Avoiding Head of Line Blocking in Directional Antenna

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Abstract

One of the attractive features of directional antennas is their higher channel reuse: by transmitting the signal only in one direction, an antenna avoids interfering with communication going on in the other directions and focuses more of the power in the primary direction. In existing directional MAC protocols a single queue is used at the MAC layer; this is inherited from omnidirectional implementations. However, while there is a single channel state in omnidrectional transmission (either the channel is busy or not), the state of the channel varies with the desired direction of transmission in directional antennas. Thus, existing implementations which use a single FIFO queue potentially leads to Head of Line blocking if the medium is busy in the direction of the packet at the top of the queue but is available in other directions. We propose a new queuing organization which could take advantage of the channel more effectively using the underlying antenna system by eliminating Head of Line Blocking. We also identify a problem with the directional virtual carrier sense implementation due to side-lobes and provide a solution to it. Our results indicate that by using a greedy approach to schedule the packet which has the least wait time increases the overall throughput and reduces end-to-end delay considerably, especially under heavy loads.

1. Introduction

Omni-directional Antennas (OAs) – antennas that spread the transmission power in all directions away from the antenna – are the most common type of antenna used in wireless networks, including Mobile Ad hoc Networks (MANETs). While these antennas are inexpensive and well supported, they cause significant channel under utilization: most of the transmitted power is not directed towards the receiver and ends up blocking other potential transmissions. As a result, researchers have begun to explore an alternative technology, namely *Directional Antennas* (DAs) [10].

In DAs, the transmission energy can be formed into a beam at a particular angle. Thus, the transmission energy is focused towards the useful communication direction, allowing other neighboring nodes to have concurrent transmissions in different directions, and significantly increasing the channel capacity. Another desirable feature of DAs is the extended range of the transmission because the transmission energy is focused more narrowly. Accordingly, the DAs appear to hold significant promise of improving the capacity of MANETs.

DAs present unique technical challenges that are not present in OA operation. As a result, several researchers have explored alternative Directional MAC (DMAC) protocols [7, 1, 6, 2, 8, 3]. In addition, problems in directional antennas like deafness[4] and routing [1, 5, 2, 10] have been studied and solutions have been proposed.

In this paper, we identify an additional problem that arises in DAs: Head of Line (HoL) Blocking. More specifically, MAC level use prioritized FIFO queues for packets to be sent on the medium. While this is fine in most shared media, including OAs, it gives rise to HoL blocking in directional antennas. This effect occurs because it is possible for the medium to be free in some directions but not others. If a packet at the top of the queue is blocked, it prevents other packets from being transmitted even if their direction is free.

Consider the scenario in Figure 1 where a node A is communicating with nodes B, C and D. Let node A's queue have packets to node B,C and D waiting for transmission. Nodes B and E are engaged in communication. Node A has to wait till the communication between node B and E is complete. This is logical if the packets are

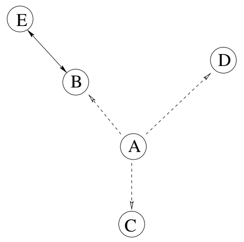


Figure 1. Head of Line blocking

being sent in omni-directional mode. If node A starts sending packets, then it can interfere with the ongoing communication between nodes B and E. However, in the case of directional mode, this does not always hold true. In the above example, node A could schedule the packet for node C instead of waiting on node B. According to the best of our knowledge, there is no existing work on discussing the queuing policy to take advantage of the directional nature of the transmission. This paper characterizes this problem and proposes and evaluates a solution to it.

The contributions of this paper are: (1) We investigate the performance of an existing Directional MAC (DMAC) layer and analyze the effect of the HoL blocking; (2) Based on our observations, we propose modifications to the existing DMAC and evaluate its performance under a range of scenarios; (3) We discovered and corrected an inefficiency in the neighbor discovery process of DMAC that could lead destructive behavior. Simulation results indicate that the improved DMAC outperforms the existing DMAC in terms of throughput and end-to-end delay.

The remainder of this paper is organized as follows. Section 2 provides an overview of the directional antenna model and the MAC layer that are assumed in this paper. In Section 3, the design and implementation of the proposed protocol are described. Experimental results evaluating the improved implementation are presented in Section 4. Finally, Section 5 presents conclusion and future work.

2. Background

This section briefly overviews some background information regarding directional antennas (DAs) and the directional MAC protocol. There are two main types of DAs: (1) Switched Beam; and (2) Steerable. In switched beam antennas, space is divided into a fixed number of equally divided sectors. Figure 2 shows an 8 sector switched beam antenna. A beam is transmitted in one

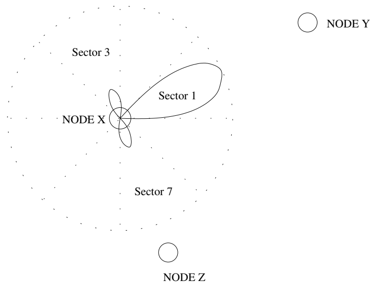


Figure 2. Switched beam antenna

sector at a time. The coverage pattern of the beam in a particular sector will consist of a main lobe and side lobes as shown in the Figure 2. If the node knows the sector in which the next hop node is situated, then it will transmit the signal in that particular sector. In this paper, we focus on the Switched Beam Antenna model since they are simpler and cheaper than steerable antennas. However, the problem also exists in steerable antennas and the proposed solution can be applied to them.

2.1. Overview of DMAC

To enable the use of DAs at the physical layer, a directional MAC protocol which exploits their features is needed. We use a directional MAC protocol called DMAC which uses an RTS-CTS handshake similar to the 802.11 protocol. The remainder of this section describes the main features of DMAC.

2.1.1. AoA cache: To enable directional communication, the DMAC tracks the direction in which a node's neighbors are located (tracked as a $\langle node, angle \rangle$ pair). These values are maintained in an "Angle of Arrival" Cache (AoA cache). This cache is populated and updated with every transmission heard by a node.

When sending a packet, the AoA cache is queried to get the angle recorded for the next hop destination node. If the cache does not have a matching entry, the packet is transmitted in an omni-directional mode. Otherwise, the packet is transmitted in the sector matching the angle fetched from the cache. The transmission is attempted in the directional mode for a fixed number of times; if this retransmission limit is reached, the cached entry is purged and packet transmission is attempted omni-directionally.

2.1.2. Virtual carrier sensing In 802.11, Virtual Carrier sensing is carried out by maintaining a "Network Allocation Vector" (NAV) that tracks the time until the channel will become available. In the case of DMAC, virtual carrier sensing needs to be altered to take advantage of the spatial reuse provided by the directional antenna by tracking the availability of each sector individually. If a node hears an ongoing transmission in a particular angle then an appropriate space of channel around that angle should be marked as busy. This is done by maintaining a "Directional NAV" (DNAV) table. The angles around the node that is marked busy is determined according to a constant "DNAV delta angle"(δ_{dnav}). If the angle of arrival is aoa, then the space marked as busy for the duration of the transmission is $(aoa-\delta_{dnav})$ (called *lower-bound angle or* lb) to $(aoa+\delta_{dnav})$ (called *upper-bound angle* or ub).

Let a_t be the angle in which the packet needs to be transmitted. Let $DNAV_j$, lb_j and ub_j be the j^{th} DNAV entry and its associated lower-bound and upper-bound angles respectively. E_{sel} is defined as the entries selected in DNAV for a given a_t and is determined as follows.

$$E_{sel} = \{DNAV_j \mid \forall\, j \; such\; that \; ((lb_j <= a_t) \wedge (ub_j >= a_t))\} \quad (1)$$

Let w_i be the wait time for the i^{th} entry in the set E_{sel} and n be the number of entries in the E_{sel} as given Equation 1. Let W_{max} be the maximum wait time for a given a_t. It is given by the equation 2.

$$W_{max} = max(w_i) \; where \; i \in 1..n \quad (2)$$

The queuing policy implemented in DMAC is as follows. Each packet is assigned a priority. The routing layer maintains a FIFO queue for each priority. The DMAC layer then acquires a packet from the routing queues and then transmits it with appropriate handshake. DMAC uses *Strict priority scheduling*: each packet is assigned a priority and packets are transmitted strictly in priority order.

3. Design and Implementation

The problem of Head of Line (HoL) blocking was explained in Section 1. In order to address HoL, we modify the queuing discipline to enable the transmission of the packet that has the minimum waiting time first. Sensing the channel every time for each packet can be ineffective. We now describe the mechanism by which a packet is selected for transmission based on the information present in the DNAV.

3.1. Using DNAV for scheduling

Each node maintains a directional NAV (DNAV) table as explained in Section 2. The packet queue is examined to determine the packet with the least wait time. This wait time can be determined by examining the DNAV table and checking the wait time for the packet's angle of transmission. The maximum wait time can be found out by using Equation 2 if the direction for the packet is known.

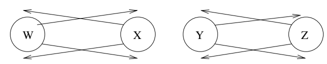


Figure 3. Effect of Deafness

The DNAV does not always reflect the actual state of the channel. Consider nodes W, X, Y and Z in Figure 3. Let nodes X and Y be within transmission range of node W. When the node W is communicating with node X, node Y should ideally mark its DNAV appropriately indicating the wait time in the direction of node W. If node Y is busy communicating with node Z, then node Y will be "deaf" to node W. This inhibits the DNAV update at node Y. Since the state of DNAV does not reflect the channel state in the direction of node W, all calculations using the DNAV entries may not always be correct. This paper does not try to solve the deafness problem. Deafness causes under performance of our protocol. In the presence of a reasonable mechanism to reduce the deafness, the proposed protocol should perform even better. We now describe the approach taken to measure the angle of transmission and the scanning of packets for least wait time.

3.2. Transmission angle calculation method:

When a node receives a packet from the physical layer, the antenna is able to determine the approximate angle of arrival of the signal. In the course of this study, we discovered a situation that causes erroneous updates of the AoA cache. Consider the case where node X is locked to sector 1 and is about to communicate with node Y (Figure 2). A packet sent by Z may still be received at Y with the side lobes. Since the maximum gain is found in the main lobe of the coverage pattern, the angle of arrival for the packet transmitted from node Z is marked as the main lobe of sector 1 instead of sector 7. Even though node Z could listen to a packet transmitted from sector 1 of node X through the side lobe effect, this would be an inefficient use of the transmission power; a packet should always be transmitted along the main lobe pointing toward the direction of the recipient. Erroneous DNAV also leads to ineffective virtual carrier sense. For example, when node X wants to send a packet to node Z and the channel along sector 1 is busy: X will wait until sector 1 is idle even if the channel along sector 7 is idle. Further, if 7 is idle but 1 is not, transmission will proceed even though Y will not be able to receive.

In order to address this problem, DMAC was modified to overcome such false updates. If the antenna is locked toward a sector, then the DNAV is not updated with the angle of arrival. It is updated only when the antenna is in omni-directional mode. This modification does not lead to missing many true updates since nodes are only receiving directionally when they are actively receiving packets. When passively listening, nodes are in omni-directional mode. This modification improves the correctness of DNAV entries and has lead to an increase in the throughput for the studied scenarios.

3.3. MAC layer Buffers

The routing layer inserts the packet to be transmitted by the MAC layer into a queue which is referred as *"Interlinking queue"* (IQ) in this paper. There is an additional queue maintained in our implementation called as the *"MAC Queue"* (MQ). The MAC layer dequeues the packets from IQ and buffers them in MQ. The MAC layer always dequeues the packet with the least wait time from MQ for transmission.

The number of packets to be examined each time can be adjusted by setting the appropriate buffer size for the MQ. The packets in MQ can be scanned only when a new packet needs to be transmitted. This reduces the computation at the node considerably while preserving the ability to examine various packets.

In the proposed solution, MQ is implemented as a linked list. Each entry has a pointer to the packet as well as a record of information related to it (next hop id, angle of Transmission, priority of the packet and the time at which the NAV expires). In the remainder of this section, some of the design issues encountered are described.

3.3.1. Packet Priority The IQ in DMAC is implemented as a set of FIFO queues, one for each priority. The priorities are enforced when packets are buffered into MQ. If there are two or more packets with the same priority and no other packets with higher priority, then the one with the least wait time is scheduled for next transmission.

Parameter	Value
Omni-directional range	250m
Directional range	450m
Directional antenna model	Switched beam
Mobility	none
Propagation Channel Frequency	$9.14 * 10^8$ Hz
Path loss Model	Two Ray
Transmission power	24.5 dBm
Receiver sensitivity	-68.1 dBm
Directional gain	10.0 dB
Antenna Model	Switched Beam
Directional NAV Delta Angle	22.5 degrees

Table 1. Simulation Parameters

3.3.2. Handling omni-directional packets: While dequeuing packets from IQ, it may happen that the head of IQ is a broadcast packet or a packet whose next hop is not found in the AoA cache. Such packets are sent omni-directionally. Omni-directional packets have the largest wait time of all the other packets that need to be transmitted directionally since it must wait for all the sectors to be clear. Hence, we chose not to buffer such packets in MQ. Omni-directional packet is scheduled for transmission only after all the packets in the MQ are transmitted; however, no more packets are inserted into MQ while an omni-directional packet is pending. Once the MQ is empty, the omni-directional packet is scheduled for transmission. Buffering mechanism is resumed after the transmission of this omni-directional packet. However, in the case of high priority packets and omni-directional packets a form of HoL still remains. More specifically, we do not allow a lower priority packet (or a directional packet) can be sent completely before the wait time on the higher priority packet (or omni-directional packet) expires. This is a design decision that we will reexamine as part of our future work. The details are described in Algorithm 1.

4. Performance Evaluation

The QualNet 3.6 simulator [9] is used in this study. Table 1 lists the relevant simulation parameters. We used *Strict priority scheduling* for the packets with the number of priority values set to three. Hence there are 3 FIFO queues.

Algorithm 1 Algorithm to pick up the packet from the Interlinking queue

```
while Interlinking Queue is not empty and number of
pkt ∈ MAC-Queue < QUEUESIZE do
  {Check the packet at the head of Interlinking
  queue. Do not dequeue it.}
  P = Packet at the head of Interlinking queue
  if P is a packet that is to be sent directionally then
    P = Dequeue the packet from the Interlinking
    queue.
    Insert P to the MAC Queue
  else
    {It is an omni-directional packet}
    break the loop
  end if
  if MAC Queue is not empty then
    PktTransmit = Select the packet which has the
    least wait time respecting the priorities from the
    MAC Queue;
  else
    if Interlinking queue is not empty then
      PktTransmit = Fetch from the Interlinking
      queue
    else
      {There is no packet to be transmitted.}
      return
    end if
    return PktTransmit
  end if
end while
```

To ensure that the improvements are not simply due to increase in the overall queue size because of the addition of MQ, we decided to keep the overall queue capacity in our implementation the same as that in the original implementation. More specifically, the length of the $MQ + IQ$ is equal to the length of the original IQ. The length of IQ is set to 50000 bytes for the original implementation. Static routes were used for the simple scenario and the grid topology.

In the remainder of this section we first present simulation results with an illustrative hand-crafted topology followed by more complex grid topologies. In case of Constant Bit Rate (CBR) connections, packets are sent at fixed time intervals called *sending interval* (*sending rate* is the inverse of sending interval). Of course, the problem of HoL occurs when nodes have to forward or originate packets for different destinations which can be reached by different sectors. Having such nodes creates *hotspots* in the scenario.

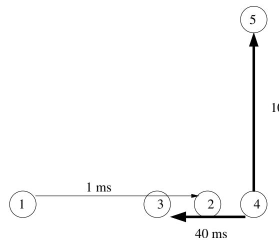


Figure 4. Simple Topology

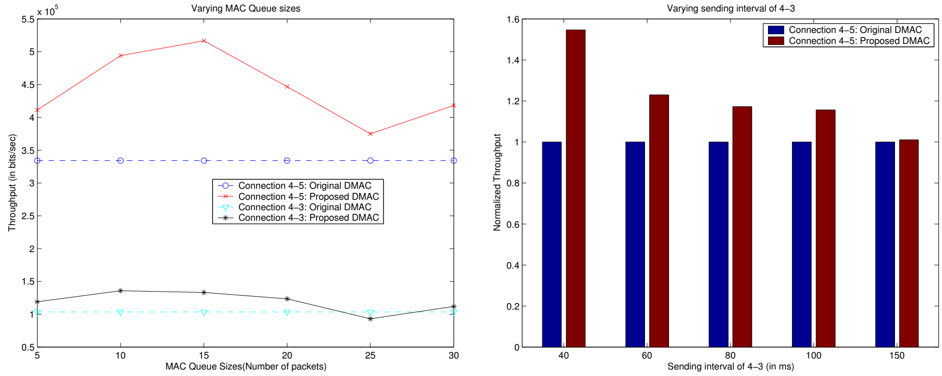
4.1. Simple Topology:

Figure 4 shows an illustrative scenario that isolates the HoL problem using CBR connections.The arrows indicate the direction of flow of traffic. The packet sending interval (in milliseconds) is also shown. Node 4 is within the transmission range from nodes 1. Node 4 is the source of two CBR connections as shown in the Figure 4. A CBR connection from node 1 to 2 is called the *"Throttling connection"* that is in line with the connection from 4 to 3 connection but running in the opposite direction.

As shown if Figure 5(b), we now systematically vary the sending rate of the connection 4-3 and study the effect of HoL blocking on connection 4-5 with the proposed queuing policy. Figure 5(b) indicates that if the interval of the connection 4-3 is low, then a large improvement in 4-5 is observed. When the interval of connection 4-3 is higher, then the percentage improvement goes low.

Since node 4 has two connections going out, the packets destined for node 5 will be blocked if the packet at the head of the queue is destined for node 3 and FIFO policy is observed. The proposed protocol will be able to solve this problem. By observing that the channel is idle in the direction of node 5 and there are packets destined for node 5, node 4 picks up the packet and delivers it to the node 5 (instead of blocking until the channel first becomes available towards 3). One can see that for higher sending intervals of connection 4-3, the original implementation and our implementation behave similarly the MQ mainly contains packets destined for node 5. Since, there are no packets in the MQ destined for node 3, the HoL effect is lesser which leads to lesser improvement.

We now vary the *MQ* length from 5 packets to 30 packets keeping CBR packet size constant (1536 bytes). The sending interval of the throttling connection 1-2 is set as 1 packet every 1 ms. The high sending rate on the throttling connection will keep the channel on the left



(a) Throughput v/s MAC Queue size

(b) Throughput of 4-5 v/s Sending interval of 4-3

Figure 5. Simple Topology: Throughput and Average End-to-End delay

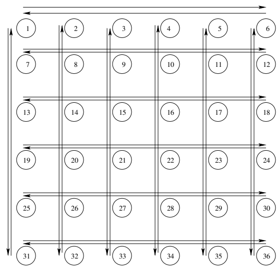


Figure 6. Grid topology

side of node 4 busy most of the time. The sending intervals of connections 4-3 and 4-5 are set to 1 packet every 10 ms and 40 ms respectively. As shown in the Figure 5(a) the connection 4-5 has has higher throughput (55% higher than the original throughput).

4.2. Grid topology:

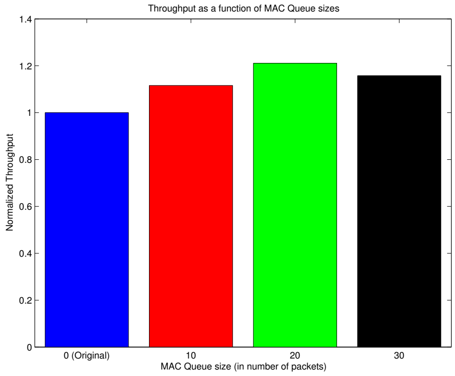
This section presents the results with the grid topology consisting of 36 nodes arranged in a 6×6 grid. Each node is placed 250 m away from the vertical and horizontal neighbor. The connection pattern shown in Figure 6 is used. In this scenario, the routes are configured statically so that the packets always flow either in horizontal straight line or vertical straight line across the grid. The simulation consisted of 24 CBR connections as shown by arrows in Figure 6.

4.2.1. Effect of MAC Queue length: The modified DMAC outperforms the original protocol as shown in Figure 7(a); an improvement of 21% can be seen. The proposed DMAC protocol has lower end-to-end delay as well (Figure 7(a)); as much as 20% reduction of average end-to-end delay is achieved due to the reduced wait time in the presence of HoL blocking.

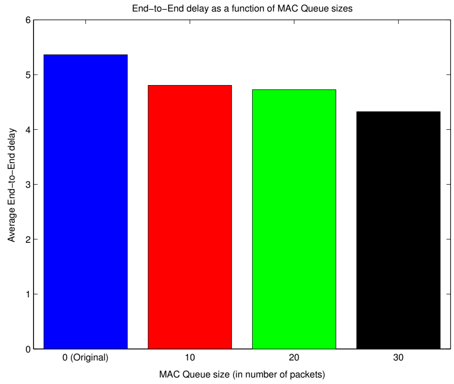
The proposed solution also performs better in terms of jitter (the standard deviation of delay) as shown in Table 2. The packet drops when the *IQ* overflow are marginally reduced. The packets dropped due to the exceeded retransmit limit are more in our implementation than in the original implementation as shown in the Table 2. We believe that this is because of the ineffective virtual carrier sensing in DMAC. This is an area that we are targeting for future work.

4.2.2. Effect of packet sending interval: The effect of the sending interval on the throughput is shown in Figure 7(c). As the sending interval increases there are fewer *hotspots* created. Note that the effectiveness of the proposed queuing mechanism varies directly with the number of *hotspots* created. Tapping the channel reuse can be exploited only in such cases because of the ability to pick the right packet from the queue. Otherwise, the proposed implementation will perform as good as the original one. The best case improvement in throughput was around 21% higher than the original implementation and was observed in the case when sending interval was set to 20 ms as shown in the graph 7(c).

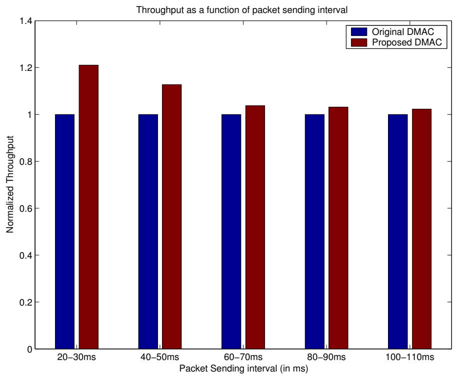
The end-to-end delay is shown in the graph 7(d). Our protocol provides much lower end-to-end delay reductions. The IFQ drops has significantly reduced in the proposed protocol. When the sending interval is set to 100-110 ms, we get improvement as high as 40% in the IFQ drops. Again, the packet drops due to exceeded retry limit are higher in the proposed protocol.



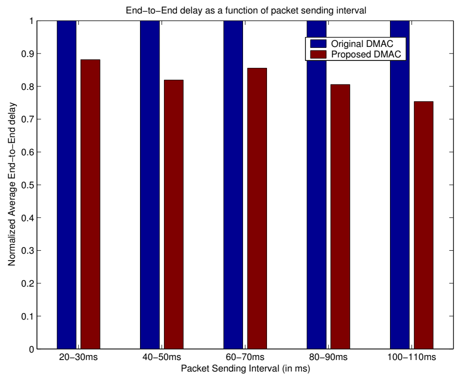
(a) Normalized throughput v/s MAC queue length



(b) Average End-to-End delay v/s MAC queue length



(c) Normalized throughput v/s sending interval



(d) Normalized average End-to-End delay v/s sending interval

Figure 7. Grid Topology: Throughput and Average End-to-End delay

MAC Queue length	Average Jitter(in s)	IQ Drops	Retry limit drops
Original	0.770165284	41633	1722
10	0.720823299	41175	1905
20	0.653387439	40828	1991
30	0.658129317	41148	1955

Table 2. Jitter and packet drops when MAC queue length is altered

5. Conclusion and Future work

Directional Antennas (DAs) have several potential advantages over omnidirectional ones: they provide higher channel reuse, better quality connections, and/or lower transmission power. However, they introduce several challenges that have thusfar prevented this potential from being fully realized by higher level protocols. Many of these challenges are being addressed by ongoing research and some solutions are starting to emerge.

In this paper, we identify another problem that reduces the effectiveness of DAs. More specifically, we describe a Head of line Blocking problem that occurs due to the FIFO queuing policy with the existing directional MAC protocol. FIFO queuing is typically used at the MAC layer because the state of the channel is boolean: it is either available or busy. However, in DAs, the channel may be available in some directions but not others: if the top packet is destined to a busy direction, it will block all subsequent packets, including those that can be transmitted. The problem is addressed via a new greedy queuing policy and a modified D-NAV update mechanism. The new implementation outperforms the existing one in almost all cases in terms of overall throughput and end-to-end delay.

We used a single MQ implementation that was scanned to determine the smallest wait time packet. An alternative implementation is to have one queue for each $\langle sector, priority \rangle$. This *per-sector* queue design will be as effective as the current design for Switched Beam Antennas. However, this approach was not chosen for two main reasons. Firstly, Steerable Antennas, which does not have the concept of sectors, will be unable to use the design. While this can be approximated by quantizing the angles, it will lead to difficulties in determining the least wait time packet. Secondly, having multiple queues will split the available buffer space statically among the transmission directions. Given that most nodes in general do not have active traffic for all sectors, this will lead to lower effective buffer space and more packet drops.

The information in DNAV may be incomplete because of the deafness. Recently, Choudhury et. al [4] proposed a mechanism to reduce the deafness problem in directional antennas. We conjecture that such mechanism will improve the performance of our protocol.

When an omni-directional packet is present in the *IQ*, the current design will block the succeeding packets. If such packets are not blocked, then omni-directional packet (which have maximum wait time) will starve. We would like to investigate the design of allowing the other packets to pass the omni-directional packet without letting the omni-directional packet to starve to strike a balance between higher reuse and fairness to omni-directional traffic. Similar mechanisms can be examined for the HoL blocking between high priority and lower priority packets.

The severity of HoL depends on the number of sectors, the traffic patterns and the nodes relative locations. We did not explicitly study the effect of the number of sectors or the interaction between these factors. With higher number of sectors, the chances of a sector getting blocked is lower. At the same time, higher number of sectors implies that there are more sectors which may be free. The effectiveness of HoL solution will be an intricate function of the number of sectors and "DNAV delta angle"(δ_{dnav}) and the traffic patterns. We would like to study the effect in future.

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