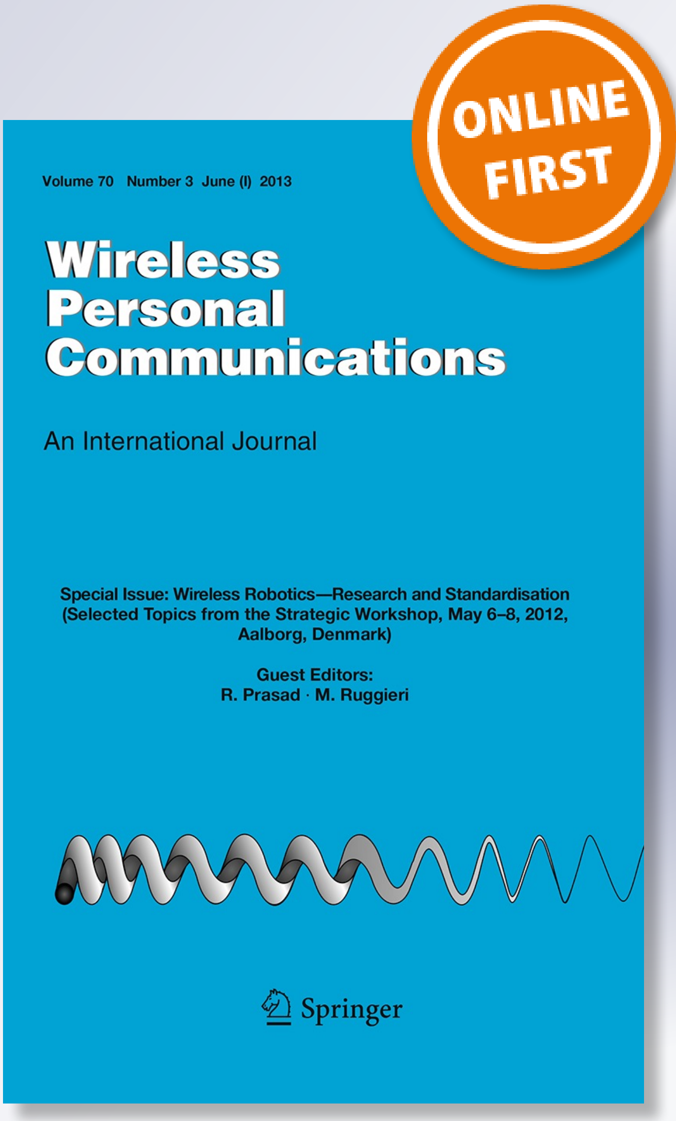
On Busy-Tone Based MAC Protocol for Wireless Networks with Directional Antennas

Hong-Ning Dai, Kam-Wing Ng & Min-You Wu

Wireless Personal Communications
An International Journal

ISSN 0929-6212

Wireless Pers Commun
DOI 10.1007/s11277-013-1206-9



Springer

Wireless Pers Commun
DOI 10.1007/s11277-013-1206-9

On Busy-Tone Based MAC Protocol for Wireless Networks with Directional Antennas

Hong-Ning Dai · Kam-Wing Ng · Min-You Wu

Abstract The application of directional antennas in wireless ad hoc networks offers numerous benefits, such as the extended communication range, the increased spatial reuse, the improved capacity and the suppressed interference. However, directional antennas can cause new location-dependent carrier sensing problems, such as new hidden terminal and deafness problems, which can severely degrade the network performance. Recently, a few schemes have been proposed to address these problems. However, most of these existing methods can only partially solve the hidden terminal and deafness problems. Some of them even bring significant performance overhead. In this paper, we propose a novel MAC protocol, in terms of the busy-tone based directional medium access control (BT-DMAC) protocol. In BT-DMAC, when the transmission is in progress, the sender and the receiver will turn on their omni-directional busy tones to protect the on-going transmission. Integrating with the directional network allocation vector (DNAV), the scheme can almost mitigate the hidden terminal problem and the deafness problem completely. We then propose an analytical model to investigate the throughput performance of BT-DMAC. The numerical results show that BT-DMAC outperforms other existing directional MAC schemes. We next evaluate the performance of BT-DMAC through extensive simulation experiments. The results show that our proposed BT-DMAC scheme has superior performance to other existing solutions, in terms of higher throughput.

H.-N. Dai (✉)
Faculty of Information Technology, Macau University of Science and Technology, Avenida Wai Long, Taipa, Macao
e-mail: hndai@ieee.org

K.-W. Ng
Department of Computer Science and Engineering, The Chinese University of Hong Kong, Shatin, NT, Hong Kong
e-mail: kwng@cse.cuhk.edu.hk

M.-Y. Wu
Department of Computer Science and Engineering, Shanghai Jiao Tong University, SEIEE Building #04-417, 800 Dongchuan Road, Shanghai, People's Republic of China
e-mail: wu-my@cs.sjtu.edu.cn

Published online: 14 May 2013

Keywords Wireless networks · Directional antennas · Medium access control · Performance analysis

1 Introduction

Many recent studies focused on using *directional* antennas in wireless ad hoc networks. Compared with an *omni-directional* antenna, a directional antenna can concentrate its transmitting or receiving capabilities to a certain direction. Thus, using directional antennas in wireless networks allows more concurrent transmissions in the vicinity of a pair of communication nodes and consequently leads to less interference to other on-going transmissions. As a result, applying directional antennas to wireless networks can significantly improve the network performance. For example, it is shown in [3,5,11,15,18,23] that applying directional antennas instead of omni-directional antennas to wireless ad hoc networks can greatly improve the network throughput.

In wireless networks with omni-directional antennas, the scheme of carrier sense multiple access with collision avoidance (CSMA/CA) was proposed to tackle the *location-dependent carrier sensing* problem, such as the hidden terminal problem. For example, IEEE 802.11 Distributed Coordination Function (DCF) [2] is one of typical CSMA/CA schemes used in in wireless networks with omni-directional antennas to solve the hidden terminal problem. Many studies simply extended IEEE 802.11 CSMA/CA mechanism to the networks with directional antennas by sending data packets directionally [5,18]. However, this simple extension of IEEE 802.11 to directional antennas may lead to the new location-dependent carrier sensing problem, such as the *new hidden terminal* problem and the *deafness* problem [5,6], which will be described in details in Sect. 2.2.

Several protocols [4,9,11,12] were proposed to tackle the hidden terminal and the deafness problem. Most of them can only solve either the hidden terminal problem or the deafness problem, but not both. Besides, many of them also suffered from the significantly increased overhead due to sending extra control frames. We will discuss the current solutions to the hidden terminal and the deafness problem in Sect. 2.3. Therefore, we propose a novel MAC scheme to solve both the hidden terminal and deafness problems with low overhead. The main contributions of this paper can be summarized as follows.

1. We identify the weakness of the current solutions to the hidden terminal and deafness problems in wireless networks using directional antennas.
2. We present a novel MAC protocol, in terms of Busy-Tone based Directional MAC (BT-DMAC) to tackle both the hidden terminal problem and the deafness problem.
3. We analyze 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 also conduct extensive simulation experiments to evaluate BT-DMAC. The results show that BT-DMAC can achieve higher throughput than the existing schemes.

The rest of the paper is organized as follows. Section 2 describes the location-dependent carrier sensing problems with directional antennas, such as the new hidden terminal problem and the deafness problem. We then describe the BT-DMAC protocol in Sect. 3. Section 4 presents the throughput analysis of the BT-DMAC protocol. We show simulation results of BT-DMAC in Sect. 5. Finally, the paper is concluded in Sect. 6.

2 Location-Dependent Carrier Sensing Problem in Directional Antennas

First, we briefly introduce directional antennas in Sect. 2.1. Section 2.2 describes the location-dependent carrier sensing problem—the new hidden terminal problem and the deafness problem. We then survey the current solutions to new hidden terminal problem and the deafness problem in Sect. 2.3.

2.1 Directional Antennas

In general, an antenna is a device that is used for radiating/collecting electromagnetic energy (radio signals) into/from space. Among various antenna types, *omni-directional* antennas are commonly used in wireless networks. An omni-directional antenna radiates radio signals in all directions. Thus, only a small percentage of radio signals can reach the desired nodes and most of them are scattered into space. The scattered radio signals can cause interference with nodes within the coverage of the antenna.

A directional antenna is an antenna (directed antenna) or an antenna system (an array of antennas), which can radiate or receive radio signals more effectively in some directions than in others. Compared with an omni-directional antenna, a directional antenna has *lower interference*, *higher spatial reuse* and *higher network capacity* [7,21,22].

There are two kinds of directional antennas: *directed antennas* and *smart antennas*. In a directed antenna, the antenna beam either fixed or adjusted to point to a certain direction by mechanical rotation. A smart antenna consists of a set of antenna elements (in a linear, planar or circular array) with digital signal-processing capability to transmit and receive adaptively. Compared with traditional directed antennas, smart antennas usually have higher performance due to directional beamforming, diversity processing, adaptive spatial reusing, etc [6].

Smart antennas can be further categorized as *Switched beam* antennas and *Adaptive array* antennas. In a switched beam antenna, the antenna beam patterns are predetermined by shifting every antenna element's signal phase. In an adaptive array antenna, arbitrary beam patterns are formed on the fly. In this paper, we only consider switched beam antennas. Figure 1 shows a switched beam antenna, which has M beams.

The radiation pattern of a direction antenna is often depicted as the gain values in each direction in space. It typically has a main beam with the peak gain and side lobes with smaller gain. Since modelling a real antenna with precise values for main beam and side-lobes/back-lobes is difficult, we use an approximate antenna pattern, which was first proposed in [14] and has been widely used in [3,7,11,22,23]. In this simplified model, the antenna pattern in space is projected to an azimuthal plane, where the main lobe of antenna can be depicted as a

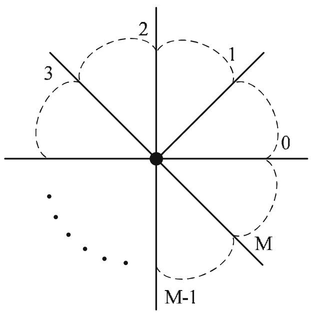


Fig. 1 The switched beam antenna with M beams

Fig. 2 The antenna model

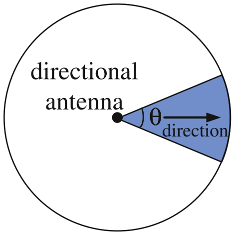
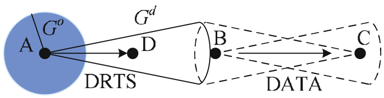


Fig. 3 Hidden terminal due to asymmetry in gain



sector with angle θ, which is denoted as the main beamwidth of the antenna. The gain outside the beamwidth is assumed to be zero. At any time, the antenna beam can only be pointed to a certain direction, as shown in Fig. 2, in which the antenna is pointing to the right. Thus, the probability that the beam is switched to cover each direction is $\theta/2\pi$. More specifically, we have

$$G^d = \begin{cases} G_m & \text{within } \theta \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

where G_m is the gain value of the main beam, which is often evaluated by dBi or dB (isotropic), i.e., the antenna gain compared to that of the hypothetical omni-directional antenna (i.e., isotropic antenna). In this paper, we assume that the antenna gain of an omni-directional antenna $G^o = 0$ dBi. In general, we have $G_m > G^o$.

Note that a switched beam antenna has two modes: an *omni-directional* mode with antenna gain G^o and a *directional* mode with antenna gain G^d, where $G^d > G^o$ since $G_m > G^o$.

2.2 Hidden Terminal Problem and Deafness Problem of Directional Antennas

Most of current MAC protocols with directional antennas are based on IEEE 802.11 DCF, which employs a CSMA/CA (Carrier sense multiple access with collision avoidance) with binary exponential back-off algorithm [2]. The IEEE 802.11 DCF is shown to perform well in wireless networks with omni-directional antennas since the usage of RTS (Request to Send) and CTS (Clear to Send) frames in DCF can significantly reduce the *hidden terminals* [10]. However, it is shown in [5,6] that the IEEE 802.11 DCF with RTS/CTS may not work well in wireless networks with directional antennas since directional antennas have the directional transmission/reception regions, which are different from omni-directional antennas. In particular, there are three new location-dependent carrier sensing problems in wireless networks with directional antennas: (i) the hidden terminal problem due to the *asymmetric antenna gains*, (ii) the hidden terminal problem due to the *unheard RTS/CTS frames*, and (iii) the deafness problem, which will be depicted as follows.

The first kind of hidden terminal problems originates in asymmetry in antenna gains. Take Fig. 3 as an example. There are 4 nodes, A, B, C and D in the idle mode and they listen omni-directionally with a gain of G^o. Firstly, node B initiates a transmission to node C by sending a Directional RTS. Then, node C will reply with a Directional CTS. Assume that node A is in idle mode and far enough away from node C, A cannot hear the DCTS from C since the omni-directional gain G^o is smaller than the directional gain G^d. Then, nodes B

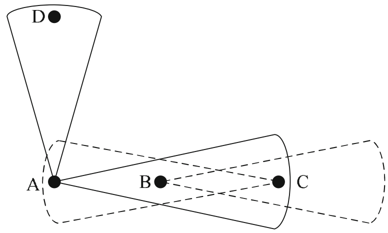


Fig. 4 Hidden terminal due to unheard RTS/CTS

and C begin data transmission by pointing their transmission and reception beams to each other with a gain G^d. While the transmission between B and C is in progress, node A wants to communicate with node D. Node A uses the directional beam toward node D to sense the channel and finds that the channel is idle. Therefore, 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 node A would interfere with the data reception of node C. In other words, a transmitter in directional mode (with G^d) and a receiver in the omni-directional 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 the difference in gains between the omni-directional and directional modes of directional antennas.

The second kind of hidden terminal problems arises when the transmitter and the receiver have not heard the DRTS or DCTS control frames. In another scenario as shown in Fig. 4, while node A is sending a packet to node D, node B sends a DRTS to node C. At this time, node C's DCTS can reach node A, however node A cannot hear it since node A is beamformed in the direction of node D. When the communication between nodes B and C is in progress, assume that node A finishes transmitting to D and has a packet to send to node B. Node A's Directional Network Allocation Vector (DNAV) indicates that the direction to node B is free. Therefore, node A begins to send a DRTS to node B, and it will lead to a collision with B's transmission. This problem will not happen with omni-directional antennas. With omni-directional communication, node B will be aware of the ongoing transmission of node A.

Another drawback of directional beamforming is the deafness problem. Briefly, the deafness is caused when a transmitter fails to communicate to its intended receiver, as the receiver is beamformed toward a direction away from the transmitter. In Fig. 5, node C wants to transmit data to node B, using the route through node A. When A gets a packet from C, it beamforms in the direction of B and forwards the packet. At this time, C is unaware of the transmission between A and B since it does not hear the communication of A and B. If it initiates the next packet to A, C will not receive the DCTS reply from A since A is beamformed to B. Node C retransmits the DRTS when no response is received from A. This process will go on until the DRTS retransmitting limit has been reached. The excessive retransmission of control packets will bring a severe penalty on the network performance. Since C would increase its backoff interval on each attempt, this event can result in unfairness as well.

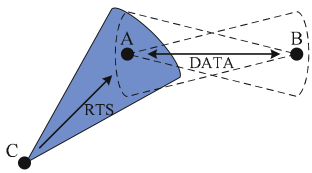


Fig. 5 Deafness problem

2.3 Current Solutions to the Hidden Terminal Problem and the Deafness Problem

Several protocols have been proposed, attempting to tackle the hidden terminal and the deafness problem [4,9,11,13,17,19]. In particular, Circular-DMAC [11,12] attempts to address both the hidden terminal problem and the deafness problem by sending sequential directional RTS frames through each antenna beam before transmitting data frames. Circular-DMAC can solve the deafness problem completely and partially solve the hidden terminal problem due to the asymmetry in antenna gains. However, this protocol cannot solve the hidden terminal problem due to the unhearing of RTS/CTS frames. Another drawback of Circular-DMAC is the significant extra overhead caused by transmitting multiple RTS frames for each data frame. As shown in [11,12], under low traffic load, Circular-DMAC performs even poorer than IEEE 802.11. Gossain et al. [9] propose an improved MAC protocol (MDA) based on Circular-DMAC. Although the deafness region is mitigated by sweeping multiple RTS and CTS frames in opposite directions, the deafness problem can not be solved completely. Besides, MDA also requires sending multiple RTS and CTS frames before each data transmission, which also brings additional overhead. ToneDMAC [4] explores using tones to solve the deafness problem with low overhead on the performance. But ToneDMAC can not solve the hidden terminal problem. RI-DMAC [19] explores a polling scheme initiated by the receiver to address the deafness problem. Although this MAC scheme performs better than both Circular-DMAC [11] and ToneDMAC [4], it cannot solve the deafness problem completely. Besides, RI-DMAC does nothing to the hidden terminal problem. Directional MAC with Deafness Avoidance (DMAC-DA) [13] is proposed to address both the hidden terminal problem, the deafness problem and the deaf zone problem. Multiple RTS or CTS frames are used before a data communication in order to avoid the possible collisions. In addition to DNAV (used to avoid collisions), a deaf neighbors table (DNT) is proposed to mitigate the deafness. However, DMAC-DA also shares some common drawbacks of Circular DMAC and MDA, i.e., transmitting multiple RTS/CTS frames for each data transmission. Besides, maintaining additional DNT at each node also increases the complexity of MAC design.

In summary, most of the above protocols can only solve either the hidden terminal problem or the deafness problem, but not both. Besides, many of them also suffered from the significant overhead caused by transmitting multiple control frames (RTS and CTS). Therefore, we propose a Busy-Tone based Directional MAC protocol (BT-DMAC) to solve both the hidden terminal problem and the deafness problem with low overhead. In our previous work [8], we have given the basic description of our protocol and some preliminary numerical results as well as some basic simulation results on linear networks. In this paper, we present the complete analytical model and the extended simulation experiments on large scale grid networks as well as random networks to evaluate BT-DMAC. Both the numerical results and the simulation results show that our proposed BT-DMAC can achieve the superior performance to other existing directional MAC schemes.

3 Busy Tone Based Directional MAC Protocol

We first present an overview on BT-DMAC operation in Sect. 3.1. Section 3.2 describes the antenna model used in BT-DMAC. We then discuss the neighbor discovery issue in Sect. 3.3. Section 3.4 presents the detailed design of the busy tones. We then give several examples to illustrate that BT-DMAC can effectively solve both the hidden terminal problem and the deafness problem in Sect. 3.6.

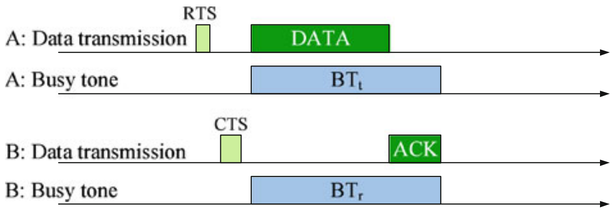


Fig. 6 The time diagram of BT-DMAC

3.1 Overview of BT-DMAC

Similar to other directional MAC schemes based on IEEE 802.11 DCF [4,9,11,13,17,19], we also reserve the RTS/CTS scheme of DCF and the Directional Network Allocation Vector (DNAV) in BT-DMAC. Thus, BT-DMAC has a good backward compatibility with IEEE 802.11 DCF. Specifically, in BT-DMAC, each transmitter contends the channel by sending a DRTS frame. When the receiver receives the DRTS frame successfully, the receiver replies with a DCTS frame. After the successful hand-shaking, the data transmission will proceed immediately. All the other nodes receiving either DRTS or DCTS will set their DNAV values and defer the channel access until the end of the transmission.

Different from other existing directional MAC protocols, we use busy tones to protect the on-going transmission. In particular, when the data transmission is in progress, the transmitter and the receiver will turn on the transmitting busy tone (BT_t) and the receiving busy tone (BT_r), respectively in order to protect the on-going transmission. The BT_t and BT_r are transmitting in the control sub-channel so that the tones will not collide with the on-going transmission in the data sub-channel. The time diagram with the operations of two nodes A and B is shown in Fig. 6. Details about BT-DMAC will be described in details as follows.

3.2 Antenna Model

In the network, each node are equipped with two interfaces: one interface is associated with a switched beam antenna and another one is associated with an omni-directional antenna. A switched beam antenna has M beams, as shown in Fig. 1.

In this paper, we assume that the antenna gain is mainly determined by the main antenna beam while the other smaller antennas gains, called sidelobes and backlobes can be ignored. In this model, the main lobe of antenna can be depicted as a sector with angle θ, which is denoted as the main beamwidth of the antenna, as as shown in Fig. 2. The antenna gain within the beamwidth θ is given by Eq. (1). The gain outside the beamwidth is assumed to be zero. Note that we also assume those M beams of an antenna can cover all 2π directions. Besides, those M beams do not overlap with each other. Thus, we have $M \cdot \theta = 2\pi$.

The switched beam antenna has two modes: an *omni-directional* mode and a *directional* mode. When a node is in the idle mode, as it does not know the arrival direction of a signal, it listens in all directions by switching its directional antenna to the omni-directional mode. Once a signal is sensed, the antenna begins to receive with an omni-directional 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 stores the beam information for future use. The directional mode will be used to transmit or receive RTS, CTS, data and ACK frames.

As shown in[16], the maximum distance between the transmitter and the receiver is lengthened with increased antenna gains at the transmitter and the receiver. As the directional gain

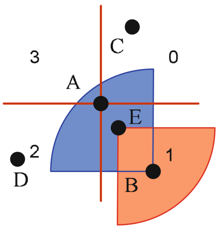
G^d is greater than the omni-directional gain G^o, directional antennas offer longer transmitting and receiving ranges. When both nodes are in the omni-directional mode, the maximum communication range is Omnidirectional–Omnidirectional (O–O) range (R_{oo}). When one node is in omni-directional mode, and another node transmits or receives directionally, the maximum communication range is Directional-Omnidirectional (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 which is the exact transmitter in advance, it can only receive the RTS frame in the omni-directional mode. Hence, the effective communication range is bounded by R_{do}.

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

3.3 Neighbor 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 hardwares. Each node listens omni-directionally 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 from which the frames are sent 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 [18] and [5]. DNAV excludes the directions and sets the corresponding durations, toward 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 receiver address matches its address, it beamforms toward 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. Figure 7 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.



The NLT of Node A

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

Fig. 7 An example of the Neighbor Location Table

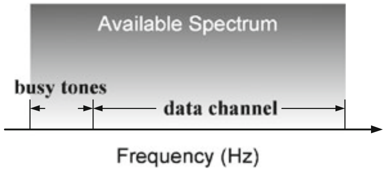


Fig. 8 Frequency chart of the BT-DMAC protocol

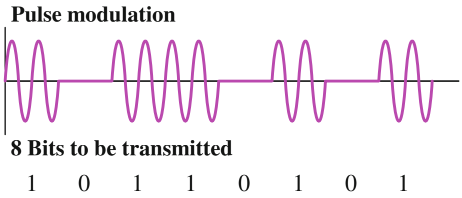


Fig. 9 Pulse modulation

3.4 Busy Tones

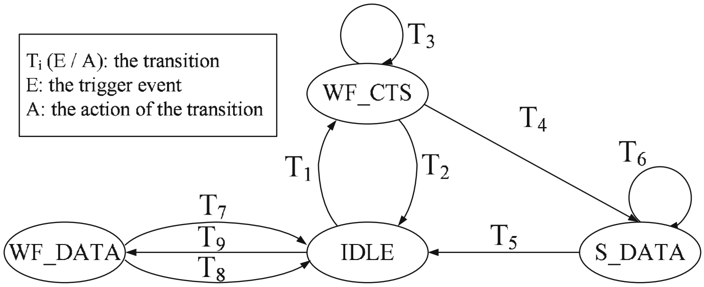
In the BT-DMAC protocol, we divide the channel into two sub-channels: one sub-channel for data transmission and another narrow band sub-channel for busy tone transmission. The RTS, CTS, ACK and Data frames are transmitted on the data channel. Two narrow band busy tones in terms of *transmitting busy tone* (BT_t) and *receiving busy tone* (BT_r) are implemented with enough spectral separation on the tone sub-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. Figure 8 shows the spectrum division of BT-DMAC.

A node receiving a busy tone needs to determine the sender of the tone and decode the beam information from the tone, then it can perform properly. A node with an identifier i chooses a tone with frequency $f(i)$, which ranges from a set of K frequencies. The value of $f(i)$ is a static hash function of the node's identifier, which can locally identify a node. A node is assumed to have no more than K neighbors, so the neighbors of a node can be assigned with different frequencies. We assume that a higher layer protocol can assign node identifiers consecutively, so $f(i)$ can be uniformly distributed over the node identifier space. Thus, we have a simple hash function f(i) as follows:

$$f(i) = (i \bmod K) + 1 \tag{2}$$

To encode the binary beam number 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. Figure 9 shows an example of the pulse modulation of 8-bit information. Since a switched beam antenna generally has a finite number of beams, only several bits are encoded in a tone and the probability of tone collisions is quite small. Thus, each tone contains the beam number that is currently used to transmit or receive. 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.

If a node has data to send, it searches its NLT to find the beam for the destination and check the availability of the beam in its DNAVs. If the beam is available, the node listens directionally by using that beam. If no busy tone is detected, the node sends a RTS immediately. If a busy tone is sensed, the node identifies 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 is deferred. If the ID does not match the destination's, then the sender will



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 >= 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. 10 Finite state machine of BT-DMAC

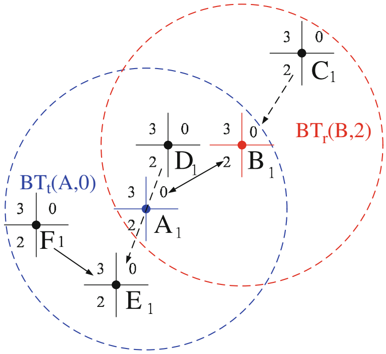
compare the beam number with that one used to communicate with the destinations in its NLT. If the beam number is identical, the node defers its transmission to avoid collision. The receiver and the transmitter turn on the busy tones until the ACK frame is received.

3.5 BT-DMAC Protocol

Figure 10 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 stays in the *IDLE* state. If it has data frames to send, it senses the medium first. If the channel for the destination direction is free (i.e., no busy tones detected), the node sends a RTS to the destination and enter the *WF_CTS* state. Otherwise, the node goes back to the *IDLE* state. If the sender in the *WF_CTS* state receives a CTS, it turns on its BT_t and begins to transmit. If there is no CTS accepted within the retry timer, it goes back to the *IDLE* state. If the sender gets the ACK reply correctly, it turns off its BT_t and goes back to the *IDLE* state. However, if the ACK cannot reach the sender within the retry timers, the sender retransmits 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 points its beam toward the sender direction and send a CTS, then turn on its BT_r. If the data frame is correctly received, the receiver replies the sender with an ACK and turn off its BT_r.

BT-DMAC can be illustrated by an example, shown in Fig. 11, where 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 senses the channel toward node B by using Beam 0. If Beam 0 is free, node A points the beam toward 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 toward the direction of A using Beam 2) and replies with a CTS, turning on its receiving busy tone, denoted by $BT_r(B, 2)$. Then it sets up a timer and enters the *WF_DATA* state. After receiving the CTS from node B, node A turns on its transmitting busy

Fig. 11 A scenario illustrates the operation of BT-DMAC



tone, denoted by $BT_t(A, 0)$ and goes into 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 retransmits the data frames until the timer expires.

In this scenario, node C which is 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 defers 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) can cause interferences with nodes A and B. Therefore, node D defers its transmission.

3.6 The Hidden Terminal and Deafness Problems with BT-DMAC

As mentioned before, since a node receives the RTS frame only in omni-directional 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 tones in the 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.

BT-DMAC can effectively solve two kinds of hidden terminal problems (due to asymmetry in gain and unheard RTS/CTS) and the deafness problem. As shown in Fig. 3, node A becomes a hidden terminal to node B because the DCTS frames cannot reach node A due to asymmetry in gain. However, if BT-DMAC is implemented in this scenario, when the transmission between node B and C is in progress, they turn on their busy tones. At this time, the busy tone sent by node C can cover node A (D–D range), and node A defers the communication with node D since it has deduced that the direction to node D is busy, which is shown in Fig. 12.

BT-DMAC can solve the second kind of hidden terminal problems as well. As shown in Fig. 13, although node A cannot hear RTS/CTS due to directional beamforming, node A can diagnose that the direction toward node B and C is unavailable by sensing the busy tones. The operation is illustrated in Fig. 13.

For the deafness problem, we explain the solution by using the scenario depicted in Fig. 5. In this scenario, nodes A and B turn on their busy tones while the transmission between them is in progress. Node C wants to send a data packet to node A. First, it senses the medium

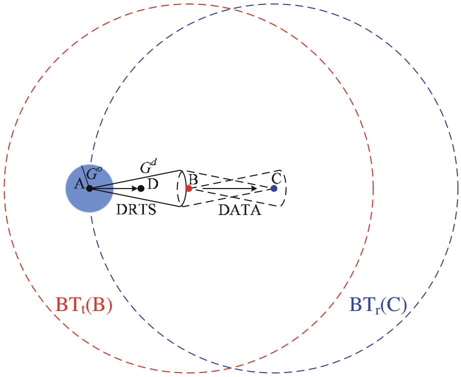


Fig. 12 BT-DMAC can mitigate hidden terminal due to asymmetry in gain

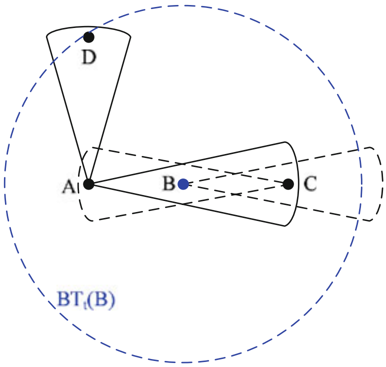


Fig. 13 BT-DMAC can mitigate hidden terminals due to unheard RTS/CTS

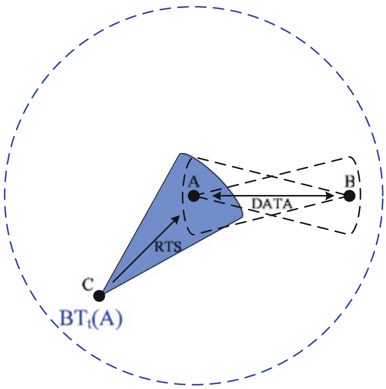


Fig. 14 BT-DMAC can solve the deafness problem

toward A and detects the busy tone. Then it identifies that the tone is from node A, thus it defers the transmission to node A as shown in Fig. 14. Therefore, the deafness can be mitigated by using BT-DMAC.

Furthermore, BT-DMAC does not prohibit other normal transmissions that will not collide with the current communication. Take Fig. 11 as an example again. In this scenario, node F wants to transmit to node E. It also senses the BT_t from node A, however it realizes that it does not interrupt the transmission between A and B when it uses the beam 1. Hence, the transmission between the nodes F and E can proceed in parallel with A and B's. Therefore, the mechanism can improve the spatial reusage.

4 Throughput Analysis of BT-DMAC

4.1 Assumptions

For easy discussion, we assume that all nodes have an identical setting (the same beamwidth θ and the same antenna gain). Besides, we also assume that the nodes are deployed in two-dimensional Poisson distribution with density λ.

The signal path loss, or the signal attenuation can be calculated by the following equation [16].

$$P_r = \frac{k P_t G_t G_r}{R^\alpha} \tag{3}$$

where k is a constant, G_t and G_r are the transmitter antenna gain and the receiver antenna gain, respectively, R is the distance between the transmitter and the receiver, P_t and P_r denote the transmitting power and the received power, respectively, and α is the path loss factor of the environment, which usually ranges from 2 to 4.

Recall that there are three communication ranges, the O–O range R_{oo}, the D–O range R_{do}, and the D–D range R_{dd}. We assume that N is the average number of nodes within the O–O range R_{oo}. Thus, we have $N = \lambda\pi R_{oo}^2$. We then calculate the average number of nodes within the D–O range and the average number of nodes within the D–D range.

From Eq. (3), the O–O range R_{oo} can be calculated by

$$R_{oo} = \left(\frac{k P_t G^o G^o}{P_r}\right)^{\frac{1}{\alpha}} \tag{4}$$

Similarly, we can calculate the D–O range R_{do} and the D–D range R_{dd} by

$$R_{do} = \left(\frac{k P_t G^d G^o}{P_r}\right)^{\frac{1}{\alpha}} \tag{5}$$

$$R_{dd} = \left(\frac{k P_t G^d G^d}{P_r}\right)^{\frac{1}{\alpha}} \tag{6}$$

We define $\gamma = \frac{G^d}{G^o}$. From Eqs. (4) and (5), we have $R_{do} = \gamma^{\frac{1}{\alpha}} R_{oo}$. Similarly, From Eqs. (5) and (6), we have $R_{dd} = \gamma^{\frac{1}{\alpha}} R_{do}$. Thus, we have $\lambda\pi R_{do}^2 = \gamma^{\frac{2}{\alpha}} N$ and $\lambda\pi R_{dd}^2 = \gamma^{\frac{4}{\alpha}} N$.

We assume that each node operates in the time-slotted mode, with a time slot τ. As shown in [20], 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. We denote the transmission times of RTS, CTS, data and ACK frames by t_{rts}, t_{cts}, t_{data} and t_{ack}, which are the multiple of τ. In this paper, we ignore the propagation delay. The throughput of BT-DMAC is based on a heavy-traffic assumption that a node always has a packet to send. The probability that a node transmits in a slot is denoted as p.

4.2 Throughput

In this paper, we adopt a discrete Markov chain model to evaluate the saturation throughput of our proposed BT-DMAC scheme. We also use this model to compare BT-DMAC with other representive existing MAC schemes, such as Circular-DMAC [11,12], Basic DMAC [5] and CSMA-OMN (CSMA scheme used for omni-directional antennas), which is based on IEEE 802.11 DCF with RTS/CTS. The throughput is calculated by the proportion of time that a

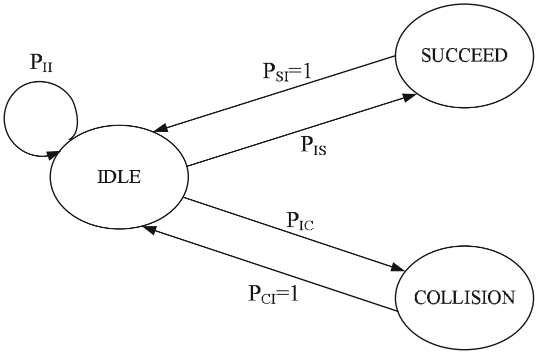


Fig. 15 The Markov chain model for a node

node spends transmitting data packets successfully on the average. We use a Markov chain model, as shown in Fig. 15. Let $P(S)$, $P(I)$ and $P(C)$ denote the steady-state probability of the states, *SUCCEED*, *IDLE* and *COLLISION*, respectively. From the Markov chain model of Fig. 15, we have

$$\text{Throughput} = \frac{P(S) \cdot t_{data}}{P(C)T_C + P(S)T_S + P(I)T_I} \tag{7}$$

where T_C, T_S and T_I are the duration time slots of *COLLISION*, *SUCCEED* and *IDLE*, respectively.

We next derive the steady-state probabilities, transition probabilities and times spent at different states of BT-DMAC.

Firstly, the duration in time slots of a node in the *SUCCEED* state is

$$\begin{aligned} T_S &= (t_{rts} + 1) + (t_{cts} + 1) + (t_{data} + 1) + (t_{ack} + 1) \\ &= t_{rts} + t_{cts} + t_{data} + t_{ack} + 4 \end{aligned} \tag{8}$$

where t_{rts}, t_{cts}, t_{data} and t_{ack} are the duration time slots of transmitting RTS, CTS, data and ACK frames, respectively.

It is obvious that the duration of a node in *IDLE* state T_I is 1 τ.

We then calculate the duration of a node in the *COLLISION* state. Since the handshake between the sender and the receiver may be interrupted during the collision period that varies from $T_1 = t_{rts} + 1$ to $T_2 = t_{rts} + t_{cts} + 2$, the length of collision period follows a truncated geometric distribution with parameter p, lower bound T_1 and upper bound T_2. The mean value of the truncated geometric distribution as T_C, which is given by

$$T_C = \frac{1 - p}{1 - p^{T_2 - T_1 + 1}} \sum_{i=0}^{T_2 - T_1} p^i (T_1 + i) \tag{9}$$

Since a node in the *IDLE* state listens omni-directionally, any node which can reach it by directional beamforming is a Directional–Omnidirectional neighbor [5]. Thus the potential interference range is D–O range instead of O–O range. Hence, the transition probability P_{II} that the node continues to stay in *IDLE* state in a slot is equal to the probability that it does not initiate any transmission and there is no node around it initiating a transmission toward it. Since the two events are independent, we have

$$P_{II} = (1-p) \cdot \sum_{i=0}^{\infty} (1-p)^i \cdot \frac{(\lambda \pi R_{do}^2)^i}{i!} e^{-\lambda \pi R_{do}^2}$$
$$= (1-p) e^{-p\lambda \pi R_{do}^2} = (1-p) e^{-p\gamma N} \quad (10)$$

From Fig. 15, the steady-state probability of the *IDLE* state can be expressed as follows

$$P(I) = P(I) \cdot P_{II} + P(S) + P(C) \quad (11)$$

Noting that $P(S) + P(C) = 1 - P(I)$, hence we have

$$P(I) = \frac{1}{2 - P_{II}} = \frac{1}{2 - (1-p)e^{-p\gamma N}} \quad (12)$$

As shown in Fig. 15, the steady-state probability of *SUCCEED* state $P(S)$ can be calculated by $P(S) = P(I) \cdot P_{IS}$. Substituting for P_{IS}, $P(S)$ can be expressed as follows

$$P(S) = P(I) \cdot P_{IS} = \frac{P_{IS}}{2 - (1-p)e^{-p\gamma N}} \quad (13)$$

To derive the transition probability P_{IS} from *IDLE* to *SUCCEED*, we need to calculate the probability $P_{is}(r)$ that node A successfully initiates a four-way handshake with node B which is r distance away from A. $P_{is}(r)$ equals the probability that node A transmits in a given time slot, node B does not transmit in the same time slot, and none of the nodes around them interfere with the handshakes. Then $P_{is}(r)$ can be calculated as

$$P_{is}(r) = p \cdot (1-p) \cdot P_1 \cdot P_2 \cdot P_3 \cdot P_4 \quad (14)$$

where P_1 is the probability that no node interferes with the RTS reception, P_2 is the probability that no node interferes with the CTS reception, P_3 is the probability that no node interferes with the data reception and P_4 is the probability that no node interferes with the ACK reception.

As depicted in Fig. 16, the sender A transmits a RTS to the receiver B. However, when the node B is in idle mode, it listens omni-directionally. When it hears the signal from A, it points its beam toward A and listens directionally. During the reception time of RTS, the node B may be interfered by the nodes within the sector region with the radius R_{dd} (D–D

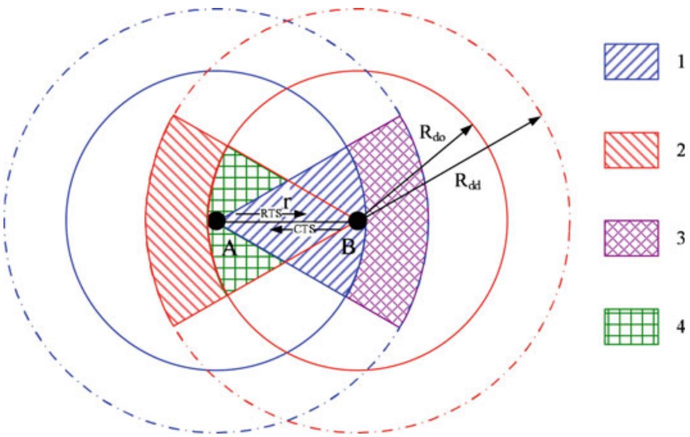


Fig. 16 The interference region for BT-DMAC

range) and the angle θ. Since the RTS frame sent by node A can prevent the nodes within region 1 from interfering with node B (by setting DNAVs), node B may only be interfered by the nodes within regions 2 and 4. Therefore, the probability that no node interferes with the reception of RTS is equal to the product of the probability that no node in the region with the radius R_{do} (D–O range) transmits in the same time slot as node A does, and the probability that no node in the region 2 transmits toward B during the (RTS+1) period.

$$P_1 = e^{-p'\lambda\pi R_{do}^2} \cdot e^{-p'(t_{rts}+1)\lambda\left(\frac{\theta}{2}R_{dd}^2 - \frac{r^2}{2}\tan\left(\frac{\theta}{2}\right)\right)} \tag{15}$$

where $p' = p\theta/(2\pi)$.

After the receiver B hears the RTS correctly, it beamforms toward node A and response with a CTS and node A listens directionally. As illustrated in Fig. 16, since the RTS sent by A can block the nodes within region 1 (setting DNAVs), node A may only be interfered by the nodes within region 3 (the size of region 3 is $S_3 = \frac{\theta}{2} \cdot R_{dd}^2 - \frac{\theta}{2} \cdot R_{do}^2$). Hence, we get the probability that no node interferes with the reception of CTS to node A.

$$P_2 = \left(\sum_{i=0}^{\infty}(1-p')^i \cdot \frac{(\lambda S_3)^i}{i!}e^{-\lambda S_3}\right)^{(t_{cts}+1)} = e^{-p'\lambda S_3(t_{cts}+1)} \tag{16}$$

where $p' = p\theta/(2\pi)$.

Since nodes A and B turn on their busy tones after starting transmission, and the nodes within the D–D range are suppressed by the busy tones. Thus, the probability that no node interferes with the reception of data frames to node B is considered to be one, i.e., $P_3 = 1$. Similarly, the probability that no node interferes with the reception of ACK to node A is one, i.e., $P_4 = 1$.

We also consider the spatial reuse of directional antennas similar to [20]. The spatial reuse factor $\sigma(r)$ is defined to be the number of possible concurrent transmissions in the combined region covered by nodes A and B. $\sigma(r)$ is the radio between the total region covered by nodes A and B and the actual area that excludes the region covered by the handshake between nodes A and B. If there is one handshake in areas 1 and 4, then in theory there may be $S_{total}/(S_1+S_4)$ concurrent handshakes in the region excluding 1 and 4. Therefore, we have

$$\sigma(r) = S_{total}/(S_1 + S_4) \tag{17}$$

Here, we just give a very rough estimation of the spatial reuse factor for BT-DMAC, and the practical parameter is lower than the theoretical value. Then we have

$$P_{IS} = \int_0^{R_{do}} 2r\sigma(r)P_{is}(r)\mathrm{d}r \tag{18}$$

Following the similar steps, we can derive the saturate throughput of Circular-DMAC [11,12], Basic DMAC [5] and CSMA-OMN. Due to space limitation, we ignore the detailed derivation of these existing MAC schemes in this paper.

4.3 Numerical Results

Based on the above throughput model, we conduct numerical analysis on the throughput of our proposed BT-DMAC. We also compare the throughput of BT-DMAC with Basic DMAC [5], Circular-DMAC [11,12] and CSMA-OMN. The main results are shown in Fig. 17, Figs. 18 and 19.

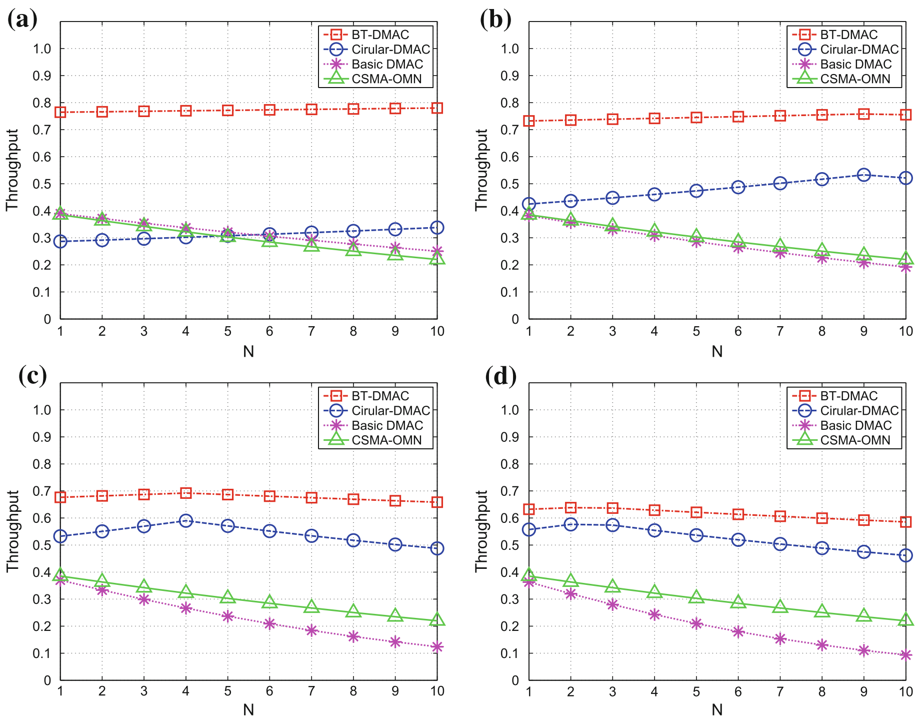


Fig. 17 Throughput comparison when $\gamma = 1$, $\alpha = 2$ and $p = 0.008$ ($t_{rts} = t_{cts} = t_{ack} = 5\tau$, $t_{data} = 100\tau$). **a** $\theta = \pi/12$ and $M = 24$. **b** $\theta = \pi/6$ and $M = 12$. **c** $\theta = \pi/3$ and $M = 6$. **d** $\theta = \pi/2$ and $M = 4$

In particular, Fig. 17 compares the throughputs of Basic DMAC, CSMA-OMN, Circular-DMAC and our proposed BT-DMAC. There is no range extension in Fig. 17 since the directional gain is regarded to be equal to the omni-directional one (i.e., $\gamma = 1$). It is shown in Fig. 17 that BT-DMAC performs much better than Basic DMAC, CSMA-OMN, Circular-DMAC at different values of the beamwidth θ (i.e., $\pi/12$, $\pi/6$, $\pi/3$ and $\pi/2$) and the number of beams M (i.e., $M = 24, M = 12, M = 6, M = 4$), respectively. Note that we must have $M \cdot \theta = 2\pi$ as shown in Sect. 3.2.

Figure 18 compares the throughputs of Basic DMAC, CSMA-OMN, Circular-DMAC and BT-DMAC, where we consider the range extension with the directional antenna gain (i.e., $\gamma = 2$). It is shown in Fig. 18 that BT-DMAC still outperforms Basic DMAC, CSMA-OMN and Circular-DMAC. This is because BT-DMAC deploys busy tones BT_t and BT_r to protect the ongoing transmission of data and ACK packets, it gains better performance. It is also shown in Fig. 18 that Basic DMAC works well when the beamwidth is narrow, e.g., the beamwidth $\theta = \pi/12$. When the beamwidth of the antenna is wider, Basic DMAC is more vulnerable to interferences with the increased number nodes. As a result, the throughput of Basic DMAC degrades significantly. For example, Basic DMAC performs even worse than CSMA-OMN when the average number of nodes $N > 7$ when $\theta = \pi/6$. Circular-DMAC performs much better than Basic DMAC when the beamwidth of the antenna is wider, e.g., the beamwidth $\theta = \pi/3$. This is because the multiple RTS frames of Circular-DMAC can effectively reduce the collisions. But, Circular-DMAC performs worse than Basic DMAC when the beamwidth of the antenna is narrower e.g., the beamwidth $\theta = \pi/12$. This is due to

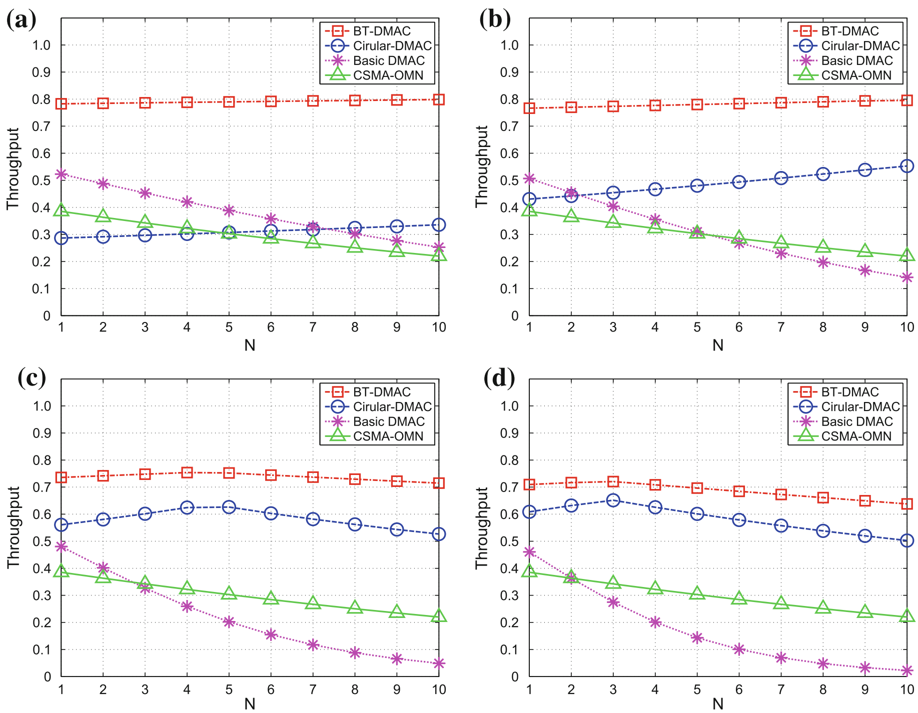


Fig. 18 Throughput comparison when $\gamma = 2$, $\alpha = 2$ and $p = 0.008$ ($t_{rts} = t_{cts} = t_{ack} = 5\tau$, $t_{data} = 100\tau$). **a** $\theta = \pi/12$ and $M = 24$. **b** $\theta = \pi/6$ and $M = 12$. **c** $\theta = \pi/3$ and $M = 6$. **d** $\theta = \pi/2$ and $M = 4$

the high cost of transmitting multiple RTS frames (recall that the number of the transmitted RTS frames is equal to the number of beams, M).

Figure 19 shows the results when the path loss factor α is 4 (which is typical in urban outdoor environments [16]). As shown in 19, BT-DMAC stills performs better than other existing MAC protocols with the larger path loss factor, implying that BT-DMAC is more robust that other existing schemes with the environment variation.

5 Performance Evaluation

In this section, we conduct extensive simulation experiments to evaluate BT-DMAC over different topologies. We extend GloMoSim 2.03 [1] with the support of multiple interfaces as well as directional antennas. In this simulator, each node is equipped with 4 directional antennas and one omni-directional antenna. The beamwidth of a directional antenna is 45 degrees. We then conduct experiments based on regular topologies (Sect. 5.1) and random topologies (Sect. 5.2).

5.1 Regular Topologies

5.1.1 Linear Topologies

We first consider a linear network, as shown in Figs. 20, 21 and 22, in which five nodes are linearly arranged. The distance between two adjacent nodes is 180 m. The transmission

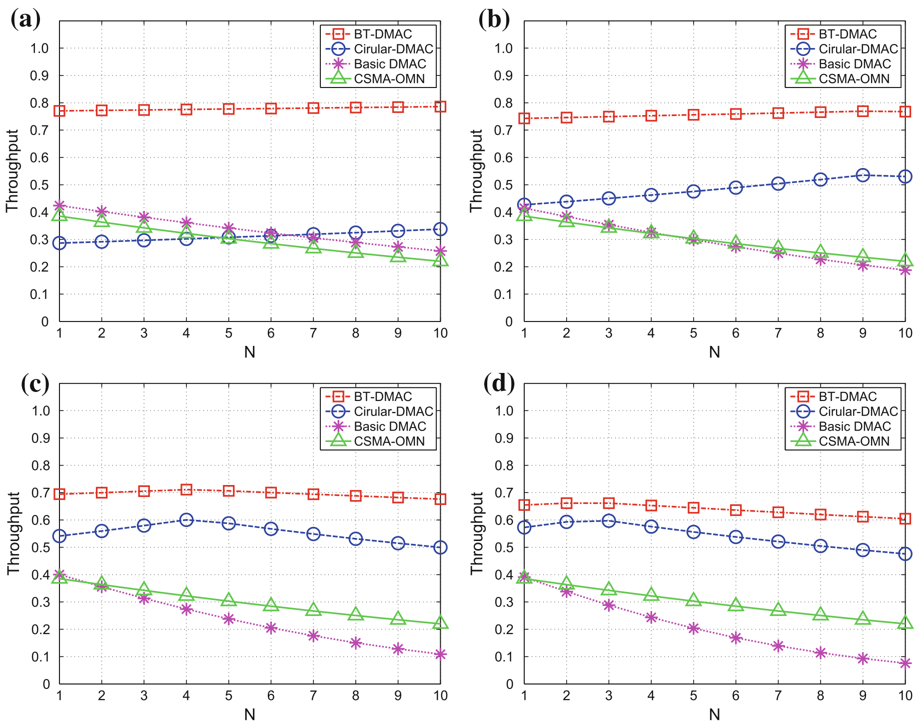


Fig. 19 Throughput comparison when $\gamma = 2$, $\alpha = 4$ and $p = 0.008$ ($t_{rts} = t_{cts} = t_{ack} = 5\tau$, $t_{data} = 100\tau$). **a** $\theta = \pi/12$ and $M = 24$. **b** $\theta = \pi/6$ and $M = 12$. **c** $\theta = \pi/3$ and $M = 6$. **d** $\theta = \pi/2$ and $M = 4$

Fig. 20 Scenario 1

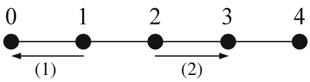


Fig. 21 Scenario 2

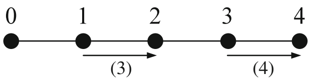
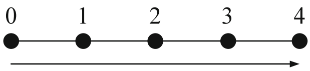


Fig. 22 Scenario 3: multi-hop



range of each node is 200 m. The bandwidth is set to be 2Mbps. We use the two-ray ground propagation model. All nodes are considered to be static. Note that the transmission range of a directional antenna is assumed to be equal to that of an omni-directional antenna.

In the first scenario as shown in Fig. 20, we assign two single-hop TCP connections, in terms of connection (1) (from node 1 to node 0), connection (2) (from node 2 to node 3). Fig. 23 presents the results for the first scenario. In Fig. 23, TCP(1), TCP(2) and Total denote the measured throughput on the connection (1), the measured throughput on the connection (2) and the sum throughput of all measured TCP connections, respectively. It is shown in Fig. 23 that Basic DMAC, Circular-DMAC and BT-DMAC outperform CSMA-OMN (IEEE 802.11 for omni-directional antennas). This performance improvement owes to the benefits of spatial reuse of directional antennas. In other words, directional antennas can support more simultaneous transmissions than omni-directional antennas. Besides, Fig. 23 also shows that

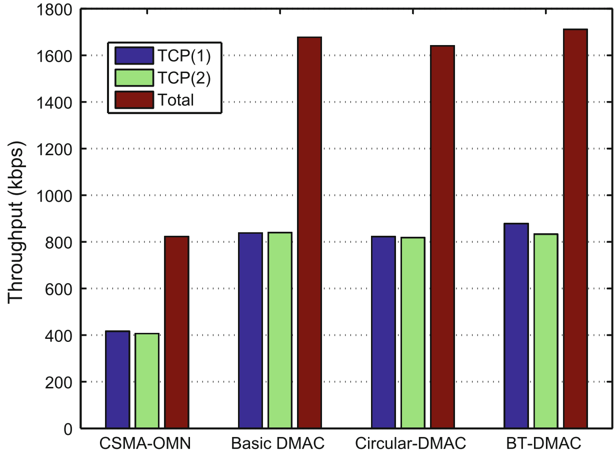


Fig. 23 Simulation results on Scenario 1

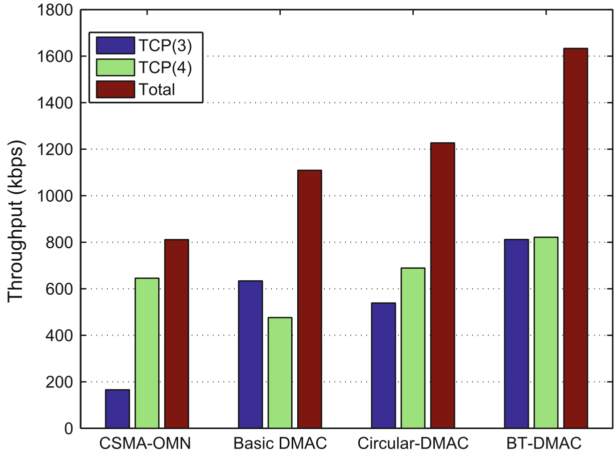


Fig. 24 Simulation results on Scenario 2

Basic DMAC, Circular-DMAC and BT-DMAC have almost the same performance (BT-DMAC slightly outperforms Basic DMAC and Circular-DMAC). The reason is that the collision probability of control packets of Basic DMAC and Circular-DMAC is quite small in this scenario, when DRTS packets are sent to two opposite directions.

The second scenario also consists of two TCP connections: connection (3) from node 1 to node 2 and connection (4) from node 3 to node 4, as shown in Fig. 21. Figure 24 presents the simulation results for the second scenario. It is shown in Fig. 24 that CSMA-OMN performs much worse than Basic DMAC, Circular-DMAC and BT-DMAC. This is because connection (3) was almost choked by the traffic of connection (4) due to the omni-directional transmission. Basic DMAC, Circular-DMAC and BT-DMAC have higher throughput than CSMA-OMN since DRTS and CTS (OCTS in Basic DMAC and DCTS in Circular-DMAC and BT-DMAC) can mitigate the interferences. However, Basic DMAC and Circular-DMAC perform worse than BT-DMAC in the second scenario. Besides, Fig. 24 also shows that both Basic DMAC and Circular-DMAC suffer from the unfairness. In Basic DMAC, OCTS frames

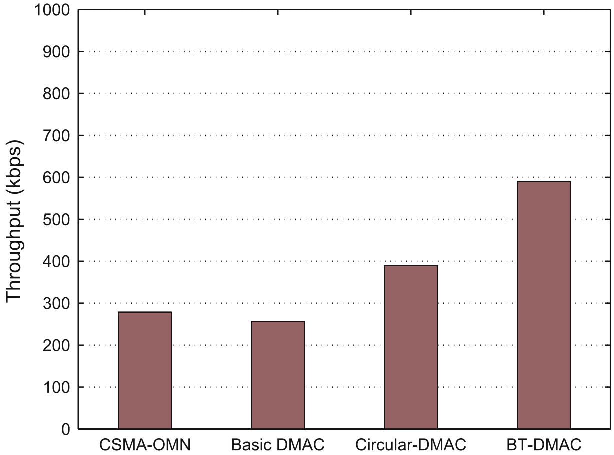


Fig. 25 Simulation results on Scenario 3

sent by node 2 can still interfere with the reception of ACK from node 4 to node 3, which results in the degraded throughput on connection (4), as shown in Fig. 24. In Circular-DMAC, DRTS frames sent by node 3 collide with the CTS reception of CTS at node 2. As a result, the throughput of connection (3) degrades. However, BT-DMAC can overcome the above drawbacks of Basic DMAC and Circular-DMAC and has a better performance.

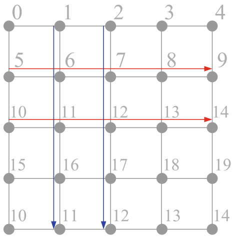
We consider a multi-hop flow from node 0 to node 4, as shown in Fig. 22. Figure 25 presents the results. As shown in Fig. 25, Basic DMAC performs even worse than CSMA-OMN. The reason may lie in the deafness problem that Basic DMAC cannot solve, while no deaf node exists in networks using omni-directional antennas. Figure 25 also shows that Circular-DMAC has a higher aggregate throughput than Basic DMAC. This improvement owes to the mitigation of the deafness problem by sending multiple RTS frames in Circular-DMAC. Figure 25 also shows that BT-DMAC outperforms CSMA-OMN, Basic DMAC and Circular-DMAC. This is because BT-DMAC harnesses busy tones to mitigate the deafness problem. When a node wants to transmit to another node, it needs to sense the medium first. When a busy tone is sensed and if potential transmission will cause collisions, a node will defer its transmission.

5.1.2 Grid Topologies

We then conduct simulations on a grid topology of 25 nodes, which is similar to [5]. The distance between any two adjacent rows is the same as the distance between any two adjacent columns, which is equal to 150 m. The transmission range of each node is 250 m so that any two row-adjacent, column-adjacent nodes or diagonal-adjacent nodes can communicate with each other. Note that the transmission range of a directional antenna is the same as that of an omni-directional antenna (similar to a linear network). We consider two sets of simulations: (1) flows with aligned routes and (2) flows with randomly chosen routes.

The first simulation begins with 4 aligned multi-hop flows as shown in Fig. 26. We assign Constant Bit Rate (CBR) traffic on each flow, which varies from 50 to 2,000 kbps. The packet size is set to be 512 bytes. Figure 27 presents the results. As shown in Fig. 27, BT-DMAC has much higher aggregate throughputs than Circular-DMAC, Basic DMAC, and CSMA-OMN. Figure 27 also shows that Basic DMAC performs even worse than CSMA-OMN.

Fig. 26 Flows with aligned routes



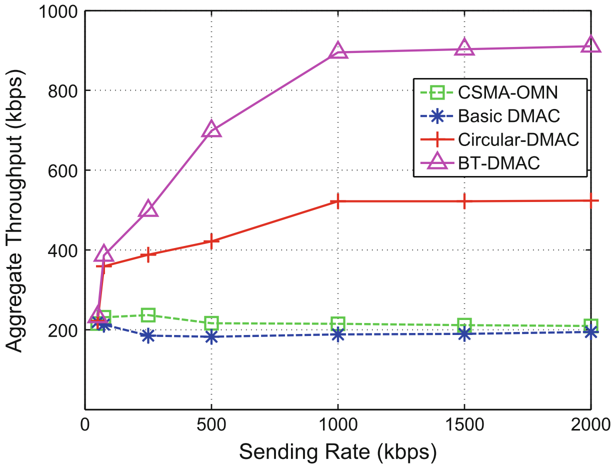
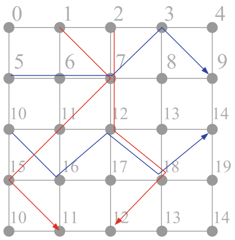


Fig. 27 Simulation results on Fig. 26

Fig. 28 Flows with randomly chosen routes



This is because the high interference caused by the aligned routes, which further confirms the previous results in [5].

We then conduct simulation experiments based on randomly chosen routes, as shown in Fig. 28. Figure 29 presents the results based on this scenario. It is shown in Fig. 29 that BT-DMAC still outperforms CSMA-OMN, Basic DMAC and Circular-DMAC. Besides, Fig. 29 also shows that the aggregate throughputs of all the schemes under randomly chosen routes are higher than those under aligned routes. The improvements can be attributed to the enhanced spatial reuse of the wireless channel due to the *unaligned* routes (Fig. 27).

5.2 Random Topologies

We than consider a random network, in which 50 static nodes are randomly placed in $2{,}000 \times 2{,}000\,\text{m}^2$ area. The transmission range of each node is set to 250 m, which is identical to

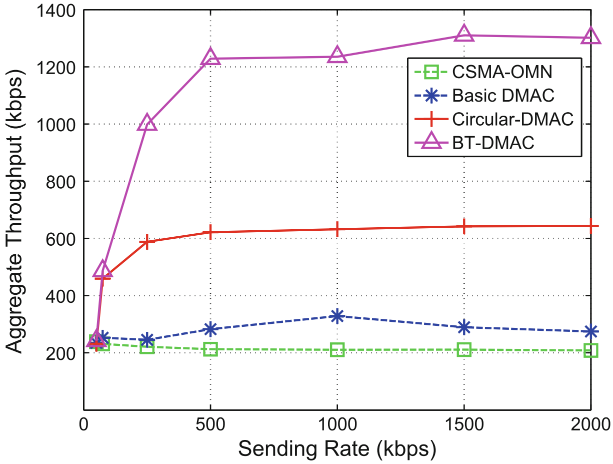


Fig. 29 Simulation results on Fig. 28

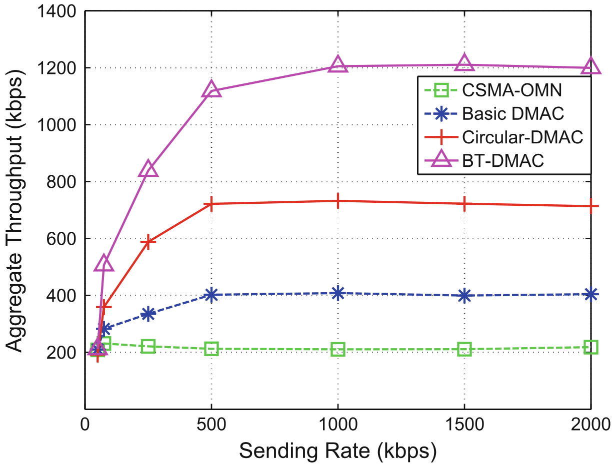


Fig. 30 Simulation results on 10 random topologies

both a directional antenna and an omni-directional antenna. The destination node of a packet is randomly chosen from any of the neighbors that are at least 600 m away. Data packets are routed on the shortest path, which is computed by Dijkstra's algorithm and saved at each node along the path. The data rate at each flow varies from 50 to 2,000 kbps.

Figure 30 compares the average aggregate throughputs of CSMA-OMN, Basic DMAC and Circular-DMAC, and BT-DMAC over 10 random topologies. As shown in Fig. 30, BT-DMAC outperforms CSMA-OMN, Basic DMAC and Circular-DMAC.

5.3 Discussions

In this paper, we evaluate the performance of our proposed BT-DMAC by comparing with several representative MAC schemes, such as Circular-DMAC, Basic DMAC and CSMA-OMN by conducting simulation experiments. Due to the space limitation, we do not compare BT-DMAC with other directional MAC schemes by conducting empirical studies. In fact, we can roughly estimate the performance of other directional MAC schemes, such as MDA [9], ToneDMAC [4], RI-DMAC [19] and DMAC-DA [13]. Specifically, our proposed BT-DMAC shall outperform ToneDMAC and RI-DMAC since BT-DMAC can completely solve both the hidden terminal problem and the deafness problem while ToneDMAC and RI-DMAC can only solve the deafness problem and do nothing to the hidden terminal problem. Besides, BT-DMAC shall outperform MDA and DMAC-DA although MDA and DMAC-DA have a slightly better performance than Circular-DMAC [9,13]. This is because both MDA and DMAC-DA need to transmit multiple RTS/CTS frames for each data transmission, which inevitably leads to the additional overhead.

6 Conclusion

Directional antennas offer numerous benefits, but they also cause new collisions, such as new hidden terminal and the deafness problems. Although a few schemes have been proposed to address these problems, many of them only offer partial solutions to these problems. Some of them even bring significant performance overhead. In this paper, we propose a new MAC protocol named BT-DMAC, which can completely solve both the hidden terminal problem and the deafness problem with low overhead.

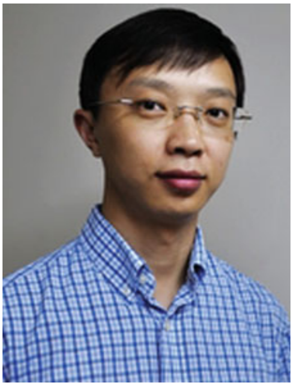
This paper describes the BT-DMAC scheme and analyzes its performance. We also present the analytical model of BT-DMAC and evaluate its performance. Both the numerical and simulation results show that BT-DMAC can achieve much higher throughput than other existing schemes, such CSMA-OMN, Basic DMAC and Circular-DMAC. BT-DMAC also maintains a high spatial reuse and alleviates the interferences from hidden terminals and deafness.

References

1. Global Mobile System Simulator. (2002). http://pcl.cs.ucla.edu/projects/glomosim/.
2. IEEE 802.11. (2007). Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.
3. Bao, L., & Garcia-Luna-Aceves, J. (2002). Transmission scheduling in ad hoc networks with directional antennas. In *Proceedings of ACM MobiCom*.
4. Choudhury, R. R., & Vaidya, N. H. (2004). Deafness: A MAC problem in ad hoc networks when using directional antennas. In *Proceedings of IEEE ICNP*.
5. Choudhury, R. R., Yang, X., Vaidya, N. H., & Ramanathan, R. (2002). Using directional antennas for medium access control in ad hoc networks. In *Proceedings of ACM MobiCom*.
6. Dai, H. N., Ng, K. W., Li, M., & Wu, M. Y. (2013). An overview of using directional antennas in wireless networks. *International Journal of Communication Systems, 26*(4), 413–448.
7. Dai, H. N., Ng, K. W., Wong, R. C. W., & Wu, M. Y. (2008). On the capacity of multi-channel wireless networks using directional antennas. In *Proceedings of IEEE INFOCOM*.
8. Dai, H. N., Ng, K. W., & Wu, M. Y. (2007). A busy-tone based MAC scheme for wireless ad hoc networks using directional antennas. In *Proceedings of IEEE GLOBECOM*.
9. Gossain, H., Cordeiro, C., & Agrawal, D. P. (2006). Minimizing the effect of deafness and hidden terminal problem in wireless ad hoc networks using directional antennas. *Wireless Communications and Mobile Computing*, *6*, 917–931.
10. Gummalla, A. C. V., & Limb, J. O. (2000). Wireless medium access control protocols. *IEEE Communications Surveys and Tutorials*, *3*(2), 2–15.
11. Korakis, T., Jakllari, G., & Tassiulas, L. (2003). A MAC protocol for full exploitation of directional antennas in ad-hoc wireless networks. In *Proceedings of ACM MobiHoc*.
12. Korakis, T., Jakllari, G., & Tassiulas, L. (2008). CDR-MAC: A protocol for full exploitation of directional antennas in ad hoc wireless networks. *IEEE Transactions on Mobile Computing*, *7*, 145–155.
13. Li, Y., & Safwat, A. (2008). On wireless ad hoc networks with directional antennas: Efficient collision and deafness avoidance mechanisms. *EURASIP Journal on Wireless Communications and Networking, 2008*, 867465. doi:10.1155/2008/867465.

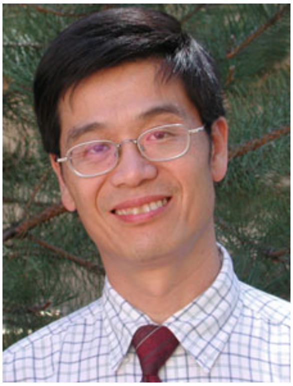
14. Ramanathan, R. (2001). On the performance of ad hoc networks with beamforming antennas. In *Proceedings of ACM MobiHoc*.
15. Ramanathan, R., Redi, J., Santivanez, C., Wiggins, D., & Polit, S. (2005). Ad hoc networking with directional antennas: A complete system solution. *IEEE Journal on Selected Areas in Communications*, *23*(3), 496–506.
16. Rappaport, T. S. (2002). *Wireless communications: Principles and practice* (2nd ed.). Upper Saddle River, NJ: Prentice Hall PTR.
17. Sekido, M., Takata, M., Bandai, M., & Watanabe, T. (2005). A directional hidden terminal problem in ad hoc network mac protocols with smart antennas and its solutions. In *Proceedings of IEEE Globecom*.
18. Takai, M., Martin, J., Bagrodia, R., & Ren, A. (2002). Directional virtual carrier sensing for directional antennas in mobile ad hoc networks. In *Proceedings of ACM MobiHoc*.
19. Takata, M., Bandai, M., & Watanabe, T. (2006). A receiver-initiated directional MAC protocol for handling deafness in ad hoc networks. In *Proceedings of IEEE ICC*.
20. Wang, Y., & Garcia-Luna-Aceves, J. J. (2004). Directional collision avoidance in ad hoc networks. *Performance Evaluation Journal*, *58*, 215–241.
21. Yi, S., Pei, Y., & Kalyanaraman, S. (2003). On the capacity improvement of ad hoc wireless networks using directional antennas. In *Proceedings of ACM MobiHoc*.
22. Zhang, J., & Jia, X. (2009). Capacity analysis of wireless mesh networks with omni or directional antennas. In *Proceedings of IEEE INFOCOM (mini-conference)* .
23. Zhang, Z. (2005). Pure directional transmission and reception algorithms in wireless ad hoc networks with directional antennas. In *Proceedings of IEEE ICC*.

Author Biographies



Hong-Ning Dai now is with Faculty of Information Technology at Macau University of Science and Technology as an assistant professor. He obtained the Ph.D. degree in Computer Science and Engineering from the Chinese University of Hong Kong in 2008. He also received the B.E. and M.E. degrees in Computer Science and Engineering from South China University of Technology. His current research interests include wireless networks, wireless sensor networks, mobile computing and distributed systems. He is a member of the ACM, a member of the IEEE and a member of IEEE Communications Society.

Kam-wing Ng is currently a Professor with the Department of Computer Science and Engineering at the Chinese University of Hong Kong in Hong Kong. His research interests are in distributed systems.



Min-You Wu is an IBM Chair Professor in the Department of Computer Science and Engineering at Shanghai Jiao Tong University. He serves as the Chief Scientist at Grid Center of Shanghai Jiao Tong University. He is also a research professor of the University of New Mexico, USA. His research interests include grid computing, wireless networks, sensor networks, overlay networks, multimedia networking, parallel and distributed systems, and compilers for parallel computers. He has published over 150 journal and conference papers in the above areas. His research has been supported by National Science Foundation, DoD, DoE, DARPA, China 863 program, China 973 program, and Natural Science Foundation of China. He is a senior member of IEEE.