A New Protocol to Mitigate the Unheard RTS/CTS Problem in Networks with Switched Beam Antennas

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Abstract— **Wireless networks with the capability for directional transmissions using switched beam antennas have increasingly been used to increase the coverage area of nodes as well as to improve spatial reuse. This paper is concerned with the unheard RTS/CTS problem that arises due to the use of directional transmissions. The problem occurs because a node, while beam-formed in one direction, cannot hear the RTS/CTS messages that arrive on another direction with information pertaining to channel reservation. A node, therefore, transmits when it should defer, leading to unnecessary collisions and degraded performance. In this paper, we propose a new MAC protocol that uses a combination of three features to combat the problem: fragmentation of packets, the use of a tone signal to alert potential collision-causing nodes during ongoing transmission, and the use of a pause period when transmission is likely to lead to a collision. As opposed to other recent work on this problem, our protocol does not assume separate data and control channels. We present simulation results showing that our protocol can reduce the number of retransmissions of data packets due to the unheard RTS/CTS problem by as much as 86%, thus improving the delay and throughput characteristics of the network.**

I. Introduction

Ad hoc as well as fixed-infrastructure wireless networks are playing an increasingly important role in a variety of commercial and military applications. The most commonly used Medium Access Control (MAC) protocol in these networks is the IEEE 802.11 [1]. The hidden and the exposed terminal problems in wireless networks are solved in the IEEE 802.11 protocol with virtual carrier sensing, wherein the transmitter and receiver exchange Request-to-Send (RTS) and Clear-to-Send (CTS) messages prior to transmission of data packets. The RTS and CTS messages inform neighboring nodes about the impending communication and thus reserve the channel.

Wireless networks have traditionally used omni-directional antennas. The use of switched beam antennas that allow for directional transmissions, however, holds the promise of improved spatial reuse, increased coverage area and a reduced number of packet losses. Unfortunately, directionality introduces new problems in the MAC layer. These include increased occurrence of the hidden terminal problem, deafness, neighbor discovery overhead, increased interference along aligned paths and the unheard RTS/CTS problem. This paper is concerned with the unheard RTS/CTS problem, first identified in [2], that occurs when a node does not hear an RTS or a CTS because it is beam-formed in a direction other than the one on which the RTS or CTS arrived. When a node does not hear the RTS/CTS messages, it misses potential information regarding the channel status and transmits when it should actually defer. The occurrence of this phenomenon leads to collisions and unnecessary retransmissions; in fact, our simulation studies show that the majority of all the packet retransmissions were due to the unheard RTS/CTS problem.

In this paper, we seek to mitigate the impact of this problem through a simple combination of three strategies: fragmentation of packets, the use of a tone signal to alert potential collision-causing nodes during ongoing transmission, and the use of a pause period when transmission is likely to lead to a collision. As opposed to other recent work on this problem [3], [4], our protocol does not assume separate data and control channels at each node. The rest of the paper is organized as follows: Section II provides a background of the IEEE 802.11 protocol and related work on MAC protocols for directional antennas. Section III describes the unheard RTS/CTS problem in detail. The three strategies we employ for our MAC protocol and the rationale behind them are explained in Section IV. We describe our MAC protocol that incorporates these strategies in Section V. Section VI presents simulation results and Section VII concludes the paper with a summary and comments on future work.

II. Background and Related Work

The IEEE 802.11 protocol requires nodes to perform physical carrier sensing before transmitting a packet. Nodes that have a packet to transmit sense the channel; if the channel is busy, nodes wait until the channel becomes free again. On the other hand, if the channel is found to be free for a length of time equal to or more than DIFS (Distributed Inter Frame Spacing), the node picks a value in the range $[0, \mathrm{CW}]$, where CW is the contention window, and sets a counter for the back-off timer to this value. When the counter value decrements to zero, the node transmits its packet. If there is a collision, the range of the contention window is doubled. The back-off counter is decremented only when the node does not sense any signal on the channel. This resolves channel contention but is inadequate to address the hidden terminal problem which arises when the physical sensing of transmissions that are likely to cause a collision is impossible.

The IEEE 802.11 protocol also specifies that nodes may optionally perform virtual carrier sensing, wherein a node that wishes to transmit a packet first sends a Request-to-Send (RTS) packet that includes a field for the duration of

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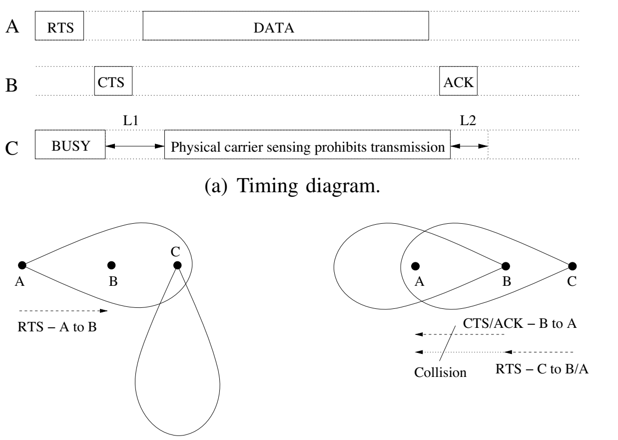
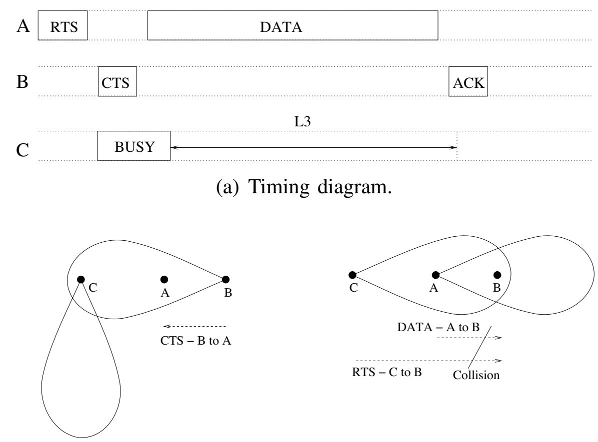


(a) Timing diagram.

(b) Node C does not hear the RTS transmitted by A to B.

(c) Node C transmits an RTS during L1 or L2 causing a collision with CTS or ACK respectively.

Fig. 1. An illustration of the Unheard RTS phenomenon.



(a) Timing diagram.

(b) Node C does not hear the CTS transmitted by B to A.

(c) Node C transmits an RTS during L3 causing a collision.

Fig. 2. An illustration of the Unheard CTS phenomenon.

the intended communication. Upon receiving the RTS, the recipient replies with a Clear-to-Send (CTS) packet that also contains the duration of communication. The data packet (henceforth identified as DATA) is sent only after the RTS/CTS exchange. All nodes in the vicinity of the sender and the receiver overhear the RTS/CTS and defer their transmissions. This is achieved with the aid of the Network Allocation Vector (NAV). The NAV on each node is updated with the duration contained in the RTS or CTS that it overhears. Before sending out the RTS, the node first checks its NAV to see if it must defer its transmission. Virtual carrier sensing serves to reserve the area covered by the transmission ranges of the transmitter and the receiver, thus solving the hidden terminal problem.

Virtual carrier sensing has been extended to networks using directional antennas with a protocol called Directional Virtual Carrier Sensing (DVCS) [5]. In DVCS, idle nodes always listen for RTS/CTS in omni-directional mode. When an RTS or a CTS is overheard in a particular direction, the node blocks transmissions on the corresponding beam. The Directional Network Allocation Vector (DNAV) maintains a list of the blocked beams and the duration for which they are blocked. A node may transmit the RTS and CTS on all beams other than the ones that have been blocked.

Many other research teams have also proposed MAC protocols for wireless networks with directional antennas. Ko *et al.* propose a MAC protocol, called Directional-MAC (D-MAC) [6], in which nodes are aware of the physical locations of each other through the use of additional hardware such as a Global Positioning Device (GPS) at each node. The authors make a conservative assumption that if a node receives from two different nodes using two different beams, there will be collisions at the receiving node. The D-MAC protocol is extended in [7] with attempts to solve several problems that occur due to assumptions made in [6]. It is shown that once a node has beam-formed using a particular beam, a packet arriving from any other direction will be dropped but will not cause a collision with the packet that is being received in the beam-formed direction.

A slightly different approach is proposed in [8] where the RTS and CTS are omni-directional to enable the transmitter and receiver to locate each other before they exchange the DATA and ACK directionally. However, this approach does not exploit the increased transmission range of directional antennas. The protocol presented in [2] is based on the DVCS strategy and proposes that all MAC layer communications be performed directionally to maximize spatial reuse.

Several interesting phenomena and new problems arise in the context of directional antennas in wireless networks [9]. To reduce the number of instances of the hidden terminal problem, some protocols transmit "busy tones" along with the DATA packets [10]. This approach requires multiple transceivers at the nodes. In Tone-DMAC [11], a separate control channel is reserved to send out tones to signal end of DATA in order to combat deafness, a common problem associated with directional communication. The Circular-DMAC protocol [12] seeks to address some of the problems arising in directional antennas by transmitting only the RTS (and not the CTS) directionally on every beam to inform neighbors of the impending communication. On the other hand, the authors of [13] suggest that both the RTS and the CTS be sent directionally on all beams to avoid all collisions. Since this involves multiple RTS and CTS packets for each transmitted data packet, both the overhead and the complexity are high.

None of the above protocols, however, attempt to eliminate or mitigate the impact of the unheard RTS/CTS problem. One can easily see that the problem is solved with the use of multiple receivers, as in [3], which allows a node to transmit directionally to another node while simultaneously listening omni-directionally for any RTS/CTS messages. Similarly, it is also easy to see that a segregation of data and control channels, as in [4], eliminates the unheard RTS/CTS problem. However, no solutions have yet been discussed in the research literature without using separate data and control channels.

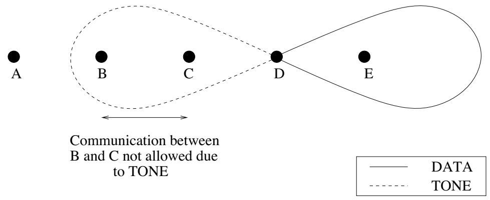


Fig. 3. An illustration of reduced spatial reuse. Note that B and C may not communicate because of the TONE transmitted by D.

III. The Unheard RTS/CTS Problem

In DVCS [5], when a node hears an RTS or a CTS not meant for itself, it defers transmission on the beam over which it heard the signal. However, if the node is listening/transmitting/receiving with another beam, it does not hear the RTS/CTS which the node would have heard had it been listening in omni-directional mode. Later when the node is ready to transmit a packet along the beam on which the unheard RTS/CTS arrived, it does not defer its transmission as it ought to do.

A. Unheard RTS

Fig. 1(a) describes the timing diagram of a scenario with three nodes that results in a collision due to an unheard RTS. Figs. 1(b) and 1(c) illustrate the transmission lobes at two instances of time in this scenario. In Fig. 1(b), node C is within the transmission range of node A. At this instant when A sends an RTS to B, C is beam-formed using some other beam, either sending to or receiving from a direction other than that of A. Node C does not update its DNAV table with the information that it should defer on the beam in the direction of A. Fig. 1(c) illustrates a later instance when B is sending a CTS to A simultaneously as C is sending an RTS to A after completion of its earlier transmission/reception in another direction. As shown in Fig. 1(c), the RTS from C will collide at A with the CTS from B.

A collision would similarly occur if at the later instance shown in Fig. 1(c), node C sends an RTS to A/B just when B is sending an ACK to A. This RTS from C will collide with the ACK from B at A. Node A assumes that the DATA it sent to B was not received satisfactorily. This triggers a retransmission of the same DATA packet from A to B, for which node A must again perform both physical and virtual carrier sensing.

B. Unheard CTS

Fig. 2(a) describes the timing diagram of another scenario with three nodes that results in a collision due to an unheard CTS. At the time instant illustrated in Fig. 2(b), node C does not hear the CTS from A intended for B because it is beam-formed in another direction. Later, as illustrated in Fig. 2(c), since node C does not have its DNAV set to defer transmissions in the direction of A/B, the DATA from A to B and the RTS from C to B collide.

IV. MAC Protocol Features to Mitigate Unheard RTS/CTS Problem

Our goal in developing a new MAC protocol is to reduce the number of instances in which a collision occurs due to the unheard RTS/CTS problem. In this section, we describe the three important features of our MAC protocol that help serve this goal:

- Fragmentation of packets into smaller chunks transmitted individually but acknowledged collectively.
- Use of a short TONE signal in between fragments to inform other nodes capable of causing collisions with the ongoing transmission.
- A *pause period* when a node has returned from directional mode to omni-directional mode and has a packet to transmit.

Our protocol, referred to in this paper as F-DMAC-TONE (for *Fragmentation-based Directional MAC with TONE*), is an extension of the IEEE 802.11 MAC protocol [1] and DVCS [5]. When a node returns from directional to omni-directional mode and wishes to transmit in a direction other than the direction it just transmitted/received on, it checks the DNAV for that direction. If this has not been set, it means one of two things: either the channel is free in that direction and the node is free to transmit or the channel is not free and the node missed the channel reservation messages. In the following, we describe each of the above three features of our protocol which together increase the probability that a node is informed of the true channel status before it initiates a transmission.

A. The Pause Period

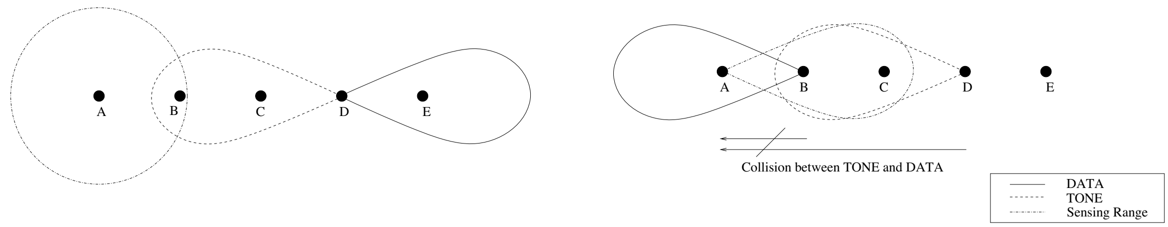
Observing the timing diagram of the unheard RTS scenario in Fig. 1(a), we see that when node C returns from directional to omni-directional mode, there is a time period of length L1 during which it is unsafe to transmit (will collide with the CTS from B) but its physical carrier sensing does not prohibit transmission. Later, when the physical carrier sensing would again permit a transmission, there is a time period of length L2 during which it is unsafe to transmit (will cause a collision with the ACK from B).

Similarly, observing the timing diagram of the unheard CTS scenario in Fig. 2(a), we see that there is a time period of length L3 during which it is unsafe to transmit (will collide with DATA from A) but its physical carrier sensing does not prohibit transmission.

It must be noted here that these unsafe durations for node C are so only because of ongoing communication between nodes A and B. As there is no way for a node to physically sense if there indeed is ongoing communication, a pause period before transmission every time that a node returns from directional mode to omni-directional mode increases the probability that the node learns of the true status of the channel before attempting transmission.

B. TONE Signals

A simple but important observation as regards collisions in our context is that they occur only when there are at least three nodes aligned approximately in a straight line. A collision at



(a) TONE from D does not reach A when A is sensing in omni-directional mode.

(b) Collision between TONE from D and DATA from B at A when A is receiving in directional mode.

Fig. 4. An illustration of the collisions due to TONE problem.

a node (say, X) can occur between the packets transmitted from two nodes if and only if the two nodes are reachable using the same beam from node X. If the two nodes are reachable from X using different beams, one of the packets will be received without error while the other will be dropped, but no collision will occur. It follows that a transmitting node can reduce the number of collisions if it can inform all nodes reachable using the beam opposite to the transmitting beam. In our protocol, we use TONEs, which are short fixed-duration signals, to alert nodes in the direction opposite to that of intended transmission. Nodes that missed the RTS/CTS messages hear the TONE which serves to confirm that there is ongoing communication.

The TONE signals do not contain any information within them. Upon hearing any signal from a particular direction, a node blocks that direction by updating the DNAV for a predetermined time duration. The purpose of the TONE is to inform the node to defer channel access for that duration. If another TONE or any other signal does not arrive within the duration set in the DNAV table, the node is free to transmit.

C. DATA Fragmentation

In the scenario depicted in Fig. 2, node C must not transmit for time L3 after it has returned from directional mode to omni-directional mode. Since node C does not know for sure if there is ongoing communication between A and B, one might argue that its pause period should be equal to L3 every time it returns from directional mode. However, such a long pause period will lead to wasted resources if there was no ongoing transmission between A and B, resulting in increased delay and degraded performance. Note that L3 is the time to transmit a DATA packet, which is too large a duration for a node to wait. Similarly, transmitting a TONE signal in the opposite direction only before and after an entire packet transmission leads to a long period (one packet transmission time) during which nodes in the opposite direction are unaware of ongoing transmission.

The rationale behind fragmentation, with a fixed-duration TONE signal used in the opposite direction of ongoing transmission in between transmissions of fragments, is that the pause period be small enough to not significantly reduce performance (the pause period need not be more than one fragment transmission time). This reduces the number of instances of collisions due to the unheard RTS/CTS problem.

V. Protocol Description

We assume a switched-beam antenna system that uses multiple radiation patterns and picks the one pattern that maximizes gain to send or receive in a particular direction. If a node is aware of the direction of the intended recipient, it sends the packet using the beam that maximizes gain in the direction of the recipient. If not, it broadcasts the packet. When a node is not sending or receiving, it is listening in omni-directional mode. A node cannot send and receive at the same time, and it cannot transmit simultaneously using different beams. Once a node has selected a beam for receiving and beam-formed in that direction, it cannot receive/listen in any other direction.

The DATA packet is fragmented in the MAC layer. The PLCP Preamble and Header are transmitted only for the first fragment and, as in IEEE 802.11, serve a number of functions including channel estimation, frequency offset estimation, clock synchronization, and automatic gain control. Subsequent fragments are preceded by a smaller per-fragment preamble of eight bits that serve to correct for any clock drift. The RTS and CTS are directional (also referred to here as DRTS and DCTS). The duration field in the DRTS and DCTS contain the sum of the transmission time of the fragments (including the protocol overhead of subsequent fragments) and the transmission time of the TONEs. Before each transmission of a fragment (except the first fragment), a TONE is transmitted in the opposite direction (opposite to the direction of RTS and the fragments). The receiver acknowledgment is through one ACK per packet at the end of the receipt of the last fragment of the packet. The ACK is sent only if all the fragments are received without errors. If the transmitting node does not receive the ACK by the predetermined timeout duration, all the fragments need to be retransmitted. For a two-fragment DATA packet, the sequence of signals that are transmitted is DRTS-DCTS-DATAFRAG1-TONE-DATAFRAG2-ACK. Given that there is only one ACK for the entire packet, our protocol, in this sense, differs from the conventional fragmentation specified in IEEE 802.11.

There exists a trade-off between the power level of the TONEs and the performance achieved due to the use of TONE signals. TONEs of power equal to that of other signals (DATA, ACK, etc.) lead to a deterioration in performance due to reduced spatial reuse and collisions between TONE and other signals.

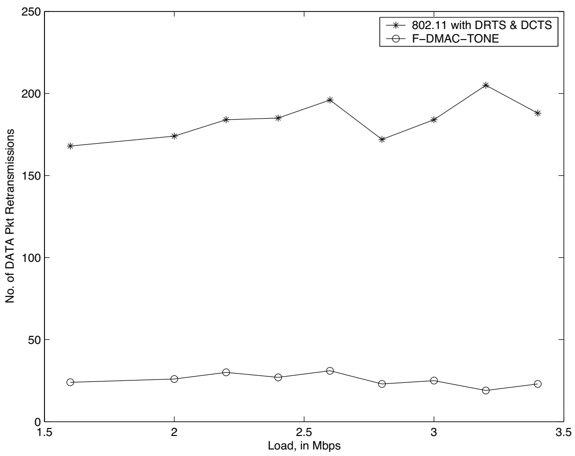


Fig. 5. Number of DATA packet retransmissions due to the unheard RTS/CTS problem.

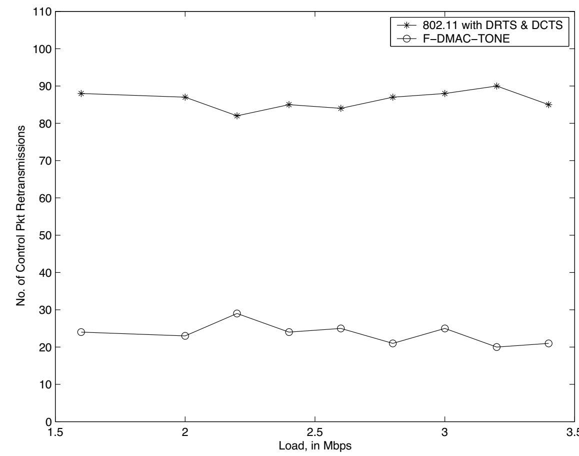


Fig. 6. Number of control packet retransmissions due to the unheard RTS/CTS problem.

Consider the scenario in Fig. 3 in which D sends DATA to E and the TONEs used are of the same power as other signals. As per our protocol, D sends out the TONE in the direction of C before the transmission of each fragment except the first one. Since the TONE has same power as all other signals, it reaches not just C but also B. Node B, upon receiving the TONE, sets its DNAV to block transmissions in that direction. Thus, B-C communication is unnecessarily disallowed due to the presence of the TONE, reducing spatial reuse.

Fig. 4 illustrates the problem of TONEs themselves causing collisions with other signals. The TONE sent by node D also reaches A at lower power. This does not prevent A from initiating communication with B, or responding with a CTS if B initiates communication to A. However, when A beamforms towards B to receive B's signal, it also receives the TONE (from D) at higher power. At A, the TONE collides with the signal from B to A.

Our MAC protocol uses TONEs at a lower power than the rest of the signals in order to solve the above two problems. Based on a simulation study of the trade-offs between the power of TONEs and performance, the power level of the TONE in our protocol is such that the transmission range of the directional TONE is no more than the maximum distance at which reception of omni-directional signals is possible.

The pause period for best performance is equal to the transmission time of a fragment but it is not obvious what the fragment size should be. A smaller fragment size allows a smaller pause period and a larger fragment size leads to a larger pause period causing greater delays due to nodes waiting unnecessarily even when there are no ongoing communications. Based on extensive simulation results and analytical reasoning, we have found that the ideal length of the pause period is the transmission time of one CTS packet (each CTS packet is of length 14 bytes). This result can also be understood with the aid of the scenario in Fig. 1. Node C may return to omni-directional mode immediately after transmission of RTS from A. Now, C must wait at least until the transmission of CTS from B to A is complete. If not, a collision results between the RTS from C and the CTS from B. Upon completion of the CTS transmission from B, C need not use the pause period feature to wait because it receives the DATA packet being sent from A to B and hence cannot transmit due to physical carrier sensing. It follows from this observation that the pause time must be at least the duration of the CTS, as anything less than this value does not serve its purpose. In general, larger pause periods lead to poorer performance because of the unnecessary extra wait in case there is no ongoing communication.

VI. Simulation Results

Our F-DMAC-TONE protocol was evaluated by a simulation study performed using Qualnet version 3.7, an event driven simulator [14]. The simulation was performed for a 25-node mesh topology. UDP is used as the underlying transport protocol and DSR is used as the routing protocol [15]. The packet size is set to a constant 512 bytes but the inter-arrival rate of the packets is varied. We assume a switched beam antenna pattern with eight main beams and no side lobes (in order to isolate problems specific to directionality and avoid the physical layer effects caused by the presence of side lobes).

F-DMAC-TONE was compared with the IEEE 802.11 protocol using Directional-RTS, Directional-CTS and DVCS [1], [5]. In our study, F-DMAC-TONE reduced the number of instances of the unheard RTS/CTS problem by 80%. The number of retransmissions of DATA packets due to this problem alone reduced by as much as 86% and the number of retransmissions of control packets (RTS/CTS) reduced by as much as 66% (as shown in Figs. 5 and 6).

The improvement using F-DMAC-TONE in terms of throughput and delay is less dramatic, though not insignificant. As shown in Figs. 7 and 8, F-DMAC-TONE achieves a 4% improvement in throughput and a 5% improvement in delay. These improvements are reasonable considering that the percentage of total packets transmitted that undergo retransmissions due to the unheard RTS/CTS problem is 2.5%. In fact, all of the DATA packet collisions in our simulation study

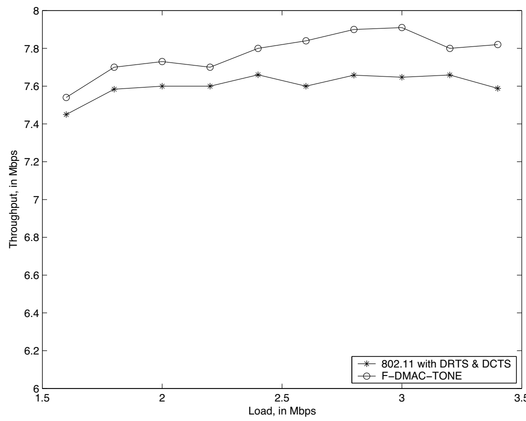


Fig. 7. Simulation results illustrating the improvement in throughput offered by F-DMAC-TONE.

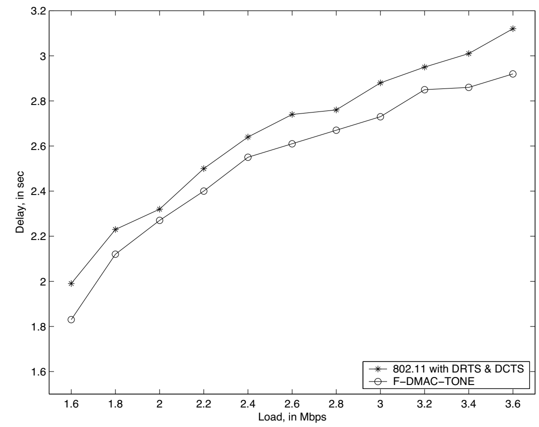


Fig. 8. Simulation results illustrating the improved delay characteristics of F-DMAC-TONE.

occurred due to the unheard RTS/CTS problem. In addition to this, about half these retransmissions were unnecessary and occurred due to a collision involving an ACK packet in response to the successful reception of the DATA packet. Further, the increase in the duration of the transmission of DATA packets (due to the greater number of control bits introduced by fragmentation) causes a marginal increase in the problem of deafness.

VII. Concluding Remarks

In this paper, we present a detailed overview of the unheard RTS/CTS problem and describe its effects within the context of a wireless network equipped with switched beam antennas. We propose a combination of three strategies to combat the problem: fragmentation, the use of tone signals, and the use of pause periods to avoid potential collisions. The F-DMAC-TONE protocol based on these strategies achieves an improvement in throughput and delay without requiring separate data and control channels at each node. Simulation results show a significant reduction in the number of instances of retransmissions due to the unheard RTS/CTS problem.

The protocol proposed here, however, does entail some increased complexity and calls for future work toward a more complete and analytical assessment of the trade-offs between complexity and the gain in performance. In this preliminary study, we have also observed that solutions to different problems sometimes work against each other (e.g., the solution to the unheard RTS/CTS problem with an increased number of overhead bits transmitted for each data packet also increases the problem of deafness). In our future work, we propose to integrate various solutions advanced for each of the several problems encountered in such networks based on a careful assessment of the relative frequency of the problems in realistic scenarios and the trade-offs involved therein.

VIII. Acknowledgments

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