 as the baseline MAC layer protocol, and thus will use 802.11-related terminology.

The deafness problem has indeed been studied extensively in recent literature (see [6] and the references therein). However, the current approaches to solve this problem uses additional resources such as additional channels, radios or busy tones [6, 9]. On the other hand, the directional hidden terminal problem due to unheard RTS/CTS is largely left unaddressed. While deafness leads to lost channel utilization due to increasing backoff intervals, the directional hidden terminal problem causes collision that impacts performance adversely. Our goal in this work is to develop a MAC protocol that solves both problems comprehensively using a *single channel* and *single radio interface*.

The rest of the paper is organized as follows: We study various scenarios in which deafness and directional hidden terminal problem would occur in Sect. 2. In Sect. 3 we discuss the existing work related to directional MAC protocols. In Sect. 4 we describe our antenna model and state the assumptions we make. We describe our directional MAC protocol design in Sect. 5. The simulation results are presented in Sect. 6. We conclude our paper in Sect. 7.

2 Deafness and directional hidden terminal problem scenarios

In this section we study various scenarios in which deafness and directional hidden terminal problem would occur. In general, deafness is caused when the transmitter repeatedly tries to send RTS to a destination but the destination does not reply with a CTS. In Fig. 1(a), if node *S* is transmitting to node *D*, it sends a directional RTS to node *D* using beam 3. Node *D* then sends a directional CTS using beam 1. Node *X* is not aware of this transmission. If it initiates a transmission to node *S*, node *S* will not respond as it is transmitting data directionally to node *D*. This causes node *X* to backoff unnecessarily resulting in poor channel utilization. Here, deafness arises because node *S* has its beam oriented in a different direction and node *X* assumes that the RTS packet is lost due to congestion. Node *X* cannot initiate a transmission to node *S* immediately when the transmission between node *S* and node *D* is over, because it has to wait for the entire backoff interval. The directional MAC protocols that send RTS or CTS in a directional manner (DRTS/DCTS) [7, 13, 18] suffer from this problem.

Another variant of the deafness problem occurs when the receiver has its beam blocked due to another transmission in its vicinity and hence it cannot respond with a CTS to prevent collision with the ongoing transmission, see Fig. 1(b). In this scenario, node *S* starts a transmission to node *D*. When node *S* sends the directional RTS, beam 4 of node *B* and beam 3 of node *A* are blocked. When node *D* sends the directional CTS, beam 2 of node *B* is blocked. Node *S* then starts its data transfer to node *D*. Now if node *B* wants to transmit to node *A*, it can send the directional RTS using beam 1 that is free. But node *A* cannot send a CTS back as its beam 3 is blocked. Thus node *B* assumes its RTS is lost due to congestion and goes into a backoff.

In Fig. 2, we demonstrate the hidden terminal problem that arises due to the use of directional antennas. Suppose node *S* wants to communicate with node *D* while node *A*

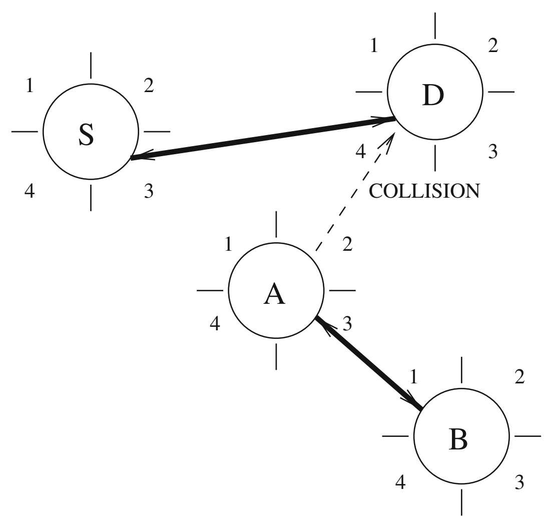
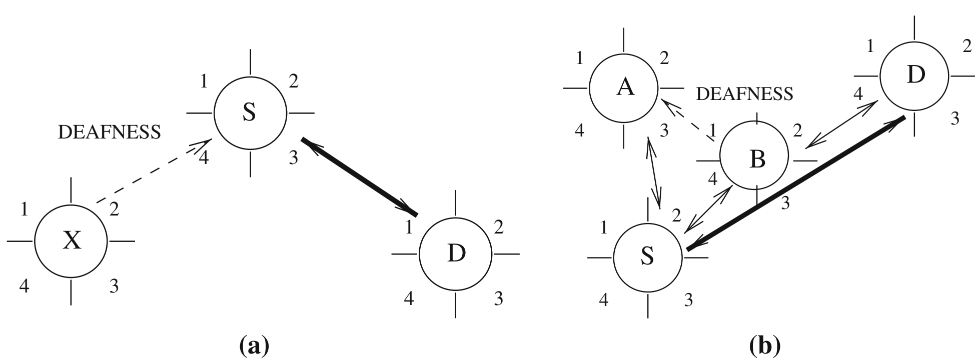


Fig. 2 Directional hidden terminal problem due to unheard RTS/CTS

Fig. 1 Deafness scenarios. (**a**) Type I, (**b**) Type II



and node *B* are already communicating. Node *A*'s antenna beam is oriented towards node *B*. If node *S* sends a directional RTS to node *D*, node *A* cannot hear it and will not block its beam 1. When node *D* sends the directional CTS packet, node *A* does not hear it and will not block its beam 2. Now after the data transfer between node *A* and node *B* is over, if node *A* wants to transmit to node *D*, it senses its beam 2 to be free. If it tries to send a directional RTS packet to node *D*, the RTS packet may collide with the data packet sent by node *S*. This kind of hidden terminal problem arises because a node misses an RTS/CTS exchange in its neighborhood and initiates a transmission to the receiver of an ongoing transmission. This scenario can turn into deafness, if collision does not occur. To the best of our knowledge, the directional hidden terminal problem due to unheard RTS/CTS has not been solved in current literature using a *single channel* and *single radio interface*.

3 Related work

In the past, majority of the research using directional antenna were focused on single hop networks and cellular networks [3, 19]. Recently, many researchers have started to use directional antenna for multi-hop ad hoc or mesh networks [4, 5, 7, 9, 12, 13, 15, 17].

In an early proposal on the use of directional antenna in multi-hop networks [14], Nasipuri et al. have proposed to send the RTS and CTS packets omni directionally so that the transmitter and receiver can locate themselves, and then send the DATA and ACK packet directionally. This solves the deafness problem but results in poor spatial reuse. Ko et al. have proposed that the nodes send directional RTS while the CTS is sent omni-directionally [12]. They assume that the transmitter knows the location of the receiver. Directional RTS leads to deafness around the neighborhood of the sender as described in Fig. 1(a).

Takai et al. have proposed the DVCS mechanism in which a node performs directional virtual carrier sensing [18]. This achieves good spatial reuse. In an similar work, Roychoudhury et al. have proposed the DMAC (directional MAC) protocol that performs all MAC layer operations in directional mode [7]. This combined with the DVCS mechanism achieves maximum spatial reuse, but it suffers from both deafness and directional hidden terminal problems.

Elbatt et al. have introduced the idea of blocked beam and unblocked beams for a node [9]. They have proposed to include the beam index (of the beam in which the DATA packet can be sent) in the RTS and CTS packets and send them in all unblocked beams. They send RTS/CTS in the blocked beams using a different channel. Thus each node needs to be equipped with two radios which are tuned to two different channels. They solve deafness but do not solve the directional hidden terminal problem.

Korakis et al. have proposed the circular-DMAC protocol [13] that tries to address the deafness problem. A node initiating a transmission, sends RTS packets directionally in all beams and the receiver node sends a single directional CTS packet. This protocol prevents deafness only in the neighborhood of the transmitter. The RTS packets are sent sequentially, so the receiver has to wait to send the CTS until the sender has sent RTS in all its beams. Some amount of inefficiency is introduced if the RTS packet towards the destination is lost, as all other nodes hearing the RTS will set their NAVs.

Huang et al. has proposed a busy tone approach [11] using multiple transceivers, capable for transmitting data packets as well as busy tones simultaneously. But this protocol suffers from both deafness and directional hidden terminal problem.

Recently, Roychoudhury and Vaidya [6] have addressed the deafness problem by sending a tone omni-directionally after the data transmission between any two nodes complete. This is a corrective approach rather than a preventive one. This approach allows a node that suffers from deafness to go into repeated backoffs, and then terminate the backoff after the data transmission is over. Also, tone aliasing can happen in this protocol. This approach does not solve the second variant of the deafness problem as described in Fig. 1(b), nor the directional hidden terminal problem due to unheard RTS/CTS.

In [10], Gossain et al. have identified the problems mentioned earlier and proposed modifications to existing directional MAC protocols to address the deafness problem. Their approach addresses both the deafness scenarios but not the directional hidden terminal problem. In [8], Cordiero et al. have proposed an optimization to the circular DMAC protocol to solve deafness and hidden terminal problem due to asymmetry in gain between directional and omni-directional antennas [7].

4 Antenna model and assumptions

In our directional MAC protocol design, we assume a switched beam antenna model which consists of *N* beams covering the entire 360°. We assume two passive antenna elements attached to a *single radio* similar to the antenna model in [6]. One antenna offers *omni-directional* mode of operation and the other offers *directional* mode of operation. Practical phased array antennas that electronically switch to different beams and change to omni-directional mode are available as commodity hardware [1].

4.1 Packet transmission

A node can send a packet either omni-directionally or directionally. Whenever a node wants to transmit omni-directionally, it uses the omni-directional antenna to transmit the packet. When a node wants to transmit directionally, it selects the appropriate beam using the directional antenna and transmits in the desired direction.

4.2 Packet reception

When a node is idle, it senses the medium in omni-directional mode when it does not know the direction from which the signal might arrive. When it detects a signal, the antenna performs an azimuthal scan [6] in order to select the beam on which the impinging signal is maximum and switch off its other beams. Once the direction is known, packet reception is done in a directional manner.

In our protocol, we assume that the directional gain is equal to the omni-directional gain, though usually the former is higher. This is achieved by reducing the transmit power when transmitting directionally. This also conserves power. We also assume that each node knows the direction to its one-hop neighbors. Each node knows the beam index used to communicate with its neighbors and the beam index used by its neighbors to communicate with it [7, 9, 18]. We do not assume that the antenna elements in different nodes should be aligned.

5 Directional MAC protocol

In this section, we describe our directional MAC protocol design and techniques to solve deafness and directional hidden terminal problem. The following intuitions form the basis of our directional MAC protocol design.

1. The deafness scenario as shown in Fig. 1(a) can be solved if the transmitter and the receiver can somehow inform their neighboring nodes about their impending transmission.
2. The deafness scenario as shown in Fig. 1(b) can be solved if the receiver that has a blocked beam finds a way to inform the sender that the transmission cannot happen without disturbing other ongoing transmissions in its neighborhood.
3. The directional hidden terminal problem due to unheard RTS/CTS can be solved if the nodes do not miss the RTS/CTS exchanges happening in their neighborhood.

The detailed description of our directional MAC protocol is presented next.

In our protocol, the RTS and CTS packets are sent *omni-directionally* while the DATA and ACK packets are sent *directionally*. This way all the neighboring nodes of the sender and the receiver are informed about their communication. However, omni-directional RTS/CTS can decrease spatial reuse, as all neighboring nodes regardless of direction will now set their DNAV.[2] In order to prevent this, we overload the RTS/CTS packets with the beam index in which the actual DATA/ACK transmission will happen directionally.

As mentioned in Sect. 4, each node knows the beam index used to communicate to its one hop neighbors. This beam index is put in the RTS packet and sent omni-directionally. Any node that receives this RTS packet, blocks the beam towards the sender of the RTS packet only if the beam index in the packet is same as the one used by the sender of the RTS packet to communicate with it. Similarly the receiver puts the beam index it uses to send the ACK packet in the CTS packet and send it omni-directionally. Now the neighbors of the receiver set their DNAVs accordingly after hearing the CTS packet. Each node maintains a neighborhood transmission table in which it stores the sources of the RTS/CTS packets it heard and the corresponding NAV durations. Here, we assume that the CTS packet also carries the address of its sender.

There is a chance that the RTS/CTS packets sent omni-directionally might collide with any other ongoing data transmission in the neighborhood. We prevent this by separating the transmission of control and data packets in time. After the exchange of the control packets, the nodes wait for a duration called *control window* before transmitting the DATA packet as shown in Fig. 3. The value of the control window is put in the RTS/CTS packets and informed to the neighboring nodes. We use the control window for the following two purposes. Firstly, it avoids collisions between control and data packets. Secondly, it allows multiple data transmissions to start in a neighborhood simultaneously if the data transmissions are in different directions and do not interfere with each other.

A node that sends the first RTS/CTS packet in a neighborhood, defines the control window and informs it to its neighbors during the control packet exchange. Any other node in the same neighborhood that wants to start a data transmission that will not interfere with the previously reserved transmission can start a RTS/CTS exchange if it can complete it within the defined control window. Note that the control window is defined by the sender of the first RTS/CTS packet. The nodes sending the subsequent RTS/CTS packets do not redefine the control window. Once the

[2] DNAV or directional network allocation vector is the mechanism to denote how long the channel has been reserved by other ongoing transmissions in a particular direction.

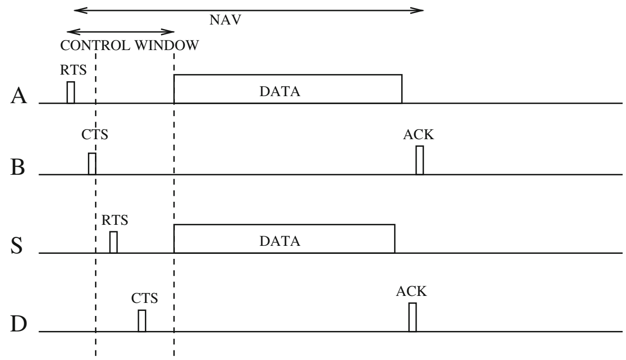


Fig. 3 Control window mechanism to prevent directional hidden terminal problem

control window is over, all the nodes that reserved a transmission can send their data in different directions simultaneously.

The size of the control window is an important factor in this approach. If the control window is large and there are only few non-interfering transmissions that can take place, it results in poor utilization of the channel. If it is small and there are more number of non-interfering transmissions that can take place, it results in poor spatial reuse. So the size of the control window is made adaptive depending on the traffic in the network. Based on our simulation experience, we define the size of the control window as a multiple of the time for a control packet exchange. A node that defines the control window chooses a value for it as $\alpha \times$ number of control packet exchanges it heard in the previous window $\times$ time for a control packet exchange, where $1 \leq \alpha \leq 2$.

Since we separate the transmission of control and data packets in time, the nodes do not miss the RTS/CTS exchange in their neighborhood, thereby preventing the *directional hidden terminal problem*. We note that the use of a time window between the reservation and actual data transfer has been used in MACA-P protocol [2]. However their objective was to increase parallelism in CSMA based MAC protocols rather than solving deafness and directional hidden terminal problem.

We address the deafness problem as described in Fig. 1(b) using a special packet called NCTS (*negative* CTS) which is sent omni-directionally when a node receives an RTS but cannot send the CTS as the beam it will use to send the ACK packet is already blocked. The NCTS packet can be sent omni-directionally because there is no data transmission going on during the control window. This informs the sender of the RTS packet that the data transmission cannot happen without interfering with the already reserved transmissions. When the node that sent the RTS packet gets the NCTS, it sends a TC (*Transmission Cancel*) packet omni-directionally. The TC packet signifies that the current transmission has been canceled; so all the neighbors now can cancel their NAV that was set due to the original RTS packet. They also cancel the control window, if sender of the TC packet has previously defined it.

5.1 Discussion

We now show how our MAC protocol solves the deafness and directional hidden terminal problem as shown in Figs. 1 and 2.

In Fig. 1(a), node *S* sends an omni-directional RTS packet with the beam index 3 to node *D*. When node *X* hears this packet, it adds an entry for node *S* in its neighborhood transmission table. Node *X* need not block its beam 2, because the beam index in the RTS packet is 3 but the beam used by node *S* to communicate with node *X* is 4. If node *X* has a packet to node *S*, it knows that node *S* is already involved in another transmission from its neighbor transmission table and waits until it completes. This way of solving deafness is a preventive approach in contrast to a corrective approach in [6].

In Fig. 1(b), node *S* sends an omni-directional RTS packet with beam index 2. Now node *A* blocks its beam 3 and node *B* blocks its beam 4. When node *D* sends the CTS packet with beam index 4, node *B* blocks its beam 2. Node *S*, then waits for the control window to get over. If node *B*, has data to transmit to node *A*, it sends a RTS packet within the control window. Now node *A* replies with a NCTS packet to node *B* informing it that the transmission cannot occur without interfering with the already reserved transmission between node *S* and *D*. Node *B* sends a TC packet to notify its neighbors that its transmission has been cancelled. This way we prevent the deafness scenario as described using Fig. 1(b).

In Fig. 2, if node *A* wants to transmit to node *B*, it sends an omni-directional RTS with beam index 3 and defines the control window as shown in Fig. 3. Node *B* sends an omni-directional CTS packet with beam index 1 echoing the same control window. Both these packets are sent omni-directionally, so that all their neighbors are aware of this transmission and set their directional NAVs appropriately. Node *S* and node *D* need not block their beams 3 and 4 respectively, as the beam index 3 in the RTS packet sent by node *A* is different from the beam index used by node *A* to send to node *S* and node *D*. If node *S* wants to transmit to node *D*, it sends an RTS packet within the control window defined by node *A* as this transmission does not interfere with the transmission between node *A* and node *B*. Thus both the DATA transmissions can start simultaneously as shown. Note that when an RTS/CTS exchange happens, no node in the neighborhood is involved in a DATA transmission and will not miss them. Thus the directional hidden terminal problem does not occur. The hidden terminal problem due to asymmetry in gain [7] is trivially solved as both the directional and omni-directional ranges are same in our protocol.

6 Performance evaluation

In this section, we evaluate the performance of our directional MAC protocol (henceforth referred to as CW-DMAC) using the qualnet network simulator [16] (version 4.0). We use the DMAC protocol [7] and IEEE 802.11 standard as a baseline for performance comparison. In DMAC, all the MAC layer operations are done in a directional manner. It is aimed towards maximum spatial reuse but it suffers from all the problems mentioned in Sect. 2. In the IEEE 802.11 standard, all the MAC layer operations are done in an omni-directional manner. It does not suffer from either deafness or directional hidden terminal problem but suffers from poor spatial reuse. Our directional MAC protocols aims to achieve as much spatial reuse as possible at the same time solving both deafness and directional hidden terminal problem using a *single radio* and *single channel*.

In all our simulations, the transmit power is adjusted such that both the omni-directional and directional transmission ranges are approximately 280 m. We use UDP as well as TCP traffic in our experiments with packet size 1024 bytes. We use the 802.11b physical layer model as implemented in qualnet and fix the data rate to 11 Mbps. We use eight directional beams (each of width 45°) in all our experiments. We do not consider node mobility in our simulation scenarios.

Initially, we study the performance of the protocols in different scenarios that bring out the advantages of our MAC protocol over DMAC and IEEE 802.11 and later show that our MAC protocol performs much better than the other protocols in generic traffic scenarios and network topologies.

6.1 Spatial reuse

In the first set of performance comparison, we use the scenario in Fig. 4 that allows for high spatial reuse. The individual throughputs of the three flows when sending at a rate of 8 Mbps are shown in Fig. 5. As the IEEE 802.11 standard uses omni-directional RTS/CTS packets, node B has to contend with transmissions from node A and node C. Node A and node C are out of interference range of each other. We can see that the throughput of the flow $B \rightarrow E$ drastically reduces because of the other two flows. DMAC does all its MAC operation in a directional manner, so it exploits the high spatial reuse in this scenario and all the three flows operate as if the other two flows are not in the neighborhood.

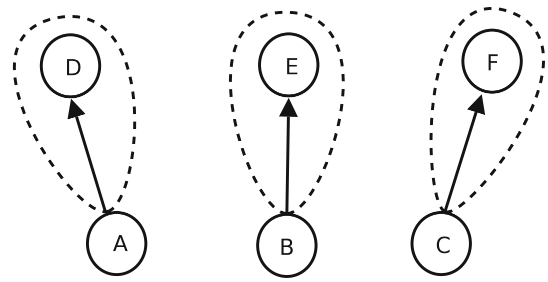


Fig. 4 Scenario (i): Scenario allowing high spatial reuse

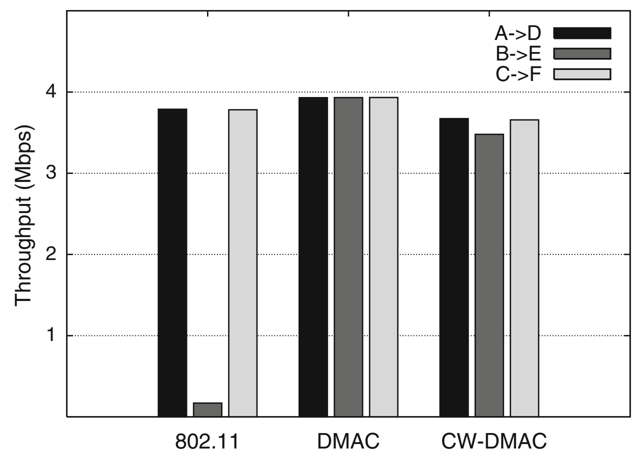


Fig. 5 Throughput of different flows in Scenario (i)

Even though we use omni-directional RTS/CTS transmissions in our MAC protocol, we use the beam index of the corresponding DATA/ACK transmission and do directional virtual carrier sensing. So when node B receives the RTS packets from node A or node C it does not need to wait for the entire transmission to complete. If it can complete an RTS/CTS transmission within the control window, it can transmit along with nodes A and C. We can see that the throughputs of all the three flows are almost equal. The throughputs are slightly lesser than that achieved when using DMAC because we suffer a little when the control window is not fully utilized. Note that this scenario does not suffer from deafness or directional hidden terminal problem and is aimed to demonstrate the spatial reuse that can be exploited by our MAC protocol even when we use omni-directional RTS/CTS transmissions.

6.2 Deafness

Next we use the scenario in Fig. 6 that brings out the deafness problem. In the scenario (ii), nodes 1 and 3 transmit to node 2. In this scenario, when one of the senders initiates a successful transmission, the receiver turns towards that sender and the other sender suffers from deafness in the DMAC protocol. In our experiments, node

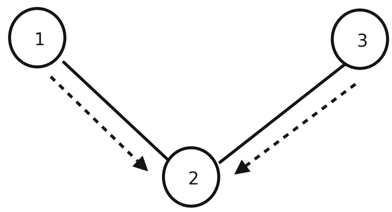


Fig. 6 Scenario (ii): Scenario to study deafness

3 initiates a successful transmission with node 2, so node 1 suffers from deafness. Even when the transmission between node 3 and node 2 is over, node 1 is in backoff. As DMAC uses directional RTS and directional CTS, node 1 is not aware of this transmission and assumes that it's RTS packet is lost due to congestion.

Figure 7 compares the aggregate throughput and throughputs of individual flows with DMAC and CW-DMAC protocols. In the case of DMAC, node 1 suffers from extended deafness and its throughput decreases when the sending rates of the flows are increased. We observed that the number of packets dropped by node 1 is very high compared to the number of packets dropped by node 3 as node 1 exceeded the RTS retransmission limit many times and dropped packets. In CW-DMAC, node 2 sends an omni-directional CTS, so node 1 knows about the transmission between node 3 and node 2. Thus node 1 does not suffer from deafness. We can see that the throughput curves of flows 1 → 2 and 3 → 2 overlap in the case of CW-DMAC. CW-DMAC also performs better than DMAC in terms of aggregate throughput.

To get a better understanding of the scenario, we show a snapshot of the backoff value chosen by nodes 3 and 1 when running DMAC and CW-DMAC in Fig. 8. When using DMAC, we can see that node 1 suffers from deafness and has to choose very high backoff values compared to node 3. In the case of CW-DMAC, the backoff values chosen by nodes 1 and 3 are comparable.

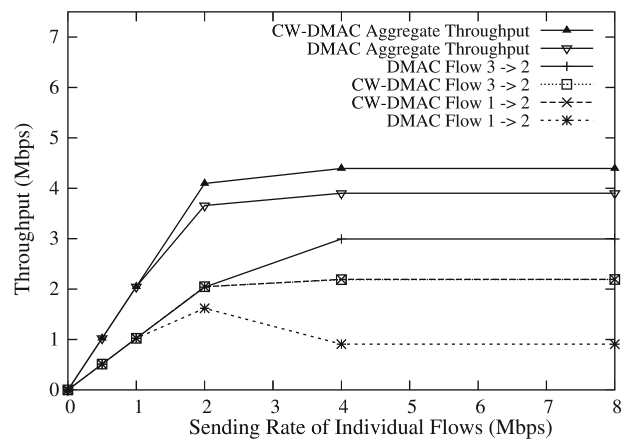
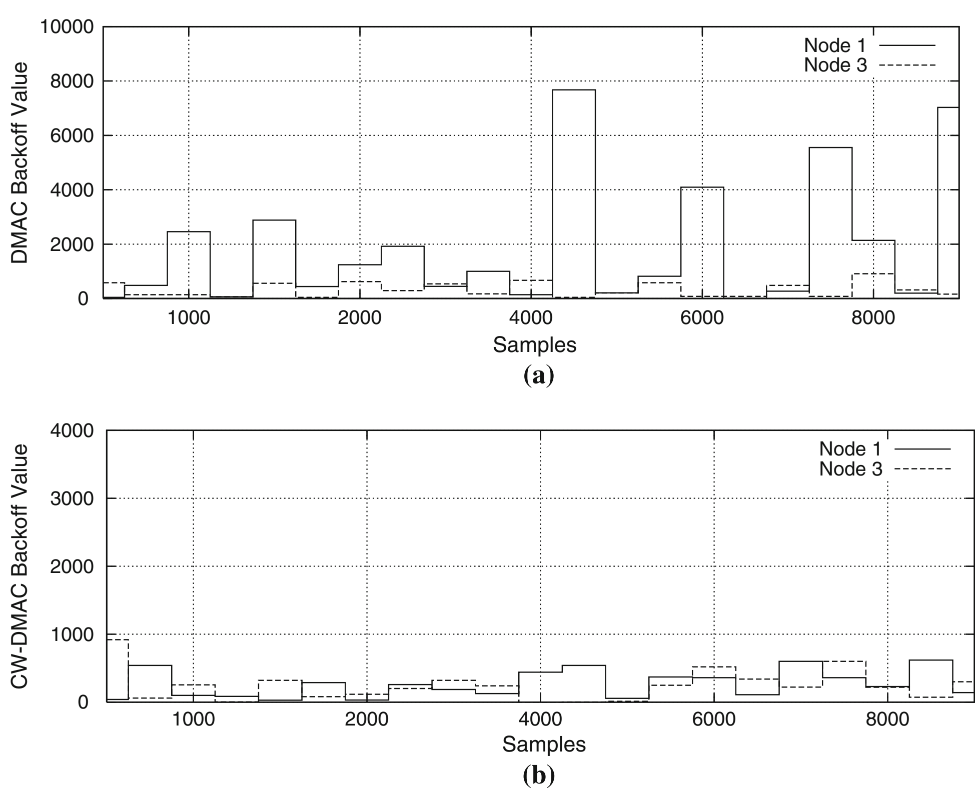


Fig. 7 Throughput of different flows in scenario (ii). The curves for CW-DMAC flow 3→ 2 and CW-DMAC flow 1 → 2 overlap

Fig. 8 Snapshot of backoff values chosen by nodes 1 and 3. (**a**) DMAC, (**b**) CW-DMAC



6.3 Directional hidden terminal problem

The scenario (iii) in Fig. 9 is used to study the effects of the directional hidden terminal problem. Here node 1 has a flow to node 3 and node 4, and node 2 to node 3. In the case of DMAC, when node 1 is transmitting to node 4, it is not aware of the transmission between node 2 and node 3. Since node 1 has a flow to node 3, if it transmits an RTS packet to node 3 it collides with the DATA packet from node 2 to node 3. In Fig. 10, we compare the throughput of the flow 2 → 3 which is affected by directional hidden terminal problem due to unheard RTS/CTS. In the case of DMAC, we can see that when the sending rate of the flows are increased, the throughput of flow 2 → 3 decreases drastically due to collision between the DATA packets from node 2 and RTS packets from node 1 at node 3. In the case of DMAC, we observed an increasing fraction of packet drops at node 2 when the rate of the flows were increased. As Fig. 10 demonstrates, CW-DMAC effectively solves this problem. We do not study the performance of IEEE 802.11 in the above two scenarios as it does not suffer from deafness and directional hidden terminal.

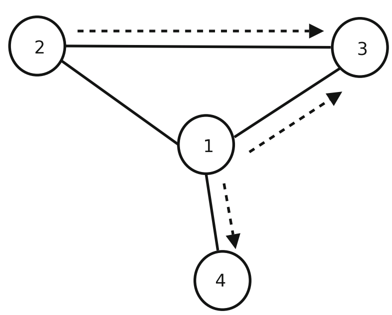


Fig. 9 Scenario (iii): scenario to study directional hidden terminal problem

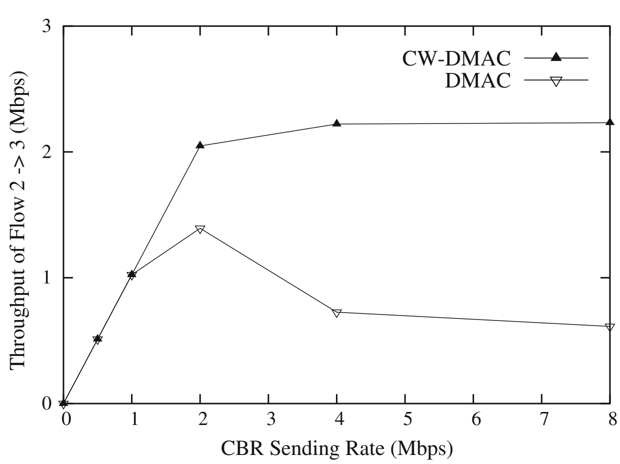


Fig. 10 Throughput of flow from node 2 to node 3 in scenario (ii)

6.4 Cascading effect of deafness

We now analyze the performance of DMAC and CW-DMAC in a linear topology (Fig. 11). We consider a flow between node 1 and 4 along the three hop path. This scenario is to demonstrate the cascading effect of deafness in a multi-hop scenario.

Figure 12 shows the throughput of the flow for the different MAC protocols. DMAC suffers from the cascading effect of deafness [7] and performs poorer than 802.11 and CW-DMAC. CW-DMAC performs better than 802.11 and DMAC as it can exploit the parallelism in transmitting packets between node 1 → 2 and node 3 → 4 as node 3 is out of the interference range of node 1.

To understand the cascading effect better, we show the RTS retransmissions at each node when using DMAC and CW-DMAC in Fig. 13. In DMAC, a node remains in directional mode when it is in backoff [7]. Thus in this topology, when node 3 is transmitting to node 4, node 2 suffers from deafness and goes into backoff. Node 1 tries to send packets to node 2 which is already in backoff in a directional mode. So node 1 in turn suffers from deafness as well. Thus, the periods of deafness are likely to be prolonged for the upstream nodes. Figure 13 shows the fraction of RTS packets retransmitted by each node for both protocols. In the case of DMAC, we see overall about 60% of the RTS packets are retransmitted, as nodes suffer from deafness. The bulk of this is in node 1 due to the above cascading effect. The number of RTS

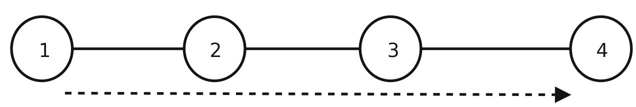


Fig. 11 Linear topology used to demonstrate the cascading effects of deafness

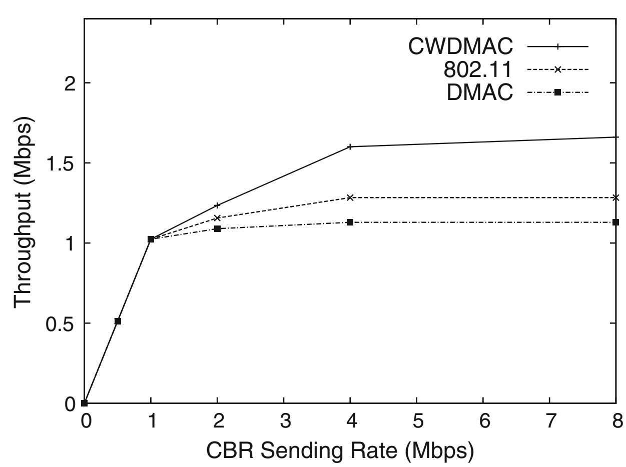


Fig. 12 Throughput of the flow 1 → 4 in the linear topology

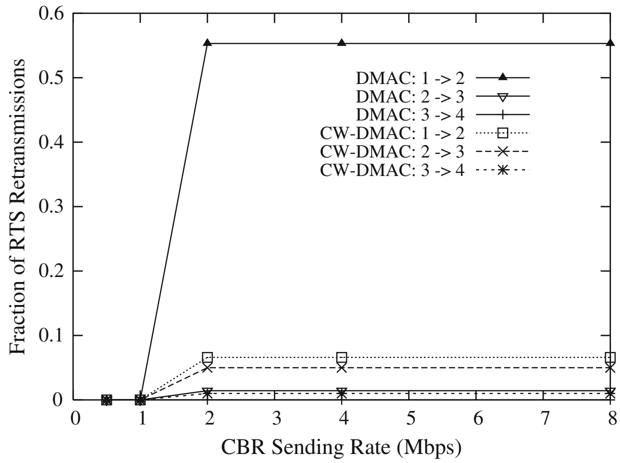


Fig. 13 RTS retransmission in a linear topology

retransmissions for CW-DMAC is very low. This demonstrates the effectiveness of CW-DMAC to address the deafness problem.

The above experiments use scenarios that target specific deafness and hidden terminal problems. We now compare the performance of DMAC and CW-DMAC for larger grid and random multi-hop topologies.

6.5 Grid topology

Figure 14 shows a 5 × 5 grid topology. The distance between adjacent nodes in the grid is about 180 m so that both adjacent nodes and diagonal nodes can communicate with each other. We study two kinds of traffic patterns in the grid topology to understand the performance of CW-DMAC and DMAC.

In Fig. 14(a), we have four multi-hop flows which are aligned along a straight line. We fix the routes of each flow statically. Figure 15(a) shows the comparison of the aggregate throughput of the four flows when using CW-DMAC, IEEE 802.11 and DMAC. DMAC performs poor compared to others because of higher interference in the direction of subsequent hops and due to the alignment of the hops along the chosen paths. The cascading effect of deafness also plays a role in DMAC's poor performance.

In the next experiment, we generate random multi-hop flows which are not aligned in the grid topology as shown

Fig. 14 5 × 5 multi-hop grid topology: (**a**) Aligned flows and (**b**) Random unaligned flows

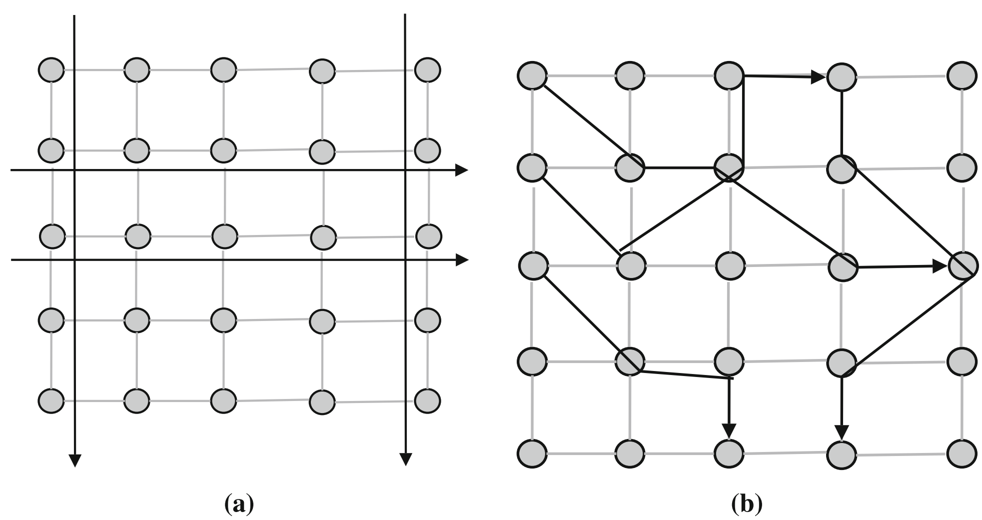
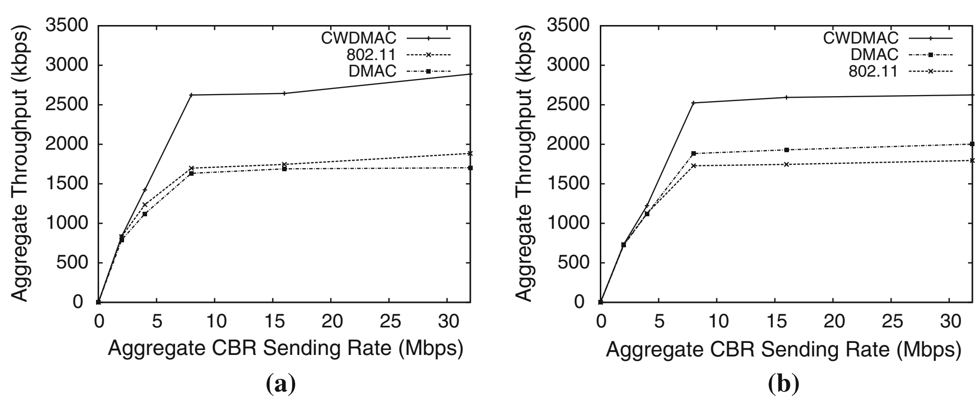


Fig. 15 Aggregate throughput in grid topology: (**a**) Aggregate throughput for aligned traffic flows in grid topology and (**b**) Aggregate throughput for random unaligned traffic flows in grid topology



in Fig. 14(b). The performance of CW-DMAC, IEEE 802.11 and DMAC are shown Fig. 15(b). It is clear from the plot that CW-DMAC outperforms both DMAC and IEEE 802.11 by exploiting spatial reuse and not suffering from deafness and directional hidden terminal problem. DMAC performs better than IEEE 802.11 as the flows are not aligned and the subsequent hops can transmit in different directions. The results shown in Fig. 15(a) and (b) are an average of 5 different runs with flows between different set of nodes.

6.6 Random topology

Next we study the performance of the different protocols in a large random multi-hop topology. Thirty nodes were randomly placed in an area of 1500 m × 1500 m. We set up five CBR flows simultaneously between randomly chosen source and destination pairs and study the throughput behavior. The routes were assigned statically. The simulation results were averaged over ten runs. Figure 16 shows the aggregate throughput as the load increases. CW-DMAC clearly outperforms DMAC by providing approximately 20% higher saturation throughput. This demonstrates that deafness and hidden terminal problems occur frequently enough in random multi-hop scenarios and our protocol effectively solves them and improves network performance. IEEE 802.11 performs the worst due to its poor spatial reuse.

Finally, we study the effect of different MAC protocols on TCP performance in the random topology. We set five FTP flows with packet size 1024 bytes between random pairs of nodes. Table 1 shows the aggregate TCP throughput achieved when using the different MAC protocols. The table shows that CW-DMAC performs better than DMAC which is better than IEEE 802.11. The packet drops and end-to-end delay in DMAC vary drastically

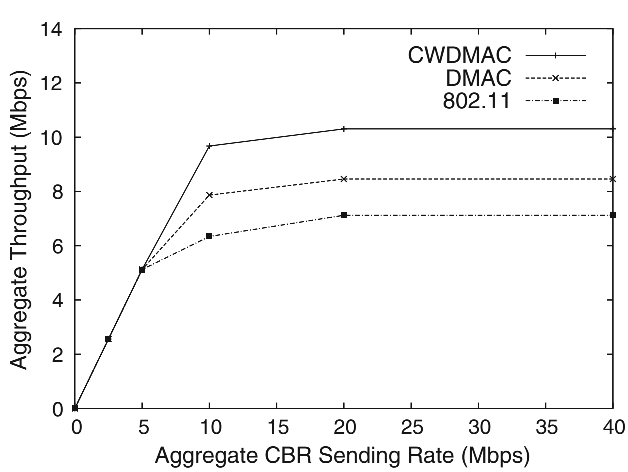


Fig. 16 Aggregate throughput in a 30 node random topology

Table 1 Aggregate TCP throughput in random topology

CW-DMAC	DMAC	IEEE 802.11
6.83	4.34	3.83

because of collisions due to directional hidden terminal problem and backoffs due to deafness. Thus the round trip time estimated by TCP increases which there by affects the congestion window size and results in poor TCP throughput.

7 Conclusion

In this paper we have addressed the issue of deafness and directional hidden terminal problem that occur when MAC protocols are designed for directional antenna based wireless multi-hop networks. We studied various scenarios in which deafness and directional hidden terminal problem could occur and proposed a new directional MAC protocol that address these problems comprehensively and solves them using a *single channel* and *single radio interface*. Current solutions in literature either do not address these issues comprehensively or use more than one radio/channel to solve them. Simulation results show that our directional MAC protocol efficiently solves both the problems at the same time gaining from the advantages of the directional antennas.

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Author Biographies

Anand Prabhu Subramanian is a Ph.D. student in the Computer Science Department at Stony Brook University, NY. He received a M.S. (2007) in Computer Science from Stony Brook University and B.E. (2004) in Computer Science and Engineering from Anna University, Chennai, India. He received the best paper award in ACM MobiSys conference in 2007. His research interests are in the areas of Wireless Networks, Systems and Algorithms. His current research focuses on improving capacity and connectivity in WiFi based ubiquitous wireless access networks. More information about his research can be found at http://www.cs.sunysb.edu/~anandps.

Samir R. Das is currently an Associate Professor in the Computer Science Department in the State University of New York at Stony Brook. He received his Ph.D. in Computer Science from Georgia Institute of Technology, Atlanta, in 1994. His research interests are in wireless networking and mobile computing, focusing on protocols, systems and performance evaluation. He received the U.S. National Science Foundation's CAREER award in 1998 and the best paper award in ACM MobiSys conference in 2007. He has been a speaker in the Distinguished Visitor program of the IEEE Computer Society during 2001–2003. He co-chaired the technical program committee for the ACM MobiHoc Symposium in 2001 and ACM MobiCom Conference in 2004. He currently serves or has served on the editorial board of the IEEE/ACM Transactions on Networking, IEEE Transactions on Mobile Computing, ACM/Kluwer Wireless Networks Journal and Ad Hoc Networks journal. More information about him and his research can be found at http://www.cs.sunysb.edu/~samir.