A Busy-Tone based MAC Scheme for Wireless Ad Hoc Networks using Directional Antennas

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***Abstract*— Applying directional antennas in wireless ad hoc networks offers numerous benefits, such as extended communication range, increased spatial reuse, improved capacity and suppressed interference. However, directional antennas can cause new location-dependent carrier sensing problems, such as new hidden terminal and deafness problems, which can cause severe penalties to the performance. Recently, a few schemes have been proposed to tackle these problems. However, these methods can provide limited solutions on the hidden terminal and deafness problems. We propose a new MAC protocol, termed the busy-tone based directional medium access control (BT-DMAC) protocol. When the transmission is in progress, the sender and the receiver will turn on their omnidirectional busy tones to protect the transmission. By combining with directional network allocation vector (DNAV), the scheme almost mitigates the hidden and the deafness problems completely. The mechanism increases the probability of successful data transmission and consequently improves the network throughput. This paper describes the BT-DMAC scheme and analyzes its performance. The simulation results also demonstrate the effectiveness of the protocol.**

I. Introduction

Directional antennas have numerous benefits, such as longer transmission range, reduced interference and increased spatial reuse. However, utilizing directional antennas in wireless ad hoc networks is still limited due to inherent constraints, such as physical size and device complexity. Besides, new location dependent carrier sensing problems, such as hidden terminals and deafness, also prevent directional antennas from being widely deployed.

The first kind of hidden terminal problems originates in asymmetry in gain. A transmitter in directional mode and a receiver in omnidirectional mode may be out of each other's range, but they may reach each other if they both transmit and receive directionally. This kind of hidden terminals arises due to different gains with omnidirectional and directional modes of directional antennas. As depicted in Fig. 1, node B transmit a Directional RTS (DRTS) to node C. Then, C will reply with a Directional CTS (DCTS). Node A is far enough from node C and listens omnidirectionally. Node A can not hear the DCTS from C since an omnidirectional gain G_o is smaller than a directional gain G_d. Then nodes B and C begin data transmission by pointing their beams to each other with the gain G_d. When the transmission between B and C is in progress, node A wants to communicate with node D. Node A senses the channel toward node D and finds that the channel is idle. Subsequently, it sends a DRTS to node D. Since node C is in directional receiving mode with a gain G_d, it is very possible that the DRTS from A interferes with node C.

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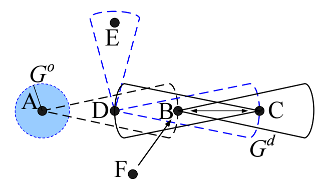


Fig. 1. Hidden terminals and deafness

The second kind of hidden terminals arises due to unheard DRTS or DCTS control frames. In the second scenario (Fig. 1), while node D is communicating with node E, node B sends a RTS to node C. At this time, node C's DCTS can reach node D, however D cannot hear it since D is beamformed in the direction of E. When the communication between nodes B and C is in progress, assume that node D finishes transmitting to E and has a data frame for node B. Since the direction to node B is free, node D begins to send a DRTS to node B, and it will lead to a collision with B's transmission.

Another drawback of directional beamforming is the deafness problem [1] [2]. Briefly, the deafness is caused when a transmitter fails to communicate with its intended receiver, when the receiver is beamformed toward a direction away from the transmitter. In Fig. 1, node F wants to transmit data to node C, using the route through node B. When B gets a packet from F, it beamforms in the direction of C and forwards the packet. At this time, F is unaware of the transmission between B and C since it does not hear the communication of B and C. If F initiates the next packet to B, it will not receive the CTS reply from B since B is beamformed to C. Node F retransmits the RTS as there is no response from B. This process will go on until the RTS retry limit has been reached. The excessive retransmission of RTS packets will give a severe penalty on the network performance. Since F would increase its backoff interval on each attempt, this can result in unfairness as well.

Several schemes attempted to tackle the directional hidden terminal and deafness problems [2]–[4]. However, to the best of our knowledge, there is no protocol that solves the hidden terminal and deafness problems completely. The other contributions of this paper are listed below:

- We present a novel MAC protocol, Busy-Tone based Directional MAC (BT-DMAC) to attack the hidden terminal and deafness problems.
- We have analyzed the performance of BT-DMAC and the numerical results demonstrate its effectiveness.
- We have also conducted simulation experiments. Our results show that BT-DMAC can achieve higher spatial reuse as compared with the existing schemes.

The rest of the paper is organized as follows. The related work is presented in Section II. Then we describe the BT-DMAC protocol in Section III. The performance evaluation of the scheme is given in Section IV. Finally, we summarize the paper in Section V.

II. Related work

Many researchers have proposed new MAC schemes for directional antennas [1]–[12]. Most of them are based on the distributed coordination function (DCF) of IEEE 802.11, which typically uses RTS/CTS frames to prevent interferences. However, these mechanisms can not prevent the the hidden terminals and the deafness problems [1] [2]. These problems have major impacts on the network performance.

Several protocols attempted to tackle the hidden terminal and deafness problems. Dual Busy Tone Multiple Access (DBTMA) [13] uses transmitting and receiving busy tones to avoid omnidirectional hidden terminals and exposed terminals. Huang et al. [8] have extended DBTMA to directional antennas. However, these two protocols have solved neither the directional hidden terminal nor the deafness problem. Circular-DMAC [3] attempts to tackle both hidden terminal and deafness problems by sending a number of directional RTS/CTS frames before transmitting data. However, transmitting multiple RTS/CTS frames for each data packet will severely degrade the performance. Choudhury et al. [2] propose a tone-based DMAC which allows neighbors of a node to classify congestion from deafness and react properly. However, this scheme cannot prevent retransmitting RTS frames from other nodes. Besides, this protocol does nothing to hidden terminals.

We propose a Busy-Tone based Directional MAC protocol (BT-DMAC) to address these problems. While the transmitter and receiver are communicating, they will turn on their busy tones to prevent possible collisions. Combining the mechanism with DNAV scheme can mitigate the hidden terminal and deafness problems almost completely.

III. Proposed Protocol

A. Antenna Model

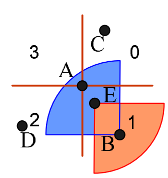
Each node has two interfaces: one is equipped with a switched beam antenna and another one is attached with an omnidirectional antenna. The switched beam antenna has two modes: *omnidirectional* mode and *directional* mode. When a node is in idle state, it will listen omnidirectionally due to the unknown arrival direction of a signal. When the direction of a signal is determined, the node will record the beam which has the maximum gain of the signal. Then the antenna will switch to that direction to receive. The directional mode will be used to transmit or receive RTS, CTS, data and ACK frames.

Since the maximum transmission range is lengthened with increased antenna gains at the transmitter and the receiver, directional antennas offer a longer transmission range due to higher antenna gains over omnidirectional antennas. When both nodes are in omnidirectional modes, the maximum communication range is O-O range (R_{oo}). When one node is in omnidirectional mode, and another node transmits or receives directionally, the range is D-O range (R_{do}), where $R_{do} > R_{oo}$. If both nodes transmit and receive directionally, the maximum communication range can be extended to D-D range (R_{dd}), which is greater than R_{do} and R_{oo}. However, since a receiver does not know where is the exact transmitter in advance, it can receive RTS only in omnidirectional mode. Hence, the effective communication range is bounded by R_{do}.

The omnidirectional antenna is only used to send busy tones. In order to cover the range of directional transmission, the transmitting power of the antenna is increased suitably. Since an omnidirectional antenna is only for sending tones, it can be easily implemented in wireless stations with low cost.

B. Neighbors Discovery

One of the hardest problems with directional antennas is to find the directions of neighbors of a node, or *neighbor discovery*. A node needs to determine where and when to point the beam to transmit or receive. In this paper, we propose a neighbor discovery scheme. Each node listens omnidirectionally when it is in the idle mode. If the node hears any frames, no matter whether the frames are intended for the node or not, it will recognize the direction of such frames and record the number of the beam as well as the identifier of its neighbor into a table, denoted by *Neighbor Location Table* (NLT).



The NLT of Node A

beam No.	neighbors	duration	available
0	C	Yes	-
1	B, E	No	10(ms)
2	D	Yes	-
3	-	Yes	-

Fig. 2. An example of the Neighbor Location Table

Previous studies [7] and [1] proposed Directional Network Allocation Vector (DNAV), which excludes the potentially collided directions and sets the corresponding durations, toward which the node is not allowed to transmit in order to avoid collisions. We integrate DNAV mechanisms with NLTs. When a node receives a RTS frame and the receipt address matches its address, it beamforms toward the transmitter and replies the RTS with a CTS frame. If the control frames are not for itself, it will update the sender's information in its NLT and set the corresponding DNAVs. Fig. 2 shows that node A has a four-beam antenna and its neighbors, C, B, D and E located in beam 0, 1 and 2 respectively. Node A stores its neighbors' location information into the NLT. When node B communicates with node E, node A will modify the corresponding entries in its NLT by reading DNAVs from the RTS/CTS frames.

C. The BT-DMAC Protocol

In the BT-DMAC protocol, two busy tones are implemented with enough spectral separation on a single shared channel. When the transmission is in progress, the transmitter and the receiver turn on the transmitting busy tone BT_t and the receiving busy tone BT_r, respectively. Each BT_t comprises two sub-tones, an ID tone and a beam number tone for the transmitting node. Each BT_r consists of two sub-tones, an ID tone and a beam number tone for the receiving node. To encode several-bit information into the sine wave, we use Pulse Modulation, which represents signals by turning the sine wave on and off. Any node hearing the busy tones learns node IDs and beam numbers from the tones and deduces whether the potential sending will interfere with the current transmission. Any attempts that may cause potential collisions are prevented.

If a node has data to send, it will search the NLT to find the beam for the destination and check the beam availability in the DNAVs. If no busy tone exists, the node will send a RTS immediately. If a busy tone is sensed, the node will identify the corresponding node ID and the beam number from the tone. If the ID matches the destination's, it is obvious that the destination is busy now and the attempt will be deferred. Else if they match, the sender will compare the beam number with that one for the destination in its NLT. If the beam number is identical, the node will defer its transmission to avoid collisions. The receiver and the transmitter will turn on the busy tones until the ACK frame is received.

Fig. 3 depicts the finite state machine (FSM) of BT-DMAC. In BT-DMAC, a node is in one of the following states: IDLE, WF_CTS, S_DATA and WF_DATA. When a node has no data to send and has not received any requests, it will stay in the IDLE state. If it has data to send, it will sense the medium first. If the channel for the destination direction is free, it will send a RTS to the destination and enter the WF_CTS state. Otherwise, it will keep in the IDLE state. If the sender in the WF_CTS state receives CTS from the receiver, it will turn on its BT_t and begin to transmit. If there is no CTS received before the timer expires, it will go back to the IDLE state. If the sender gets ACK correctly, it will turn off its BT_t and go back to the IDLE state. However, if ACK cannot reach the sender before the timer expires, the sender will retransmit the data and increase the retry counter until it reaches the maximum value. When a node in IDLE state hears a RTS, it will point its beam toward the sender's direction and send a CTS, then turn on its BT_r and enter into WF_DATA state. If the data frame is correctly received, the receiver will reply the sender with an ACK and turn off its BT_r.

The BT-DMAC protocol can be illustrated by an example, shown in Fig. 4. Nodes, A, B, C, D, E and F are equipped with four-beam antennas. When node A has data for node B, it will communicate with node B by using Beam 0. If Beam 0 is free, node A sends a DRTS frame to node B, and then goes into the WF_CTS state. After receiving the RTS, node B replies with a CTS by using Beam 2. Then it will turn on $BT_r(B, 2)$. After receiving the CTS from node B, node A turns on its $BT_t(A, 0)$

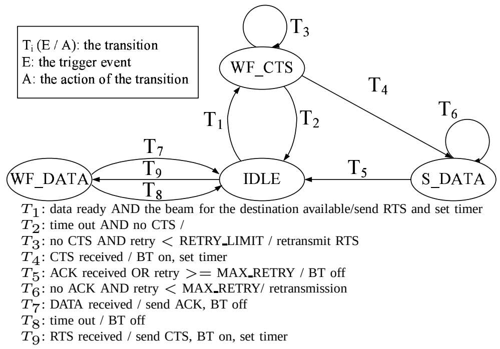


Fig. 3. The Finite State Machine of BT-DMAC

and begins to send data and goes into the S_DATA state. Upon receiving the data frame successfully, node B replies with an ACK and turns off the BT_r, entering the IDLE state. If node B does not receive data frames before the timer expires, it turns off the BT_r and enters the IDLE state. If node A receives the ACK frame successfully, it turns off its BT_t and goes into the IDLE state. Otherwise, it will retransmit the data frames until the maximum number of retries reaches. In this scenario, node C within the busy tone range of node B has data to send to B. Since it senses the $BT_r(B, 2)$ from node B, it will defer its transmission to avoid collisions. If node D within the BT ranges of node A and B wants to communicate with node E, it detects the channel first. When it senses the $BT_t(A, 0)$ from node A, it decodes the beam number (0) from the tone and deduces that its transmission will cause collisions with nodes A and B. Thus, node D will defer its transmission.

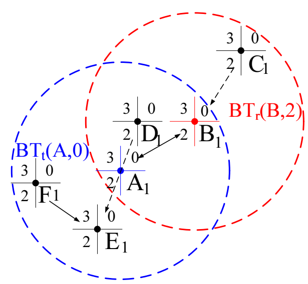


Fig. 4. a scenario illustrates the operation of BT-DMAC

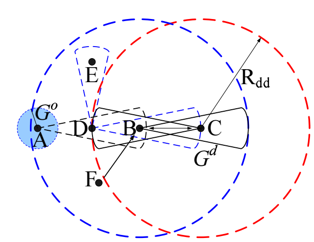


Fig. 5. BT-DMAC solves the hidden terminals and deafness problems

D. The Hidden Terminal and Deafness Problems with BT-DMAC

As we have mentioned in Section III-A, the effective communication range is bounded by R_{do}. On the other hand, the busy tone can be sensed in D-D range R_{dd} since nodes listen to busy tones with directional mode and busy tones are sent to reach the directional transmission range. The extended busy tones make it possible to reduce potential collisions further.

The BT-DMAC can effectively solve both the hidden terminal and the deafness problem. If BT-DMAC is implemented in the scenario shown in Fig. 1, nodes B and C will turn on the busy tones during their transmission period. Since the busy tones can cover the D-D range, node A senses the busy tone of node B and deduces that the direction to node D is busy. So node A defers its transmission to node D, as shown in Fig. 5. BT-DMAC also offers a complete solution to the second kind of hidden terminals. In Fig. 5, although node D can not hear the DRTS/DCTS due to directional beamforming toward node E, it can diagnose that the direction toward B and C is unavailable as it can hear the busy tones before it begins to send to node B. Besides, the deafness has been settled by using BT-DMAC. Before node F begins to send, it senses the channel first. It detects the busy tone of node B and deduces that B is busy. Then it will defer the transmission to node B.

Furthermore, BT-DMAC does not prohibit other normal transmissions. Take the example in Fig. 4 as well, node F wants to transmit to node E. It also senses the BT_t from node A, however it realizes that it will not interrupt the transmission between A and B when it uses the beam 1. Hence, F and E's transmission can be carried on in parallel with A and B's.

IV. Performance Evaluation

A. Analytical Results

The discrete Markov chain model, used in [14] [15] to study CSMA and BTMA is adopted here to evaluate the saturation throughput of BT-DMAC. We have extended the throughput model to support directional antennas and range extension is also considered in our model. The detail of theoretical model and analysis can be found in [16]. Due to the page limit, this paper only offers the numerical results of throughputs.

First, let us explain the notations which are used in the performance analysis. $\gamma = \frac{G_d}{G_o}$, where G_d and G_o are the directional gain and the omnidirectional gain respectively. The nodes are deployed in two-dimensional Poisson distribution with density λ. Suppose N is the average number of nodes within a circular region of an O-O radius. Hence, we get: $N = \lambda\pi R_{oo}^2$, $\lambda\pi R_{do}^2 = \gamma N$ and $\lambda\pi R_{dd}^2 = \gamma^2 N$. Each node is assumed to be operated in time-slotted mode, with a time slot τ. When the time slot τ is very small, the performance of the time-slotted protocol is almost the same as the performance of the asynchronous version of the protocol. The transmission time of RTS, CTS, data and ACK frames are depicted as the multiple of τ, i.e. t_{rts}, t_{cts}, t_{data} and t_{ack}. p is the probability that a node transmits a packet in a time slot.

We have compared the throughput of our proposed BT-DMAC with Basic DMAC [5], and IEEE 802.11 MAC (omnidirectional antennas) in Fig. 6 and 7. Fig. 6 shows the throughputs of the three protocols when the directional gain is regarded to be equal to the omnidirectional one ($\gamma = 1$). The results show that BT-DMAC has performed much better than Basic DMAC and IEEE 802.11 MAC at different values of the beamwidth θ ($\pi/12$, $\pi/6$, $\pi/3$ and $\pi/2$).

Directional antenna gain is considered in Fig. 7 ($\gamma = 2$). Basic DMAC works well when the beamwidth is narrow. When the antenna has a wider beam, Basic DMAC is more vulnerable to interferences as the number of neighbor nodes is increased. As a result, the throughput degrades conspicuously. BT-DMAC has outperformed Basic DMAC and IEEE 802.11 MAC. For example, when $\theta = \pi/3$ and $N = 10$, the throughput of BT-DMAC is almost 3.5 times of that of IEEE 802.11. One possible reason is that spatial reuse brought by directional antennas can counteract the bad effect of increasing interferences. When the antenna has a wider beamwidth, a transmitting nodes is more vulnerable to more interferences where Basic DMAC performs worse. Since BT-DMAC deploys busy tones BT_t/BT_r to protect the ongoing transmission of data and ACK packets, it has gained a better performance. Furthermore, the hidden terminal and the deafness problems, have been alleviated by BT-DMAC.

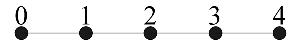


Fig. 8. The linear topology

B. Simulation Results

We have extended GloMoSim 2.03 [17] with the support of directional antennas. We try to compare our proposed protocol with Basic-DMAC and IEEE 802.11 MAC. To ensure equal conditions, we consider an identical scenario to Basic-DMAC in Fig. 8. The five nodes are linearly arranged. The distance between each two nodes is 360 meters. The transmission range of each node is 376.78 meters. The TCP packet size is 1460 bytes and the bandwidth is set to 2Mbps.

TABLE I
Simulation Result(I)

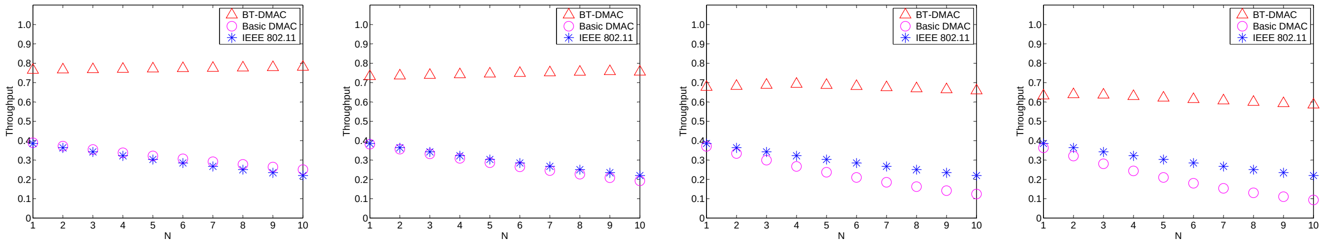
Connections	IEEE 802.11	Basic DMAC	BT-DMAC
TCP(1) (node 1 to node 0)	427.77	838.60	880.39
TCP(2) (node 2 to node 3)	436.37	839.61	828.51
Overall throughput (Kbps)	864.14	1678.21	1708.90

TABLE II
Simulation Result(II)

Connections	IEEE 802.11	Basic DMAC	BT-DMAC
TCP(3) (node 1 to node 2)	10.72	475.90	802.10
TCP(4) (node 3 to node 4)	821.77	633.21	819.95
Overall throughput (Kbps)	832.49	1109.11	1622.05

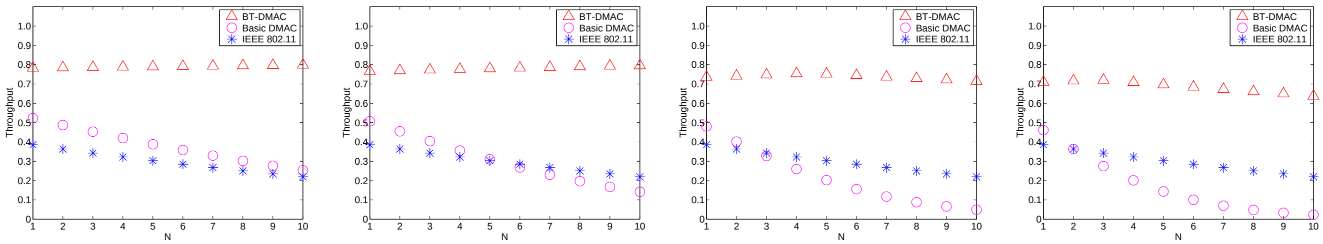
In the first scenario, we simulate two single-hop TCP connections, denoted as TCP(1) (from node 1 to node 0) and TCP(2) (from node 2 to node 3). The results of Table I show that both Basic DMAC and BT-DMAC have outperformed IEEE 802.11 MAC. Due to the benefits of spatial reuse of directional antennas, multiple simultaneous transmissions are allowed, hence the higher throughputs have been gained. Scenario 1 shows the best case for using Basic DMAC, which performs almost the same as BT-DMAC. Since DRTS packets are sent to two opposite directions, the collision probability of control packets of Basic DMAC is quite small in this scenario.

The second scenario also consists of two TCP connections: TCP(3) from node 1 to node 2 and TCP(4) from node 3 to node 4. The simulation results are given by Table II. The result of the IEEE 802.11 deployed network shows that TCP(3) is jammed by TCP(4) due to the omnidirectional transmission. Basic DMAC has gained much better performance than IEEE



(a) $\theta = \pi/12$ (b) $\theta = \pi/6$ (c) $\theta = \pi/3$ (d) $\theta = \pi/2$

Fig. 6. Throughput comparison when $\gamma = 1$ and $p = 0.008$ ($t_{rts} = t_{cts} = t_{ack} = 5\tau$, $t_{data} = 100\tau$)



(a) $\theta = \pi/12$ (b) $\theta = \pi/6$ (c) $\theta = \pi/3$ (d) $\theta = \pi/2$

Fig. 7. Throughput comparison when $\gamma = 2$ and $p = 0.008$ ($t_{rts} = t_{cts} = t_{ack} = 5\tau$, $t_{data} = 100\tau$)

802.11 scheme, as DRTS and OCTS are used to reduce the interferences. However, OCTS packets sent by node 2 can still interfere with the reception of ACK from node 4 to node 3. Therefore, the aggregated throughput has been degraded by the collisions of OCTS and ACK packets. Our proposed BT-DMAC has acquired much higher throughput than Basic DMAC and IEEE 802.11. Furthermore, the fairness using BT-DMAC is also much better than Basic DMAC and IEEE 802.11, for instance, TCP(3) and TCP(4) almost keep in the same throughput. One possible reason is that DCTS can further improve the spatial reuse. Besides, busy tones can provide better protection of on-going transmissions.

V. Conclusion

Directional antennas offer numerous benefits, but they also cause new collisions, such as new hidden terminal and deafness problems. Although a few schemes have been proposed to address these problems, the solutions are not satisfactory. In this paper, we propose a new MAC protocol, which combines busy tones with the DNAV mechanism and can solve the hidden and the deafness problems completely. The mechanism increases the probability of successful data transmission and consequently improves the network throughput.

This paper describes the BT-DMAC scheme and analyzes its performance. Both the numerical and simulation results show that BT-DMAC can achieve much higher throughput than other schemes. BT-DMAC also maintains a high spatial reuse and alleviates the interferences caused by hidden terminals and deafness. Our future work is to simulate BT-DMAC in large-scale networks and implement it in realistic networks to determine how well it performs.

References

[1] R. R. Choudhury, X. Yang, N. H. Vaidya, and R. Ramanathan, "Using directional antennas for medium access control in ad hoc networks," in *MobiCom*, 2002.

[2] R. R. Choudhury and N. H. Vaidya, "Deafness: a MAC problem in ad hoc networks when using directional antennas," in *ICNP*, 2004.

[3] T. Korakis, G. Jakllari, and L. Tassiulas, "A MAC protocol for full exploitation of directional antennas in ad-hoc wireless networks," in *MobiHoc*, 2003.

[4] H. Gossain, C. Cordeiro, D. Cavalcanti, and D. P. Agrawal, "The deafness problems and solutions in wireless ad hoc networks using directional antennas," in *IEEE Globecom Workshops*, 2004.

[5] Y. B. Ko, V. Shankarkumar, and N. H. Vaidya, "Medium access control protocols using directional antennas in ad hoc networks," in *Infocom*, 2000.

[6] A. Nasipuri, S. Ye, and R. E. Hiromoto, "A MAC protocol for mobile ad hoc networks using directional antennas," in *WCNC*, 2000.

[7] M. Takai, J. Martin, R. Bagrodia, and A. Ren, "Directional virtual carrier sensing for directional antennas in mobile ad hoc networks," in *MobiHoc*, 2002.

[8] C. S. Z. Huang, C.-C. Shen and C. Jaikaeo, "A busy-tone based directional MAC protocol for ad hoc networks," in *MILCOM*, 2002.

[9] H. Singh and S. Singh, "Smart-802.11b MAC protocol for use with smart antennas," in *ICC*, 2004.

[10] L. Bao and J. Garcia-Luna-Aceves, "Transmission scheduling in ad hoc networks with directional antennas," in *MOBICOM*, 2002.

[11] Z. Zhang, "Pure directional transmission and reception algorithms in wireless ad hoc networks with directional antennas," in *ICC*, 2005.

[12] R. Ramanathan, "On the performance of ad hoc networks with beamforming antennas," in *MobiHoc*, 2001.

[13] J. Deng and Z. Haas, "Dual busy tone multiple access (DBTMA): A new medium access control for packet radio networks," in *ICUPC*, 1998.

[14] L. Wu and P. K. Varshney, "Performance analysis of CSMA and BTMA protocols in multihop networks (i). single channel case," *Information Sciences*, vol. 120, 1999.

[15] Y. Wang and J. J. Garcia-Luna-Aceves, "Directional collision avoidance in ad hoc networks," *Performance Evaluation Journal*, vol. 58, 2004.

[16] H.-N. Dai, K.-W. Ng, and M.-Y. Wu, "A busy-tone based MAC scheme for wireless ad hoc networks using directional antennas," The Chinese University of Hong Kong, Hong Kong, Tech. Rep., Feb. 2007.

[17] The global mobile information systems simulation library (GloMoSim). [Online]. Available: http://pcl.cs.ucla.edu/projects/glomosim/