

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 tone 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

There is a strong interest in applying directional antennas or smart antennas to wireless ad hoc networks recently. 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 problems due to directional beamforming, 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. As depicted in Fig. 1, node B initiates a transmission to node C by sending Directional RTS (DRTS). Then, C will reply with a Directional CTS (DCTS). Assume that node A is in idle mode (listens omnidirectionally) and far enough from node C, 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 . However, when the transmission between B and C is in progress, node A wants to communicate with node D. Node A uses the directional beam towards node D to sense the channel and finds that the channel is idle as node C is in directional receiving mode at this moment. Subsequently, it sends a DRTS to node D. Since

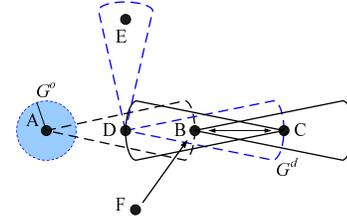


Fig. 1. Hidden terminals and deafness

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. In other words, a transmitter in directional mode (with G_d) and a receiver in omnidirectional mode (with G_o) may be out of each other's range, but they may reach each other if they both transmit and receive directionally (with G_d). This kind of hidden terminals arises due to different gains with omnidirectional and directional modes of directional antennas.

In the second scenario (Fig. 1), while node D is sending a packet to 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 packet for node B. Node D's DNAV (Directional Network Allocate Vector) indicates that the direction to node B is free. Therefore node D begins to send a DRTS to node B, and it will lead to a collision with B's transmission. This kind of hidden terminals arises as the transmitter and the receiver have not heard the DRTS or DCTS control frames. However, this problem will not happen with omnidirectional antennas.

Another drawback of directional beamforming is the deafness problem [1] [2]. Briefly, the deafness is caused when a transmitter fails to communicate to its intended receiver, as the receiver is beamformed towards 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 it initiates the next packet to B, F 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 retransmitting limit has been reached. The excessive retransmission of control packets will bring a severe penalty on the network performance. Since F would increase its backoff interval on each attempt, this event can result in unfairness as well.

Several schemes have been proposed, attempting 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 with low cost. Our main contributions of this paper are:

- 1) We have identified the weakness of existing solutions to the hidden terminal and deafness problems in wireless ad hoc networks using directional antennas.
- 2) We present a novel MAC protocol, Busy-Tone based Directional MAC (BT-DMAC) to attack the hidden terminal and deafness problems.
- 3) We have analyzed the performance of BT-DMAC and the numerical results demonstrate the effectiveness of BT-DMAC. Comparisons with other existing MAC schemes are also given.
- 4) We have also conducted simulation experiments. Our results show that BT-DMAC can achieve higher spatial reuse as compared with the existing schemes, while keeping fairness among nodes.

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 based on directional antennas [1]–[12]. There are quite a few protocols based on the distributed coordination function (DCF) of IEEE 802.11, which typically uses RTS/CTS control packets to prevent interferences. However, these mechanisms can not prevent the new location-dependent carrier sensing problems: the hidden terminals (due to asymmetry in gain and due to unheard RTS/CTS) and the deafness problems [1] [2]. These problems will have major impacts on the performance of ad hoc networks.

Several protocols have been proposed, attempting to tackle the hidden terminal and deafness problems. Dual Busy Tone Multiple Access (DBTMA) [13] uses omnidirectional 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 protocol have not solved the directional hidden terminal problems. The deafness problem is also not addressed in the two schemes. Circular-DMAC [3] attempts to tackle both hidden terminal and deafness problems by sending directional RTS/CTS packets before transmitting data sequentially. However, transmitting multiple RTS/CTS packets for each data packet will severely degrade the performance. Choudhury et al.

[2] propose a tone-based notification mechanism which allows neighbors of a node to classify congestion from deafness and react appropriately. However this scheme can not prevent retransmitting RTS requests from other nodes and it cannot mitigate the deafness completely. Furthermore, this tone-based protocol does nothing to the 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 of them 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, as it does not know the arrival direction of a signal, it will listen in all directions by switching its directional antenna to omnidirectional mode. Once a signal is sensed, the antenna begins to receive with an omnidirectional gain G_o . During the signal receiving period, the antenna performs an azimuthal scan in order to select the beam that acquires the maximum gain. Then the node will record the beam information for future use. The directional mode will be used to transmit or receive RTS, CTS, data and ACK frames.

According to the Friss equation, the maximum distance between the transmitter and the receiver is lengthened with increased antenna gains in the transmitter and the receiver. As the directional gain G_d is greater than the omnidirectional gain G_o , directional antennas offer longer transmitting and receiving ranges. 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 maximum communication range is D-O range (R_{do}). It is obvious that $R_{do} > R_{oo}$. If both nodes transmit and receive directionally, the maximum communication range can be sufficiently extended to D-D range (R_{dd}), which is greater than R_{do} and R_{oo} . However, since a receiver does not know who is the exact transmitter in advance, it can only receive the RTS frame in omnidirectional mode. Hence, the effective communication range is bounded by R_{do} .

The omnidirectional antenna is only used to send busy tones omnidirectionally. In order to cover the range of directional transmission, the transmitting power of the omnidirectional antenna is increased suitably. Since an omnidirectional antenna is only for sending tones, it can be easily implemented and mounted 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 with low cost and without additional hardware. Each node listens omnidirectionally when it is in the idle mode. If the node hears any frames (RTS, CTS, data and ACK), no matter whether the frames are intended for the node or not, it will recognize the direction which the frames are sent from by using selection diversity and determining which beam its neighbor is located in. Then it will record the number of the beam and the identifier of its neighbor into a table, called *Neighbor Location Table* (NLT).

Directional Network Allocation Vector (DNAV) is a directional version of NAV of IEEE 802.11, proposed by [7] and [1]. DNAV excludes the directions and sets the corresponding durations, towards which the node is not allowed to initiate a transmission to avoid collisions with data or control frames. We integrate the DNAV mechanism with the NLT. When a node receives a RTS frame and the receipt address matches its address, it beamforms towards the transmitter (switch to directional mode) and replies the RTS with a CTS frame. If the control frames are not for itself, it will update the sender's information in the NLT and set the corresponding DNAVs. Fig. 2 shows that a node A has a four-beam antenna and its neighbors, C, B and E, D located in beam 0, 1 and 2 respectively. Node A stores its neighbors' location information into a 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.

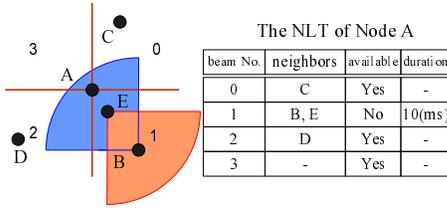


Fig. 2. An example of the Neighbor Location Table

C. The BT-DMAC Protocol

In the BT-DMAC protocol, two busy tones are implemented with enough spectral separation on the 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 comprises two sub-tones, an ID tone and a beam number tone for the receiving node. To encode several-bit information into the sine wave, there is an easy way to achieve this: Pulse Modulation, which sends signals by turning the sine wave on and off (in Fig. 3). Any node hearing the busy tones learns node identifiers 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. The busy tones occupy only a small portion of the whole frequency.

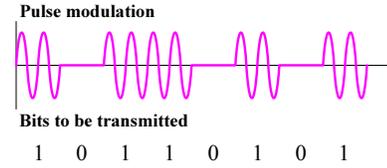
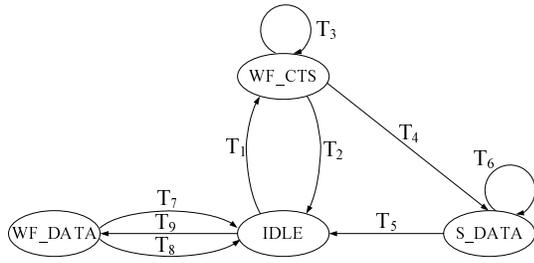


Fig. 3. The Pulse Modulation

If a node has data to send, it will search the NLT to find the beam for the destination and check the availability of the beam in the DNAVs. If the beam is available, the node will listen directionally by using that beam. If no busy tone is detected, the node will send a RTS immediately. If a busy tone is sensed, the node will identify the corresponding sender ID and the beam number from the tones. If the ID matches the destination's, it is obvious that the destination is busy now and the attempt will be deferred. If the ID does not match the destination's, then the sender will compare the beam number with that one used to communicate with the destinations in its NLT. If the beam number is identical, the node will defer its transmission to avoid collision. The receiver and the transmitter will turn on the busy tones until the ACK frame is received.

Fig. 4 depicts the finite state machine (FSM) of the BT-DMAC scheme. 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 frames to send and has not received any requests, it will stay in the *IDLE state*. If it has data frames 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 go back to the *IDLE* state. If the sender in the *WF_CTS* state receives a CTS, it will turn on its BT_t and begin to transmit. If there is no CTS within the retry timer, it will go back to the *IDLE* state. If the sender gets the ACK reply correctly, it will turn off its BT_t and go back to the *IDLE* state. However, if the ACK cannot reach the sender within the retry timers, the sender will retransmit the data and increase the retry counter until it reaches the maximum value. On the other hand, when a node in *IDLE* state hears a RTS, it will point its beam towards the sender direction and send a CTS, then turn on its BT_r . 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.5. In this figure, there are several nodes, A, B, C, D, E and F, which are equipped with four-beam antennas. When node A has data frames to send to node B, it will sense the channel towards node B by using Beam 0. If Beam 0 is free, node A points the beam towards node B, sends a RTS frame to node B, and then goes into the *WF_CTS* state. After node B receives the RTS, it switches to directional mode (beamforms towards the direction of A using Beam 2) and replies with a CTS, turning on its $BT_r(B, 2)$. Then it sets up a timer and enters the *WF_DATA* state. After receiving the CTS from node B, node A turns on its $BT_t(A, 0)$ and goes into



T_i (E / A): the transition
 E: the trigger event
 A: the action of the transition

T_1 : data ready AND the beam for the destination available/send RTS and set timer
 T_2 : time out AND no CTS /
 T_3 : no CTS AND retry < RETRY_LIMIT / retransmit RTS
 T_4 : CTS received / BT on, set timer
 T_5 : ACK received OR retry \geq MAX_RETRY / BT off
 T_6 : no ACK AND retry < MAX_RETRY / retransmission
 T_7 : DATA received / send ACK, BT off
 T_8 : time out / BT off
 T_9 : RTS received / send CTS, BT on, set timer

Fig. 4. The Finite State Machine of BT-DMAC

the S_DATA state and sends the data frames. Upon successful reception of the data frame, node B replies to node A with an ACK and turns off the BT_r , entering the $IDLE$ state. If, for any reason, node B does not receive the data packet 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 timer expires.

In this scenario, node C within the busy tone range of node B has data to send to B (using Beam 2). Since it senses the $BT_r(B, 2)$ from node B, it will defer its transmission to avoid colliding. If node D within the BT ranges of node A and B wants to communicate with node E (D and E are close enough), 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 (using Beam 0 also) will cause interferences with nodes A and B. Therefore node D will defer its transmission. The time diagram with the operations of node A and node B is shown in Fig. 7.

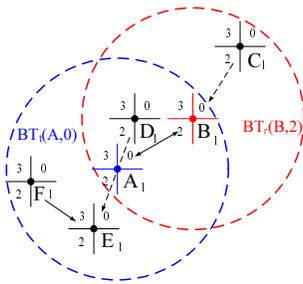


Fig. 5. a scenario illustrates the operation of BT-DMAC

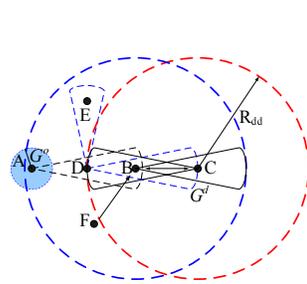


Fig. 6. BT-DMAC solves the hidden terminals and deafness problems

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

As we have mentioned before, since a node receives the RTS frame only in omnidirectional mode, the effective communication range is bounded by R_{do} . However, the busy tone can be sensed in D-D range R_{dd} since nodes listen to busy



Fig. 7. The Time Diagram of BT-DMAC

tones with directional mode and busy tones are sent to reach the range of directional transmission. The extended busy tones make it possible to reduce potential collisions further.

The BT-DMAC can effectively solve two kinds of hidden terminal problems (due to asymmetry in gain and unheard RTS/CTS) and mitigate the deafness problem. As the example shown in Fig. 1, if BT-DMAC is implemented in this scenario, the nodes B and C will turn on the busy tones during their transmission period. Since the busy tones are sent to reach the range of directional transmission and node A will listen directionally towards node D, it can sense the busy tone sent by node B in D-D range. Therefore, node A will deduce that the direction to node D is busy and defer its transmission to node D (in Fig.6). BT-DMAC offers a complete solution to the second kind of hidden terminal problems as well. In Fig.6, although node D can not hear the DRTS/DCTS due to directional beamforming towards node E, D can diagnose that the direction towards B and C is unavailable as it can hear the busy tones before it begins to send to node B. Hence, the mechanism can effectively solve the two kinds of new hidden terminal problems. Before node F begins to send, it will sense the channel first. It will detect the busy tone of node B and deduces that B is busy. Then it will defer the transmission to node B. Therefore, the deafness has been settled by using BT-DMAC.

Furthermore, BT-DMAC does not prohibit other normal transmissions that will not collide with the current communication. Take the example in Fig. 5 as well, the node F wants to transmit to the 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, the transmission between the nodes F and E can be carried on in parallel with A and B's. Therefore, the mechanism can improve the spatial reuse.

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.

Table I lists 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

TABLE I
NOTATIONS IN PERFORMANCE ANALYSIS

Symbol	Explanation
θ	the beamwidth
N	the average number of nodes within a circular region
γ	the ratio of the directional gain to the omnidirectional gain
p	the probability that a node transmits a packet in a time slot
τ	a time slot

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} .

We have compared the throughput of our proposed BT-DMAC with Basic DMAC [5], and IEEE 802.11 MAC (omnidirectional antennas) in Fig. 8 and 9.

Fig. 8 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. 9 ($\gamma = 2$). 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. Basic DMAC performs even worse than IEEE 802.11 when the average number of nodes is increased further. However, BT-DMAC has still outperformed Basic DMAC and IEEE 802.11 MAC when directional antenna gain is considered. 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 (Basic DMAC can work well when the beamwidth is narrow and the number of nodes is small). When the antenna has a wider beamwidth, a transmitting nodes is more vulnerable to more interferences (Basic DMAC performs worse). As 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, which cannot be completely mitigated by other exiting MAC schemes, have been alleviated by BT-DMAC.

B. Simulation Results

We have extended GloMoSim 2.03 [17] with the support of directional antennas. We try to compare our proposed protocol with other existing MAC schemes (Basic-DMAC and IEEE 802.11 MAC). To ensure equal conditions between Basic-DMAC, IEEE 802.11 and our proposed BT-DMAC, we consider an identical scenario to Basic-DMAC in Fig. 10. The five nodes are linearly arranged. The distance between each

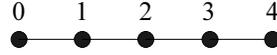


Fig. 10. The linear topology

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 II
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

In the first scenario, we simulate two single-hop TCP connections, in terms of TCP(1) (from node 1 to node 0), TCP(2) (from node 2 to node 3). The results of Table II 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. The reason is that the collision probability of control packets of Basic DMAC is quite small in this scenario (DRTS packets are sent to two opposite directions).

TABLE III
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)	823.49	1109.11	1622.05

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 III. 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 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 of possible reasons is that DCTS can further improve the spatial reuse (DCTS of node 2 won't interfere with the transmission of node 3 and node 4 again). Besides, busy tones can provide better protection of on-going transmissions.

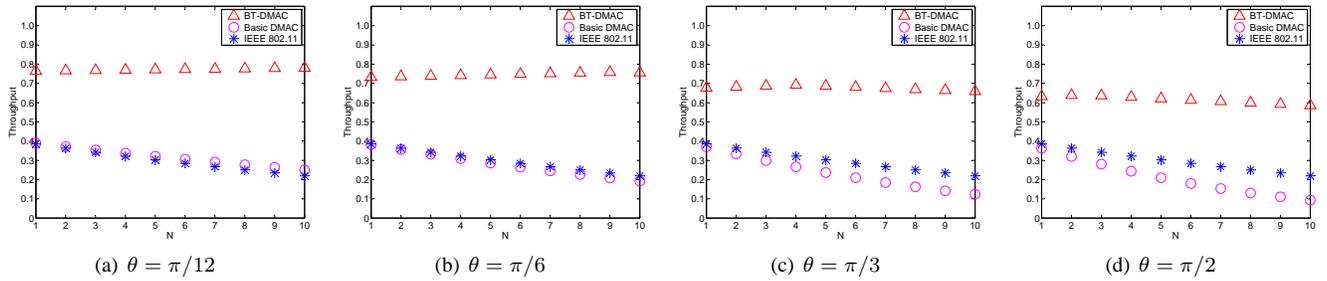


Fig. 8. Throughput comparison when $\gamma = 1$ and $p = 0.008$ ($t_{rts} = t_{cts} = t_{ack} = 5\tau$, $t_{data} = 100\tau$)

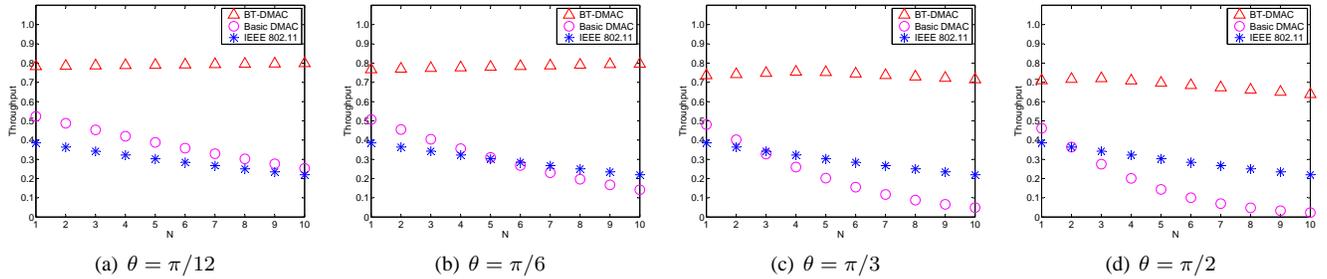


Fig. 9. Throughput comparison when $\gamma = 2$ and $p = 0.008$ ($t_{rts} = t_{cts} = t_{ack} = 5\tau$, $t_{data} = 100\tau$)

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 (BT-DMAC), 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. We have also presented the analytical model of BT-DMAC and calculated its performance. The numerical and simulation results show that BT-DMAC can achieve much higher throughput than other schemes. The BT-DMAC also maintains a high spatial reuse and alleviates the interferences from 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.

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