# Handling Asymmetry in Gain in Directional Antenna Equipped Ad Hoc Networks

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*Abstract* – **The deployment of traditional higher layer protocols (especially the IEEE 802.11 MAC protocol at the MAC layer) with directional antennae could lead to problems from an increased number of collisions; this effect is primarily seen due to three specific effects: (i) an increase in the number of hidden terminals; (ii) the problem of deafness and, (iii) a difficulty in determining the locations of neighbors. In this work we propose a new MAC protocol that incorporates *circular* RTS and CTS transmissions. We show that the circular transmission of the control messages helps avoid collisions of both DATA and ACK packets from hidden terminals. Our protocol intelligently determines the directions in which the control messages ought to be transmitted so as to eliminate redundant transmissions in any given direction. We perform extensive simulations and analyze the obtained results in order to compare our scheme with previously proposed protocols that have been proposed for use in directional antenna equipped ad hoc networks. Our simulation results clearly demonstrate the benefits of incorporating both circular RTS and CTS messages in terms of the achieved aggregate throughput.**

## I. INTRODUCTION

The usage of directional antennae permits spatial reuse and potentially, multiple interference-free transmissions can take place within the radial range of a communicating node. Moreover, by forcing the overall radiated energy to be focused in a specific direction, the coverage range in the particular direction is increased. Thus, nodes are then able to communicate with *new* neighbor nodes that are beyond the omni-directional radial range. However, the deployment of directional antennae creates some new problems. To be specific these problems are (a) an increase in the number of hidden terminals (b) causing node deafness and (c) making the determination of neighbor locations[1] more difficult [1]. The last problem is effectively solved in [1], while the first two problems are studied and solutions proposed in [2]. The previously proposed protocol in [1] advocated the circular transmission of RTS messages in order to alleviate the aforementioned problems. However, the directional transmission of the CTS message, as suggested in [1], could still leave a communication vulnerable to the first two effects. In this paper, we argue that *a combination of circular transmissions* of the RTS and CTS messages can in fact increase the robustness of medium access control to the aforementioned effects and can increase the achieved network throughput beyond that achieved by the previously proposed protocol in [1]. Towards this, we perform extensive simulations and performance evaluations (both microscopic investigations to demonstrate particular effects and macroscopic studies to enumerate large scale effects) and demonstrate the benefits of our proposed scheme.

The rest of this paper is organized as follows. We point out related efforts on MAC protocols for use with directional antennas and discuss their limitations in section II. In section III we briefly describe the main characteristics of directional antennae and the problems introduced due to their use. Our proposed protocol is presented in section IV. Section V contains our simulation results and comparisons with the scheme from [1]. Finally, section VI concludes the paper.

## II. RELATED WORK

Although the use of directional antennae has received attention fairly recently, there are a number of interesting studies on designing a suitable MAC protocol to try to address the above problems [1], [3], [4], [5], [6]. Due to space limitations we will not discuss each one of them. However, we point out that most of these schemes do not solve the problems that were listed in the previous section, completely. Except for the work in [1] the rest of the studies propose protocols that do not deal effectively with the problem of hidden nodes due to asymmetry in gain; they do not incorporate any functionality to inform a

* This work is supported in part by, the U. S. Army Research Office under the Multi-University Research Initiative (MURI) grant # W911NF-04-1-0224 and in part by NSF CAREER grant from ANI No: 0237920.

[1] We discuss these problems in brief. Details may be found in [1] and are omitted due to space limitations.

sender's and/or receiver's directional neighbors (the neighbors that are beyond the omni-directional radial range) of the intended transmission. All of these studies assume at least one omni-directional or directional control packet transmission or reception. This assumption causes the communication to be *hidden* from the directional neighbors of the sender or the receiver (or both). If this is an RTS frame, the DATA packet is vulnerable to collisions due to a packet that may be potentially transmitted by a hidden node. If on the other hand if the CTS frame is omni-directionally or directionally transmitted, the corresponding ACK packet is vulnerable to collisions. Hence, keeping our objective of informing as many neighbors as possible for an intended data transfer in perspective, we propose that both the RTS and CTS frames be transmitted circularly.

## III. PRELIMINARIES

A directional antenna consists of a fixed number of elements often referred to as an array of antenna elements. Each element is assumed to focus the available signal power in a specific direction, thereby increasing the signal strength in that direction. The shape of the directional footprint is assumed to be conical with the apex pointed in the desired direction. We assume that if we have M elements, we can provide effective omni-directional transmission with M sequential directional transmissions (Fig. 1). When idle, every node receives omni-directionally; however, when receiving a signal, it uses the array element that provides the strongest reception of the received signal. In our work we assume antennae with a predefined number of beams i.e., switched beam antennae [6].

The problem of hidden terminals appears because of both the asymmetry in gain and *unheard* RTS/CTS control frames. As pointed out earlier, omni-directional transmissions may not reach nodes that are beyond the omni-directional radial range but are within the extended directional range. Thus, these nodes may be rendered hidden if omni-directional transmissions are deployed. The drawback of *deafness* is apparent when directional antennae are deployed. Deafness refers to a case wherein a neighbor of a node (say A), unaware of node A being in directional communication with another neighbor, attempts to communicate with node A by sending RTS messages. However node A, being directionally oriented, fails to hear the RTS message. This leads to the neighbor assuming that the link to A has failed [2]. Besides the previous problems, wireless stations when using directional antennae, are required to *track* the location of their neighbors. Detailed discussions on all of these problems are found in [1] and are omitted due to space constraints.

## IV. PROTOCOL DESCRIPTION

To fully exploit the advantages of directional antennae, nodes should transmit all of their frames directionally. However, mechanisms are needed to deal with the aforementioned problems. We propose the CRCM (*Circular RTS* and *CTS MAC*) protocol. It is designed with an objective of addressing all of the above problems and is based on the IEEE 802.11 MAC; however, it uses exclusively directional transmissions and precludes omni-directional transmissions. The schemes support functionalities to inform a node's neighbors of its intended communications.

The design of our protocol first requires that the RTS message be transmitted directionally and circularly, until it spans the area around the transmitter. The node initiates the circular transmission by sending the RTS message in a predefined direction (say with beam 1 as in fig. 1).

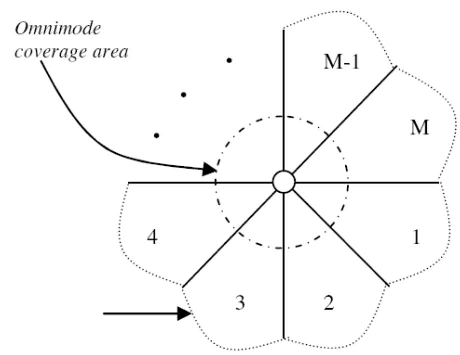


Fig. 1: The circular directional transmission

Subsequently, it shifts to the beam on the right and sends the same RTS message with beam 2 and so on. Finally, the sequential transmissions *circularly cover* the entire area around the transmitter. This procedure is depicted in fig.1. The RTS contains the duration of the 4-way handshake (IEEE 802.11) and informs the transmitter's neighbors about the impending data transmission. Neighbors that hear the RTS message execute an algorithm to decide on whether or not they are required to preclude transmissions in the direction of the sender-receiver pair, so as not to harm the ongoing communication. This procedure is similar to that proposed in [1]. In [1] however, at the end of the circular RTS transmission, the sender waits in omni-directional mode for the CTS frame from the receiver. It then uses the same beam to send the CTS message, directionally. Consequently, not all of the receiver's neighbors are made aware of the impending DATA and ACK transmissions. As a result, the scheme in [1] does not protect the ongoing communication from possible hidden terminals in receiver's neighborhood. In particular, these nodes can initiate transmissions that can cause a collision during the ACK reception at the transmitter. To deal with this problem CRCM uses an efficient mechanism for the directional transmission of CTS, in order to inform the receiver's neighbors about the intending transmission.

With CRCM, the receiver after sending the directional CTS towards the transmitter will transmit directional CTS messages towards what we refer to as *unaware* *neighboring nodes*. Unaware neighboring nodes are those nodes that are in the coverage range of the receiver but not in that of the transmitter. In fig. 2 we depict how CRCM notifies all the nodes that potentially can interfere with the transmission between A and B. Note here that CRCM avoids the transmission of the CTS in those directions that are already covered by the circular RTS message. In particular, the CTS message is transmitted in a *semi-circular range* (fig. 2) that is *maximally disjoint* from the direction in which the RTS message was received.

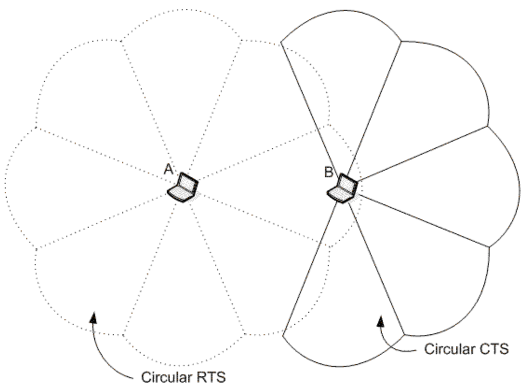


Fig. 2: The space coverage of CRCM

If the RTS and CTS control frames are exchanged during a predefined time period, the DATA and ACK directional packet transmissions take place, as per the IEEE 802.11 MAC rules. The receiver's neighbors execute the same algorithm, as did the transmitter's neighbors in order to decide on whether or not to defer transmissions towards the sender-receiver pair[2].

Except for the discovery mechanism, we provide a scheme for location tracking and maintenance, which further helps alleviate interference from hidden stations.

Stations maintain a *location table* with a record for each neighbor. In each record, the node stores its node-ID, the beam from which it heard the neighbor's packet, that neighbor's ID, and the beam that the neighbor used to send the packet towards itself. For example in table 1, node A has a record for node B, where it stores information to reflect that A can reach B using beam 4 (its own beam), while B can reach A using beam 2 (B's beam).

The table is continuously updated upon overhearing any transmission.

TABLE I

| Me | Neighbor | My beam | Neighbor's beam |
|---|---|---|---|
| A | B | 4 | 2 |

In every packet, the transmitter includes a identification number that corresponds to the beam that was used to send that packet. Thus, the receiver of that packet may update its relative record for that transmitter. This information is also contained in the RTS-CTS control frames. Even though this mechanism is not needed for location tracking (since nodes use selection diversity) it is useful when neighbors have to decide on whether or not to defer their intended transmissions towards a specific direction. Every neighbor, that receives one of the circularly transmitted RTS/CTS frames, examines its Directional Network Allocation Vector (*D-NAV*) to identify those beams via which, if transmissions are initiated, will interfere with the currently announced communication. If any such beam is identified, the node will defer transmissions on that beam for the duration specified in the control message [1]. The D-NAV, maintained by every terminal, uses a table to keep track of the directions and the corresponding durations for which the directions are to be avoided.

Consider the scenario depicted in fig. 3. In this example, there is a directional ongoing communication between nodes A and B.

TABLE II

| Me | Neighbor | My beam | Neighbor's beam |
|---|---|---|---|
| C | B | 4 | 2 |
| C | A | 2 | 4 |

Node A sends packets to node B using beam 4, while node B uses beam 2 to send packets to A. In their control frames, nodes A and B include this "beam information". Node C, upon receiving the control frames, is made aware of this information. It then checks its D-NAV and finds out that it can "see" nodes A and B using beams 2 and 4. The records in the D-NAV table are shown in table 2. Thus, now, node C knows that it must not initiate a transmission using either beam 2 or beam 4, for the duration specified in the RTS/CTS messages, since if such a transmission is initiated it would cause a collision. Correspondingly, node C will defer any intended transmissions using beams 2 and 4 for the specified duration.

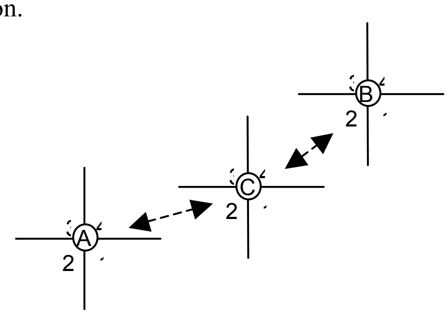


Fig. 3: An example scenario where A and B communicate

We mention here that the circular RTS and CTS respect ongoing transmissions; if a station's D-NAV does not allow RTS transmissions toward certain directions, the station will not transmit the RTS (while performing circular transmissions) in those directions. For each such forbidden direction, it simply omits transmission in the

[2] We describe this algorithm later.

particular direction and transmits the RTS in the next possible sequential direction.

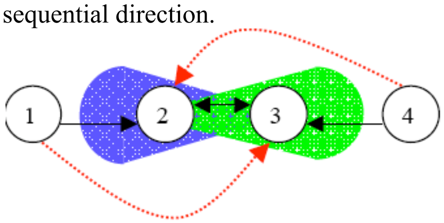


Fig. 4: The scenario 1

## V. Performance Evaluation

Our simulations are performed in OPNET, version 10.0. We chose the specific tool because it offers very good support for simulating directional antennas. The antenna editor tool of OPNET supports the creation of arbitrary 3-D gain patterns. The main beam can be aimed at any arbitrary point in three-dimensional space and the energy received at every node is computed automatically by OPNET kernel procedures.

The destination of a packet generated at station *i* is chosen randomly from the set of the node *i*'s neighbors. The packet size is 1024 bytes and the data rate is 2 Mbps.

Every simulation is run for 200 seconds with a warm up period of 50 seconds. We use the aggregate network throughput, which is defined as the fraction of the channel bandwidth that carries successful data transmissions, as our metric of interest in our performance evaluations. In our simulations, we use nodes that are equipped with antenna arrays of 4 elements. When a simulation is started, the *Location Table* of each station is empty; it is gradually updated, as the simulation makes progress. We compare the performance of CRCM with the circular RTS or CRTS scheme proposed in [1] to see whether our intuition for improving [1] can be verified by experiment.

### V.1. Scenario 1

For our first set of simulation tests we choose the scenario depicted in fig. 4. This scenario demonstrates the benefits of the CRCM scheme as compared with the CRTS scheme in [1]. The alignment of the four nodes along a line as shown can be especially harmful to the CRTS scheme. As depicted in fig. 4, stations 2 and 3 exchange packets. On the other hand station 1 sends packets to the station 2 exclusively and similarly, station 4 sends packets to station 3. When station 2 wants to send a data packet to 3, with the CRTS scheme in [1], it sends an RTS message, circularly; however, that message is not be received by station 4 since this station is currently idle and hence in the omni-directional mode. Station 3 will respond with a directional CTS message towards station 2. Subsequently, station 2 begins the transmission of its data packet. Since the handshake between stations 2 and 3 does not provide station 4 with any information with regards to the impending communication, station 4 decides to start a transmission while station 3 is in the process of transmitting its ACK to 2. The RTS message from station 4 and the ACK message from station 3 would then collide at station 2. If station 4 were to know about the ongoing transmission between stations 2 and 3, the above situation could have been avoided.

This is exactly what is achieved by the circular CTS messages. In this case station 4 will hear the CTS sent circularly by station 3. Thus, it would defer its transmission until the communication between stations 2 and 3 is completed. Thus, the overall throughput in the scenario considered is improved. The results from our simulations, shown in fig.5, are in support of our argument. We observe a gain in throughput by as much as 35 % at high loads.

For the next set of simulation experiments we choose a grid topology with 25 stations. The destination of a packet generated at any station is chosen randomly from the set of the station's neighbors. Using the grid topology, we expect nodes to experience the hidden terminal problem, as a node cannot hear all the transmissions. The results of the simulations in terms of throughput are depicted in fig.6.

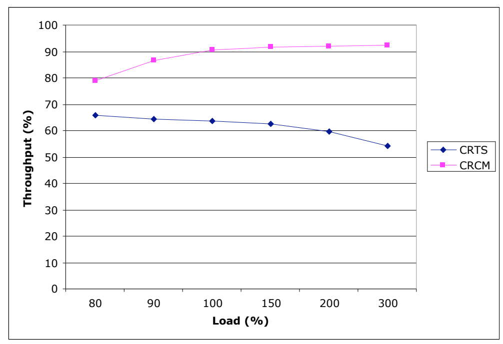


Fig 5: Comparison of CRCM with CRTS for scenario 1

### V.2. Scenario 2

As seen from the results, when the offered load is high, the circular CTS, significantly improves the performance in terms of the achieved throughput (by approximately 22 %). This is due to the fact that, for the CRTS, as the load increases, the probability of having a hidden node transmitting such that the transmission collides with an ACK increases.

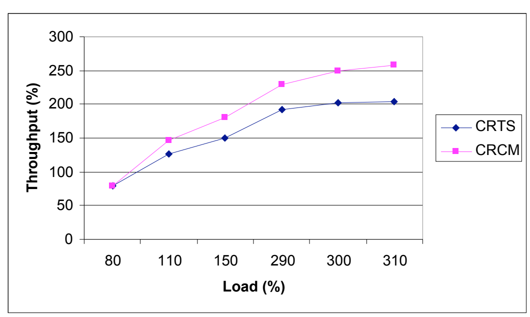


Fig. 6: Comparison of CRCM with CRTS for scenario 2

However, with the circular CTS these effects are practically eliminated. Note that both the protocols achieve a throughput that is higher than 100%. This is a direct consequence of the spatial reuse possible due to the use of directional antennae. The spatial re-use allows more than two pairs of nodes that are in the geographical vicinity of each other, to communicate simultaneously using the same channel.

### V.3. Scenario 3

In this scenario we measure the performance of the two protocols with random topologies that consists of 60 nodes. We assume that the nodes are located in a 1250X1250 $m^2$ square area. The omni-directional coverage range of each node is 250 meters. The results are depicted in fig.7. As evident, even in scenarios that are randomly generated, there's an improvement in the achieved throughput when circular CTS is employed. The improvement increases with the load for the same reasons as those with the previous scenario, i.e., the probability of collisions due to asymmetry in gain increases with the channel traffic if only the circular RTS is employed.

Finally, we study the effects of mobility on the proposed scheme. We again consider the scenario 3. We examine cases with both low as well as high mobility for the nodes. With low mobility nodes are assumed to move with speeds of 2 meters/sec whereas with high mobility they move at 10 meters/sec. In fig. 8 we show the results of the experiments with the static and mobile deployments with CRCM.

As seen from the results, there is a slight decrease in the throughput (approximately 8% for the case of the low mobility and 14% in case of high mobility) with mobility. When nodes are mobile, there is a possibility that one of the nodes that participates in a data transmission (either as transmitter or receiver) moves outside the directional range of the other. Thus, the packet under transmission is lost. We observe that this phenomenon causes the degradation in throughput. However, the modest levels of degradation demonstrate the viability of our protocol even in highly mobile scenarios.

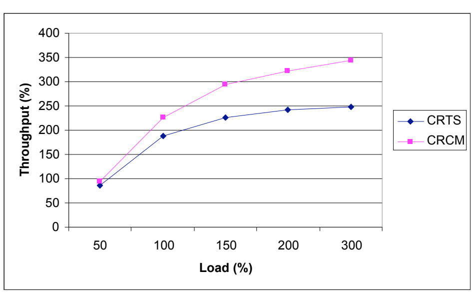


Fig. 7: Comparison between CRTS and CRCM for scenario 3

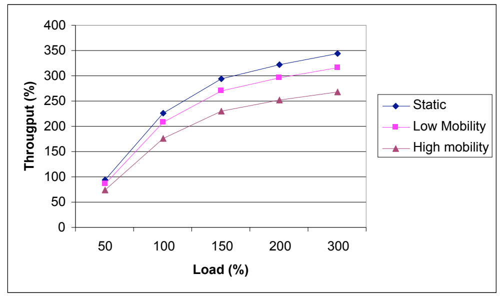


Fig. 8: The effect of mobility in CRCM

## VI. CONCLUSIONS

In this work we propose a complete approach that solves the hidden terminal problem due to asymmetry in gain, arising due to the deployment of directional antennas in ad hoc networks. We propose the transmission of both the RTS and the CTS message in a circular fashion so as to inform potential hidden nodes of impending communications. Our scheme (which we call CRCM) ensures that the circular control messages overlap minimally to ensure the elimination of redundant transmissions in common directions. We perform extensive simulations on specific simple topologies as well as random topologies with both static and mobile scenarios to evaluate the benefits of our proposed scheme. The simulation results demonstrate that our protocol is very efficient in dealing with the problem; the benefits are especially evident when the channel traffic is high. CRCM outperforms the previously proposed CRTS scheme in all the considered scenarios.

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