Using Directional Antennas in Multi-Hop Wireless Networks: Deafness and Directional Hidden Terminal Problems

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ABSTRACT

We describe the issues of *deafness* and *directional hidden terminal* problems that occur when MAC protocols are designed using directional antennas. We study various scenarios in which these problems could occur and design a MAC protocol that uses a single radio and single channel to solve them. Current solutions in literature either do not address these issues comprehensively or use more than one radio/channel.

1. INTRODUCTION

Most of the existing technologies in wireless multi-hop networks typically assume the use of omni-directional antennas by all nodes. The wireless channel is shared and a single transmission along a multi-hop path inhibits a large number of nearby nodes. Directional antenna is a technology that solves this problem. Recently many approaches [2] (and references therein) have been proposed that aim to benefit from the ability to communicate in a desired direction. Though directional antennas offer many benefits such as spatial reuse, increased coverage, better link reliability and increase in network capacity, they also present new problems. Deafness and Directional Hidden Terminal problem are two such problems which have a serious effect on network performance when left unaddressed.

Deafness occurs when a transmitter fails to communicate to its intended receiver, because the receiver's antenna is oriented in a different direction. The hidden terminal problem occurs when the transmitter fails to hear the RTS/CTS exchange between another pair of nodes and causes collision by initiating a transmission to the receiver node of the ongoing communication. The deafness problem is studied extensively in recent literature [2] (and references therein) but the directional hidden terminal problem due to unheard RTS/CTS is largely left unaddressed. While deafness leads to lost channel utilization due to exponential backoff, the directional hidden terminal problem causes collision that impacts performance more adversely. Our goal is to develop a MAC protocol that uses only a single channel and single radio and solves these problems efficiently.

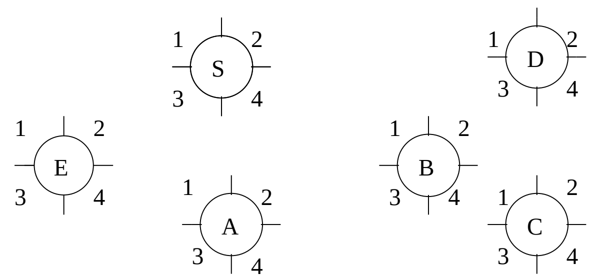

Figure 1: ***Sample network with each node having 4 directional beams***

2. DEAFNESS AND HIDDEN TERMINAL PROBLEM SCENARIOS

In Figure 1, if node A is transmitting to node B, it sends a directional RTS in beam 2 and node B uses beam 3 to send the CTS. Node E is not aware of this transmission and if it initiates a transmission to node A, node A will not respond. This cause node E to backoff unnecessarily resulting in poor channel utilization. Here deafness arises because node A has its beam oriented in a different direction and node E assumes that the RTS packet is lost and goes into a backoff.

In the second scenario, deafness occurs because the receiver node has its beam blocked by another transmission and it takes a precautionary step and does not send the CTS. Consider the following situation: Node A sends an RTS to node D so that beam 4 of node S and beam 3 of node B are blocked. When node D sends a CTS, beam 2 of node B is blocked. When this transmission is going on, if node B wants to start a data transmission to node S, it uses beam 1 which is not blocked. But node S needs to use beam 4 to send the CTS which is blocked ans so it does not send the CTS. Thus node B suffers from deafness and goes into a backoff.

For more details, refer to "Using Directional Antennas in Multi-Hop Wireless Networks: Deafness and Directional Hidden Terminal Problems", WINGS LAB Techreport at http://www.cs.sunysb.edu/∼samir/pub.html

In the third scenario, we show a kind of hidden terminal problem that occurs only when directional antenna is used. Suppose node S wants to communicate with node D while nodes B and node C are already communicating. Now node B's antenna is oriented towards node C. If node S sends an RTS to node D, node B cannot hear it and will not block its beam 1. Also when node D sends a CTS, node B will not block its beam 2. Now after the data transfer between node B and node C is over, if node B tries to send an RTS to node D, then it may collide with the data packet sent by node S. 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.

3. ANTENNA MODEL AND ASSUMPTIONS

We assume a switched beam antenna model which consists of N beam patterns. Whenever a node wants to transmit in a particular direction, it selects the appropriate beam and transmits data. The antenna system offers two modes of operation: *Omni* mode and *Directional* mode. We can imagine there are two passive antennas attached to a single radio. When the node is idle, it senses the medium in omni-directional mode. When it detects a signal, the antenna performs an azimuthal scan in order to select the beam on which the impinging signal is maximum. We assume that the directional range is equal to the omni-directional range. This can be achieved by reducing the transmit power when sending directionally. Thus we can conserve power when transmitting directionally. We also assume that each node knows the direction to all its neighboring nodes. We can run a neighbor discovery protocol (NDP) and find the directions of the neighboring nodes using the angle of arrival (AoA) of the NDP packets.

4. DIRECTIONAL MAC PROTOCOL

In our directional MAC protocol, RTS/CTS packets are sent omni-directionally and DATA/ACK packets are sent directionally. The RTS/CTS packets are overloaded with two additional parameters: *angle of directional transmission* and *control window* (described later). Whenever a node transmits an RTS, it includes in the RTS packet the angle in which it would send the data packet directionally and sends it omni-directionally. Thus it informs all of its neighbors about the impending transmission. When the intended receiver gets this packet, incase the beam it would use to send the ACK packet is free, it sends an omni-directional CTS packet which consists of the angle in which it would send the ACK packet.

Once the RTS/CTS exchange is done, it waits until the control window [1] is over and send the DATA packet directionally. If any other node wants to transmit data, and it will not interfere with the previously reserved data transmission, it can start an RTS/CTS exchange if it could complete it within the window. The first RTS packet defines the window and the subsequent control packets modify this value so that all the data transmission start at the same time in different directions.

Let us consider an example. In Figure 1, if node A wants to transmit to node S, it starts to send an RTS and defines the control window as shown in Figure 2. Node S sends a CTS

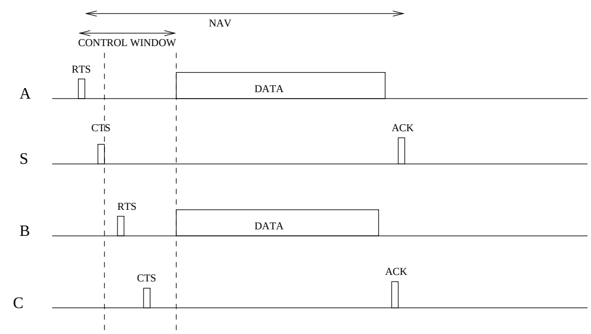

Figure 2: ***Basic Operation***

packet adjusting the control window as shown. Both these packets are sent omni-directionally, so that all their neighbors are aware of this transmission and set their directional NAV appropriately. If node B wants to send to node C, it sends an RTS with the control window as this transmission will not interfere with the DATA transmission between node A and node S. Thus both the DATA transmissions can start simultaneously as shown. Note that when an RTS/CTS exchange happens, no node in the neighborhood is invloved in DATA transmission and will not miss them. Thus the directional hidden terminal problem does not occur.

In order to solve the deafness as described in scenario two, we use a special packet called NCTS (*negative* CTS) which is sent when a node receives an RTS and it cannot send CTS as its beam is blocked. When a node that sent an RTS gets a NCTS, it sends another packet TC (Transmission Cancel) to say all its neighbors that the current transmission is cancelled so that the other nodes can cancel their NAV that was set due to the RTS packet. Both NCTS and TC are sent omni-directionally.

The size of the control window is a multiple of the time for an RTS/CTS exchange. It can be made adapative depending on the number of RTS/CTS exchanges a node heard in the previous window. A node defines the control window as α $\times$ number of RTS/CTS exhanges in the previous window $\times$ time for an RTS/CTS exchange where $1 \leq \alpha \leq 2$.

5. CONCLUSION AND FUTURE WORK

We have proposed a directional MAC protocol that uses a single radio and single channel to solve the deafness and directional hidden terminal problem in multi-hop wireless networks. We are currently implementing our protocol and other directional MAC protocols in the qualnet simulator for a comparitive performance evaluation.

6. REFERENCES

[1] A. Acharya, A. Misra and S. Bansal. MACA-P: a MAC for concurrent transmissions in multi-hop wireless networks. In *First IEEE Percom 2003 Conference*, pages 505–508, March 2003.

[2] R.R. Choudhury and N.H. Vaidya. Deafness: A MAC problem in ad hoc networks when using directional antennas. In *10th IEEE International Conference on Network Protocols (ICNP)*, October 2004.