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An SDMA-based MAC protocol for wireless ad hoc networks with smart antennas ☆

Neng-Chung Wang [a,*], Yu-Chun Huang [b]

[a] Department of Computer Science and Information Engineering, National United University, Miao-Li 360, Taiwan, ROC
[b] Department of Computer Science and Information Engineering, Chaoyang University of Technology, Taichung 413, Taiwan, ROC

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ABSTRACT

A wireless ad hoc network consists of a set of wireless devices. The wireless devices are capable of communicating with each other without the assistance of base stations. Space Division Multiple Access (SDMA) is a new technology designed to optimize the performance of current and future mobile communication systems. In this paper, an SDMA-based MAC protocol (S-MAC) for wireless ad hoc networks with smart antennas is proposed. The proposed protocol exploits the SDMA system to allow reception of more than one packet from spatially separated transmitters. Using SDMA technology provides collision-free access to the communication medium based on the location of a node. The proposed protocol solves the hidden terminal problem, the exposed terminal problem, and the deafness problem. Simulation results demonstrate the effectiveness of the proposed S-MAC in improving throughput and increasing spatial channel reuse.

1. Introduction

A wireless ad hoc network is a network of self-organizing wireless devices able to directly communicate with one another [1–3]. Each node in a wireless ad hoc network functions both as a host and as a router. Two nodes can communicate directly if they are within transmission range of each other.

The design of IEEE 802.11 assumes an omni-directional antenna at the physical layer. Existing antenna systems are equipped with omni-directional antennas in wireless ad hoc networks. Therefore, the mobile nodes share a single wireless channel. Using omni-directional antennas leads to lower spatial channel utilization because only one pair of communicating nodes can transmit data at the same time.

New ideas about increasing network throughput by using smart antennas, which allow the nodes to transmit packets in different spatial channels, have been proposed. Smart antennas [4–6] can enhance network throughput more efficiently than omni-directional antennas in wireless ad hoc networks [7–10]. Smart antennas offer some advantages that enhance spatial reuse of the wireless channel and extension of the transmission range. To use the advantages of smart antennas in wireless ad hoc networks requires an efficient MAC protocol. In this paper, a new MAC scheme designed to improve network throughput performance and spatial channel utilization is proposed.

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* Corresponding author. Tel.: +886 37 381899; fax: +886 37 354326.
E-mail addresses: ncwang@nuu.edu.tw (N.-C. Wang), s9367607@mail.cyut.edu.tw (Y.-C. Huang).

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In recent studies, several MAC protocols have been proposed that suitably adapt IEEE 802.11 for directional antennas. However, directional transmissions in wireless ad hoc networks result in serious location information problems [11,12]. The transmitter must know the location of a receiver to turn the beam in a suitable direction before transmitting Request-to-Send (RTS) frames. The transmitter creates the appropriate beam patterns, depending on the location of a receiver. Some studies assume that the location of a node may be obtained using a Global Positioning System (GPS) [3,7,13,14]. Other studies assume the transmission of data through the routing layer in order to acquire information about the location of a receiver, or the location of a receiver. In [15], RTS frames are transmitted omni-directionally in order to find the location of a receiver. Korakis et al. [11] proposed a MAC protocol for full exploitation of directional antennas that scans the entire area around a transmitter in order to find the location of a receiver or a transmitter. Although this scheme attempts to extend the communication range, circular transmission increases delay time and incurs a large control overhead. Ko et al. proposed a MAC protocol that utilizes the directional transmission capability of a directional antenna to improve bandwidth efficiency, called Directional MAC (D-MAC) [7]. Lal et al. proposed a MAC protocol that exploits the creation of spatial channels designed to enhance the throughput for ad hoc networks [9]. This scheme uses Space Division Multiple Access (SDMA) technology with smart antennas.

The rest of this paper is organized as follows. In Section 2, related work is presented. Section 3 describes the proposed SDMA-based MAC protocol in detail. In Section 4, the performance of the proposed protocol is compared with other MAC protocols through simulation. Conclusions are provided in Section 5.

2. Related work

In this section, the relevant background that includes the concept of IEEE 802.11, D-MAC, and Lal's MAC is introduced.

2.1. IEEE 802.11

IEEE 802.11 [16] is a popular protocol that defines the functions of the MAC and PHY layers in wireless ad hoc networks and infrastructure networks. This popular protocol assumes the use of omni-directional antennas at the physical layer. IEEE 802.11 MAC protocol uses a handshake mechanism implemented by exchanging small control packets identified as Request-to-Send (RTS) and C1ear-to-Send (CTS) packets. The successful exchange of these two control packets reserves the channel for transmission thereby preventing collision occurrences. However, this mechanism wastes the network capacity because the control packets reserve the wireless media over a large area. The IEEE 802.11 MAC protocol exploits the binary exponential backoff algorithm to resolve channel contention. When a frame exchanging sequence between two nodes is in progress, all other nodes within range of the transmitter or the receiver defer their transmission to avoid interference with the ongoing sequence. In IEEE 802.11, every station maintains a duration value, known as the Network Allocation Vector (NAV).

According to the RTS/CTS handshaking, the transmitter sends the RTS frame to the receiver before transmitting the data frame. The receiver replies to the CTS frame after receiving the RTS frame. Other nodes overhear the RTS or CTS frame and awake to someone who wants to send packets, update the NAV, and wait for the end of transmission. A node updates the value of the NAV with the duration field specified in every frame. The duration field records how long the medium is to be reserved during this period.

In wireless ad hoc networks, RTS/CTS handshaking is normally used to deal with the common hidden terminal problem, which is intended to reduce collision occurrence. All nodes share the medium when a frame is in the process of exchanging a sequence. Although this ensures that reservation of the wireless media will prevent collision occurrence, it will also squanders spatial channel utilization. This problem is the so-called exposed terminal problem.

2.2. Directional MAC (D-MAC)

Ko et al. proposed a Directional MAC (D-MAC) using directional antennas to improve bandwidth efficiency [7]. D-MAC protocol is similar to IEEE 802.11 in many ways. D-MAC send an acknowledgment (ACK) immediately after the DATA, as in 802.11. However, with D-MAC, the ACKs are sent using a directional antenna rather than using an omni-directional antenna.

In IEEE 802.11, if a node *N* is aware of an on-going transmission between two other nodes, node *N* will not participate in a transfer itself. That is, *N* will not send all RTS, or send a reply to an RTS from another node while the transfer between other two nodes is in progress. In brief, if antenna *T* at node *N* has received an RTS or CTS related to an on-going transfer between two other nodes, then node *N* will not transmit anything using antenna *T* until that other transfer is completed.

Antenna *T* is considered to be "blocked" for the duration of that transfer and each node can determine when a blocked antenna should become unblocked. When using directional antennas, while one directional antenna at some node may be blocked, other directional antennas at the same node may not be blocked. This allows transmission using the unblocked antennas. With D-MAC, omni-directional transmission of a packet requires the use of all the directional antennas; an omni-directional transmission can be performed if none of the directional antennas are blocked.

2.3. Lal's MAC

Smart antennas used in wireless networks provide many benefits including a wider coverage area, higher spatial reuse, and higher network capacity [17–21]. The smart antenna system associates multiple antenna elements with a signal processing capability to automatically optimize its radiation and reception pattern in response to the signal environment. The most sophisticated utilization of smart antenna technology is in a Space Division Multiple Access (SDMA) system. This employs advanced processing techniques to locate and track mobile terminals, and adaptive steering transmission signals directed toward users and away from interferers [9,22–25]. In theory, a smart antenna system with M elements can support M spatial channels per conventional channel. The SDMA system allows multiple nodes to operate in the same frequency/time slot and uses the smart antenna to separate signals. The SDMA technology uses a smart antenna system that employs an adaptive array algorithm by using intelligent signal processing to steer the antenna pattern in the direction of the desired user and places nulls in the direction of the interfering signals.

Lal et al. proposed a MAC layer protocol using SDMA [9]. In this scheme, a node receives more than one packet from spatially separated transmitters. To achieve multiple receptions at a particular time requires the synchronization of these transmitters. Before a receiver initiates reception, the node must send an omni-directional RTR (Ready-to-Receive) frame to a transmitter containing a unique training sequence about the receiver. Each transmitter replies with a directional RTS message containing a unique training sequence about the transmitter. This scheme transmits RTS/CTS/DATA/ACK using a directional transmission mode intended to reserve transmission (Directional-NAV). After reception of the RTS frame, the receiver simultaneously sends the directional CTS to all transmitters. Finally, data frames are transmitted directionally toward the receivers. After the data packets are received, the receiver replies with a simultaneous directional ACK. Unfortunately, the RTR and RTS frames used in this scheme are longer than the typical size of a control frame in IEEE 802.11. Because non-blind beam forming requires a unique training sequence that is reasonably orthogonal to all other sequences, using such a sequence also increases the packet sizes. The longer RTR frames create the extra overhead in the scheme.

3. Proposed SDMA-based MAC protocol

In this section, the proposed SDMA-based MAC protocol (S-MAC) is described. S-MAC is based on IEEE 802.11 Distributed Coordination Function (DCF). Consequently, the physical carrier sensing, the virtual carrier sensing, and the random backoff procedure of the proposed S-MAC are the same as that of IEEE 802.11 DCF. Each node in our scheme is equipped with smart antennas. In S-MAC, each node transmits or receives more than one packet from spatially separated nodes. The traditional beamforming and beam-steering techniques assume there is only one transmission direction of the node, but spatial division processing combines signals by using multiple antenna elements of association to communicate more than one node within a separated space. The proposed S-MAC enhances network capacity and substantially increases spatial reuse.

3.1. Modified RTS/CTS handshake

In wireless ad hoc networks, using an omni-directional transmission mode is effective for determining the location of a destination node because nodes in wireless ad hoc networks are free to move anywhere independently. In the proposed S-MAC, the location of the intended receiver is obtained by using omni-directional RTS.

The modified RTS/CTS handshake of the proposed S-MAC is as follows.

1. Omni-directional RTS (Request-to-Send): node A sends a RTS frame using the omni-directional mode. Initially, transmitter node A wants to send a packet to receiver node B, but node A does not know the location of node B. Therefore, node A broadcasts RTS to find the location of node B using the omni-directional transmission mode. Node A sends RTS to all the nodes in its coverage range. The neighbors (other than node B) receiving RTS from transmitter node A realize that node A wants to communicate with node B. The neighbors in the coverage range of transmitter node A check their respective beam table so as not to interfere with the communication between nodes A and B.
2. Omni-directional CTS (Clear-to-Send): node B sends a CTS frame using the omni-directional mode. After receiving RTS, receiver node B broadcasts CTS in its coverage range using omni-directional transmission. The neighbors (other than node A) which receive CTS from receiver node B realize that node A wants to communicate with node B. The neighbors of receiver node B check their respective beam table, and the nodes avoid interfering in the communication between node A and node B. Based on the direction in which CTS is received, the neighbors update the beam information on node B. The neighbors in the coverage range of receiver node B update their respective beam table according to the beam information in CTS. This beam information on the communicating nodes is attached to the CTS. Therefore, the neighboring nodes do not interfere with the communication process.
3. Omni-directional BDTS (Beam-Direction-to-Send): node A sends a BDTS frame using the omni-directional mode. The BDTS control frame must be modified in order to forward beam information about the communicating nodes to the neighbors. Transmitter node A broadcasts BDTS in its coverage range using omni-directional transmission after receiving CTS. The neighbors (other than node B) in the coverage range of transmitter node A update their respective beam table according to the beam information in BDTS. The beam information on the communicating nodes is attached to the BDTS. Therefore, the neighbors avoid collision and the hidden terminal problem due to asymmetry in gain.

4. Directional DATA: the transmitter sends data to the receiver using the directional transmission mode.
5. Directional ACK: the receiver replies by sending an ACK to the transmitter using the directional transmission mode.

For example, as shown in Fig. 1, node *A* wants to transmit information to a destination node *B* in a wireless ad hoc network. Node *A* is the transmitter, node *B* is the receiver, D-ACK represents a reply with ACK using the directional transmission mode, D-DATA indicates that data is sent using the directional transmission mode, and omni-RTS/CTS/BDTS represents the transmission of RTS/CTS/BDTS using the omni-directional transmission mode. In the omni-directional transmission mode, each node uses four antenna elements having individual beams of 90°, and beam widths covering 360° to simultaneously broadcast a control frame using all the beams. Therefore, the coverage area in S-MAC is wider than the conventional MAC protocol using omni-directional antennas.

The RTS/CTS handshaking attempts to reserve the wireless channel and exchange location information. CTS/BDTS handshaking attempts to forward the beam information to the neighbors. The transmitter sends a RTS frame to all nodes in its coverage area. These nodes, excluding the receiver in the coverage area of the transmitter, check their beam tables. Therefore, they do not interfere with the communication between the transmitter and the receiver. Otherwise, these nodes update the location information and duration value according to the RTS. The transmitter must send RTS to find the expected receiver of location information. The receiver determines the location of the transmitter based on acceptance of the direction of RTS. The nodes in the coverage area of the receiver update the location information in their respective beam table based on the CTS. The modified CTS and BDTS frame formats are shown in Figs. 2 and 3, respectively.

The CTS/BDTS frame has a few additional attributes: (a) the sender beam and (b) the receiver beam. The CTS/BDTS control frame must be modified in order to forward the beam information on the communicating nodes to the neighbors. The beam information of the communicating nodes is attached to the CTS/BDTS frame. Therefore, neighbors in the coverage area of the transmitter and receiver can prevent collision during communication. Because directional transmissions result in serious problems with location information, the proposed S-MAC exploits omni-directional transmission of control frames to prevent problems from occurring. In addition, the proposed S-MAC uses omni-directional RTS/CTS frames to find the location of the receiver.

3.2. Beam table

The proposed S-MAC protocol employs a simple scheme to prevent collision and increase throughput. Using the SDMA system, medium access was assigned to the nodes based on their locations. In this scheme, each node must maintain a beam table. The transmitter must have the beam information of the intended receiver to point the beam in the appropriate direction.

Fig. 4 shows how these nodes set up their beam tables. It is assumed that node *A* transmits data to node *B* in this example. Initially, each beam table is empty and is updated upon every reception. Nodes *B* and *C* are neighbors that hear the omni-directional RTS from node *A*. The beam information of the transmitter is attached to the RTS frame. In the RTS frame, nodes *B* and *C* obtain the relative beam direction of node *A*. Tables 2 and 3 show the results after nodes *B* and *C* have updated their beam tables.

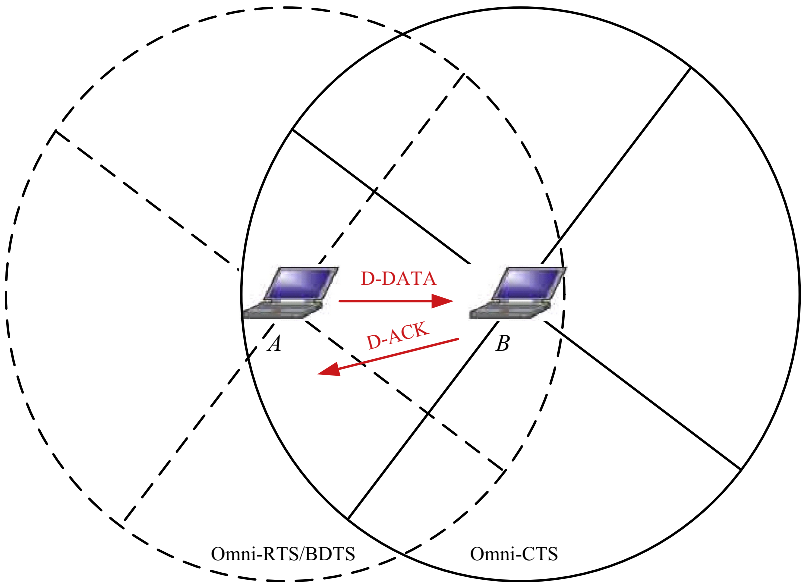

Fig. 1. The MAC protocol handshake.

Bytes	2	2	6	1	1	4
	Frame control	Duration	Receiver address	Sender beam	Receiver beam	FCS

Fig. 2. The modified CTS frame format.

Bytes:	2	2	1	1	4
	Frame control	Duration	Sender beam	Receiver beam	FCS

Fig. 3. The BDTS frame format.

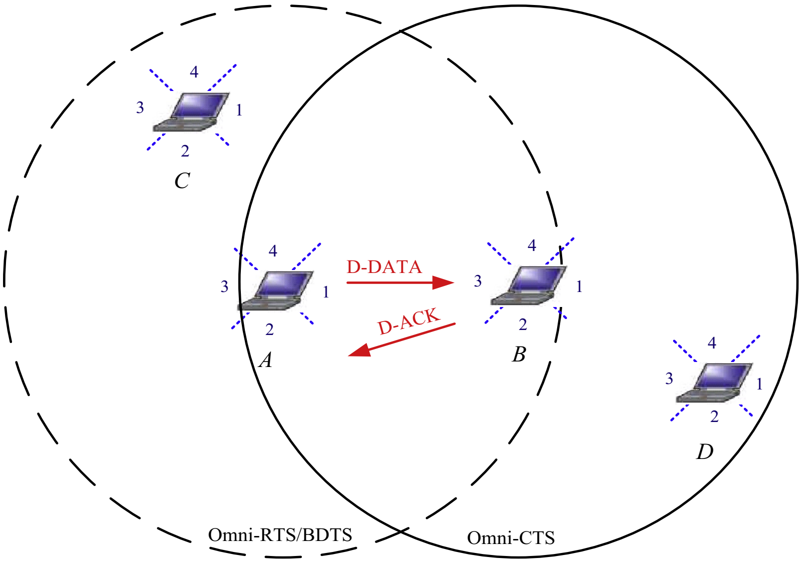

Fig. 4. Communication based on SDMA.

Nodes *A* and *D* are both in the coverage area of node *B*, receiving the CTS frame. Nodes *A* and *D* obtain the relative beam direction of node *B*. Tables 1 and 4 show the results after nodes *A* and *D* have updated their beam tables. The beam information on the communicating nodes is attached to the CTS and BDTS frames. All nodes maintain the data in their beam tables when they receive a control frame, such as the omni-directional RTS/CTS/BDTS frame. The proposed scheme maintains the beam tables by broadcasting RTS/CTS/BDTS to prevent collision. The scheme is based on the SDMA mechanism to achieve multiple transmissions; thus, the performance greatly improves network capability.

3.3. Modified Network Allocation Vector (NAV)

The Virtual Carrier Sense (VCS) mechanism in IEEE 802.11 was essentially designed to calculate the duration value of a frame. The length of all remaining frames in the sequence must be known as *priori*. In this mechanism, every station maintains a duration value, which is called the Network Allocation Vector (NAV). When nodes hear a RTS/CTS frame, they examine this duration value. Based on NAV, nodes can also recognize whether the transmission medium is busy or not and can prevent collision accordingly.

Table 1
The beam table of node *A*.

Me	Neighbor	My beam	Neighbor's beam
A	*B*	1	3

Table 2
The beam table of node *B*.

Me	Neighbor	My beam	Neighbor's beam
B	*A*	3	1

Table 3
The beam table of node *C*.

Me	Neighbor	My beam	Neighbor's beam
C	*A*	2	4

Table 4
The beam table of node *D*.

Me	Neighbor	My beam	Neighbor's beam
D	*B*	3	1

The proposed scheme modifies VCS in IEEE 802.11, and is shown in Fig. 5. The omni-directional NAV contains the RTS/CTS/BDTS handshake. This scheme assigns an omni-directional NAV which is shorter than the conventional NAV. If other nodes do not interfere with this transmission and prevent collisions, these nodes start communicating once a BDTS frame has been sent. The duration value would be attached to the RTS/CTS/BDTS frames. When the nodes hear a control frame (RTS/CTS/BDTS), they update their NAV. According to their beam tables, all the nodes can estimate whether interference with a communicating action will occur. Based on the beam information of the received CTS/BDTS, the neighbors decide to initiate a block if it is necessary to defer their transmission in a specific beam direction. The value of the beam NAV is updated from the duration field of the overheard CTS/BDTS.

3.4. Improvement in wireless ad hoc networks

In IEEE 802.11, RTS/CTS handshaking is always used to cope with the common hidden terminal problem. However, the directional transmission of RTS/CTS most often used in directional MAC protocols generates the hidden terminal problem. The proposed protocol solves the hidden terminal problem, the exposed terminal problem, and the deafness problem.

3.4.1. Hidden terminal problem due to unheard RTS/CTS

Directional transmission of RTS/CTS leads to a new hidden terminal problem [3,11,13]. In the proposed S-MAC, each node unnecessarily wastes time while waiting for the end of a communication. Because smart antennas employ the SDMA mechanism, numerous nodes can communicate at the same time without influencing one another. Therefore, they can enhance network throughput and increase spatial reuse.

The example shown in Fig. 6 assumes that communication between nodes *A* and *B* is in progress, with node *A* transmitting to node *B*. Using the beam information that is contained in the CTS/BDTS, the neighbors know that node *A* is receiving data using beam 1 while node *B* is receiving data using beam 3. If node *E* wants to transmit data to node *B*, node *E* determines that

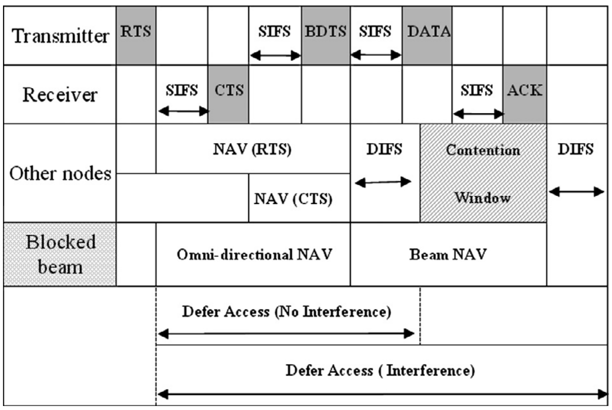

Fig. 5. The NAV of RTS/CTS/BDTS.

it cannot interfere with the transmission already in progress. If node *E* wants to transmit data to node *A*, it recognizes that this could interfere with the reception of node *A*. Therefore, node *E* defers its transmission through beam 3, updates its beam NAV, and avoids collision.

3.4.2. Exposed terminal problem

As is also shown in Fig. 6, according to the IEEE 802.11 MAC protocol, when a communication between nodes *A* and *B* is in progress, the neighbors *C*, *D*, and *E* must defer their transmissions until the current communications are finished. In the proposed S-MAC, if node *E* wants to transmit data to node *D*, node *E* acknowledges that it cannot interfere with the communication already in progress. This solves the exposed terminal problem and increases the spatial reuse of a wireless channel.

3.4.3. Deafness

A conspicuous problem with a directional MAC protocol such as D-MAC [7] is deafness, identified and discussed in [13,14]. The example shown in Fig. 6 assumes that node *A* is transmitting data to node *B*, and node C wants to send RTS to node *A*. Node *A* beams in the direction of node *B* using directional antennas. Node *A* does not receive the RTS nor does it reply with CTS. In the proposed S-MAC, after node *C* receives the BDTS frame, it knows that node *A* is sending data using beam 1 while node *B* is receiving data using beam 3. Node *C* realizes that it cannot interfere with the communication already in progress. Node *C* sends RTS to node *A*. Node *A* responds with CTS simultaneously using beams 2, 3, and 4. Node *C* sends data using beam 2, and node *A* receives data using beam 4. The S-MAC scheme solves the deafness problem and allows more than one simultaneous communication.

3.4.4. Hidden terminal problem due to asymmetry in gain

A directional hidden terminal problem occurs when the directional beam of a higher gain is used. The proposed S-MAC solves this problem as follows: As in the example shown in Fig. 7, this problem is caused by neighbor *C*, which is far enough from node *B* to avoid hearing the omni-directional CTS. If node *C* transmits the omni-directional RTS to node *B*, it may interfere with the ongoing communication because node *B* is receiving data from node *A*. The proposed scheme is able to prevent this from happening. When node *C* overhears a BDTS frame from node *A*, it realizes there is ongoing communication between nodes *A* and *B*. Node *C* knows that node *B* is transmitting data to or receiving data from node *A* using beam 3. Node *B* communicates with node *C* using beam 3. Node *C* realizes that it will interfere with the reception of node *B*. Therefore, node *C* defers its transmission through beam 1 and updates its beam NAV table until the current communication finishes.

4. Performance evaluation

In this section, the software and parameters used in the simulation are introduced. In addition, we will compare the proposed S-MAC with IEEE 802.11 [16], D-MAC [7], and Lal's MAC [9].

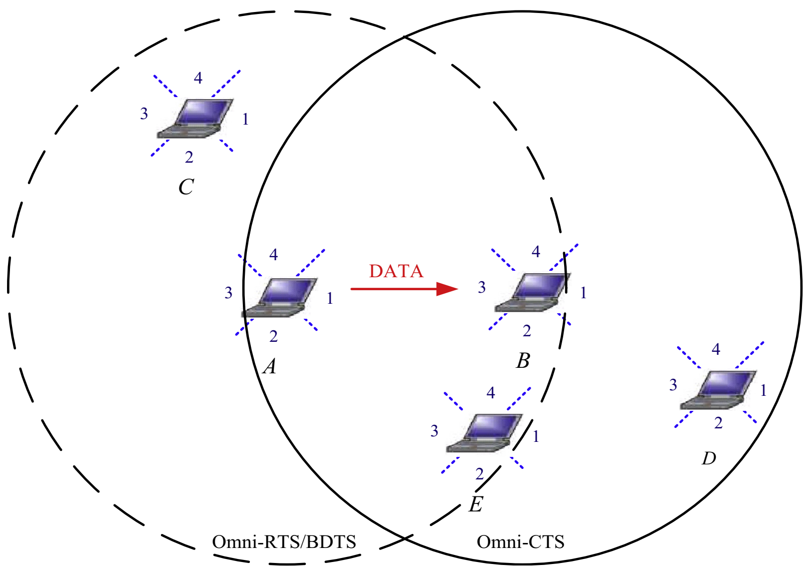

Fig. 6. An example of the hidden terminal problem due to unheard RTS/CTS.

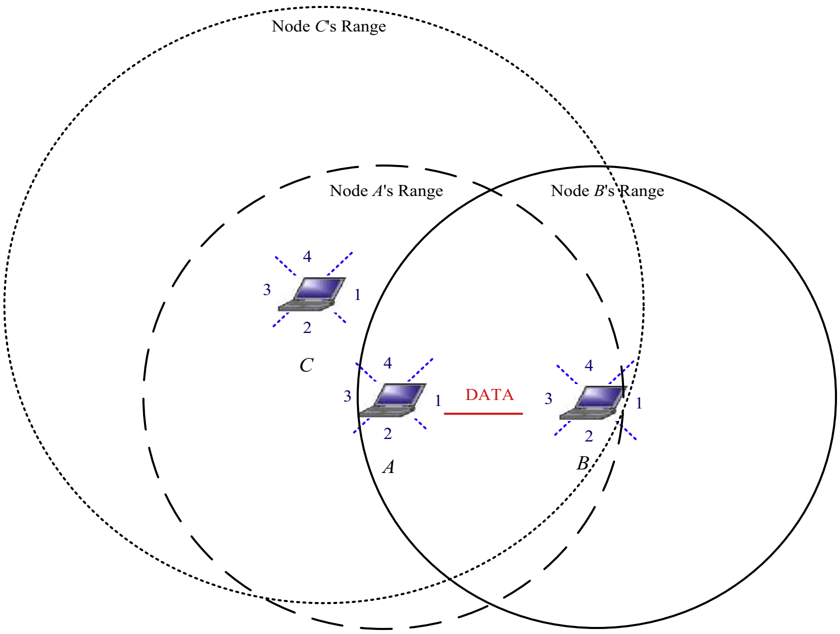

Fig. 7. An example of the hidden terminal problem due to asymmetry in gain.

4.1. Simulation environment

A performance evaluation using NS2 (Network Simulation 2) was conducted. In the following simulations, some assumptions about the parameters of the system architecture have been made. Each node was equipped with antenna arrays of 4 elements. The omni-directional transmission range was 150 m. The directional transmission range was 250 m. The beam width of the directional transmission was 90°. The data packet size was 1024 bytes. Data transmission rate was set to 11 Mbps. The Short Interframe Spaces (SIFS) was 16 microseconds and the Distributed Coordination Function Interframe Spaces (DIFS) was assumed to be 50 microseconds. The sender and receiver were randomly chosen. Each node was randomly assigned an initial energy. At the start of every simulation the beam table of each node was empty and was gradually updated as the simulation progressed. The performance metrics used were as follows:

1. Network throughput: the throughput of the overall nodes in the network.
2. Network utilization: the number of nodes using the wireless channel to transmit packets in the network.
3. Transmission time: the amount of time taken to go from the start of the transmission to the arrival of the data at the destination node.

4.2. Simulation results

4.2.1. A random topology

Seventy nodes were arranged at random in a square area 500 m × 500 m. In this simulation, the network size varied between 10 and 70 nodes and the effects of this were observed. Fig. 8 shows the average throughput of the four schemes using a varied number of nodes. In general, the throughput increased when the number of nodes increased. The throughput of S-MAC was roughly 720% of IEEE 802.11, 280% of D-MAC, and 135% of Lal's MAC. In this simulation, the proposed S-MAC significantly increased the throughput. IEEE 802.11 performed the worst because of the exposed terminal problem. D-MAC performed poorly as a result of the hidden terminal problem due to the unheard RTS/CTS, as well as due to asymmetry in gain. In Lal's MAC, the transmitter nodes deferred their communication until the received RTR led to increased transmission time and reduced throughput performance.

Fig. 9 shows an overall comparison of network utilization and mobile nodes of the four schemes. It can easily be seen that the performance of network utilization in S-MAC was better than that in IEEE 802.11, D-MAC, and Lal's MAC. S-MAC improved the spatial reuse of the wireless channel because of the four beams used in the SDMA technique; consequently, more pairs of nodes could communicate simultaneously without interference. Lal's MAC had poor performance because the RTR and RTS frames that were used in the Lal's MAC scheme were longer than the typical size of a control frame in IEEE 802.11.

4.2.2. A grid topology

In the next two simulations, a grid topology with 25 nodes and random data flows was conducted. The length of each grid was 100 m. Fig. 10 shows a grid topology with 25 nodes.

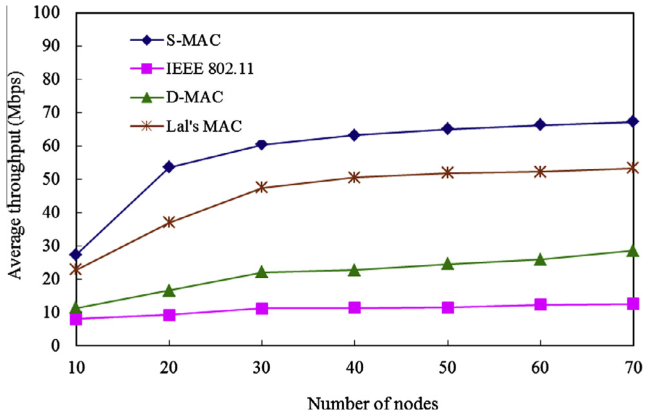

Fig. 8. Average throughput vs. number of nodes.

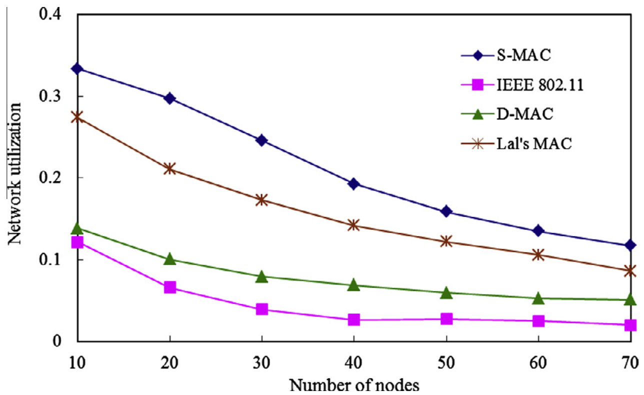

Fig. 9. Network utilization vs. number of nodes.

Fig. 11 shows the average throughput vs. various data lengths. In small packet transmission, the throughput of S-MAC was roughly 300% of IEEE 802.11, 190% of D-MAC, and 170% of Lal's MAC. In large packet transmission, the throughput of S-MAC was roughly 600% of IEEE 802.11, 400% of D-MAC, and 180% of Lal's MAC. These simulation results demonstrated that S-MAC enhanced network throughput due to increased spatial reuse.

Fig. 12 shows the packet transmission time for the various data lengths in the network. In this simulation, the proposed S-MAC outperformed IEEE 802.11, D-MAC, and Lal's MAC. In S-MAC, such conservative collision avoidance largely nullified the benefits of spatial reuse. In IEEE 802.11, most of the nodes spent more time in the wait state after perceiving that the channel was busy. In D-MAC, directional transmissions interfered with more nodes. Therefore, S-MAC yielded the most satisfactory simulation results.

In the next simulation, a grid topology with aligned data flows was conducted. In this simulation, the network size varied between 9 and 81 nodes and the effect of average throughput in the grid topologies was observed. The length of each grid was 100 m. Fig. 13 shows a grid topology with 25 nodes and 4 aligned data flows.

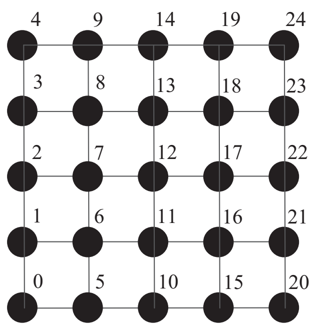

Fig. 10. A grid topology with 25 nodes.

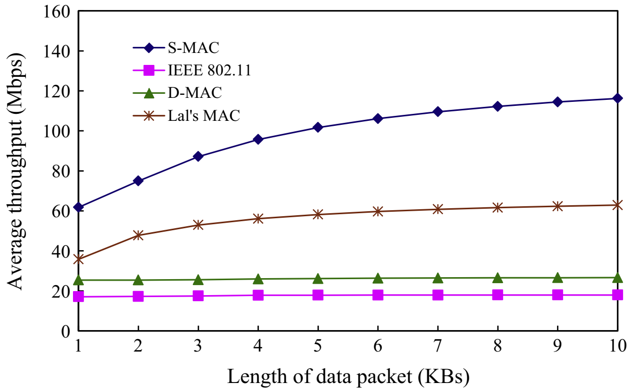

Fig. 11. Average throughput vs. length of data packet.

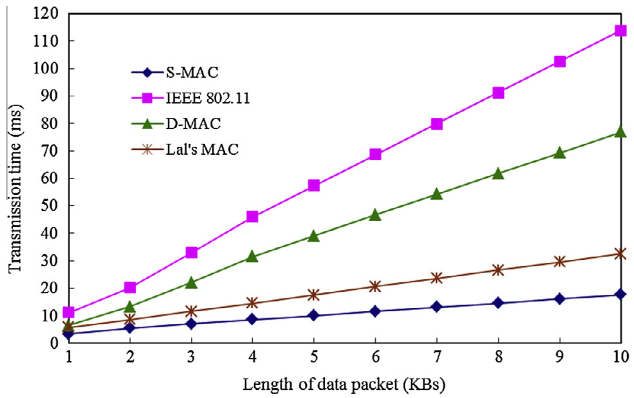

Fig. 12. Transmission time vs. length of data packet.

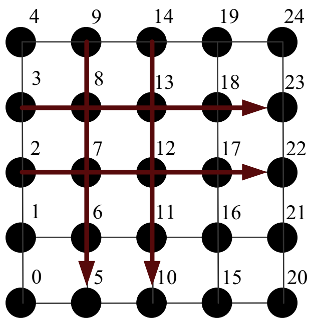

Fig. 13. A grid topology with 25 nodes and 4 aligned data flows.

Fig. 14 shows the throughput performances of the proposed S-MAC, IEEE 802.11, D-MAC, and Lal's MAC. The proposed S-MAC outperformed IEEE 802.11, D-MAC, and Lal's MAC. The throughput of S-MAC was roughly 530% of IEEE 802.11, 260% of D-MAC, and 235% of Lal's MAC. This was because deafness occurred in D-MAC due to directional transmission of RTS/CTS. IEEE 802.11 had the worst throughput performance because of poor network utilization. Most of the nodes deferred their transmission until the current communication was complete. In Lal's MAC, all nodes periodically transmitted RTR and polled neighbors for packets. Therefore, Lal's MAC more frequently caused RTR collision when the number of nodes was greater than 49. Furthermore, the RTR and RTS frames were longer than the typical size of a control frame in IEEE 802.11, and Lal's MAC had extra control overhead decreasing performance. The proposed S-MAC could simultaneously communicate in four different directions. Therefore, S-MAC prevented collision and had the highest throughput performance of all.

In the next two simulations, a grid topology with 25 nodes and aligned data flows was conducted. The length of each grid was 100 m.

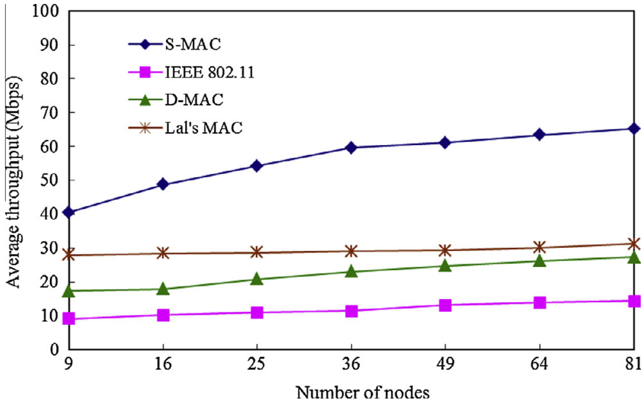

Fig. 14. Average throughput vs. number of nodes.

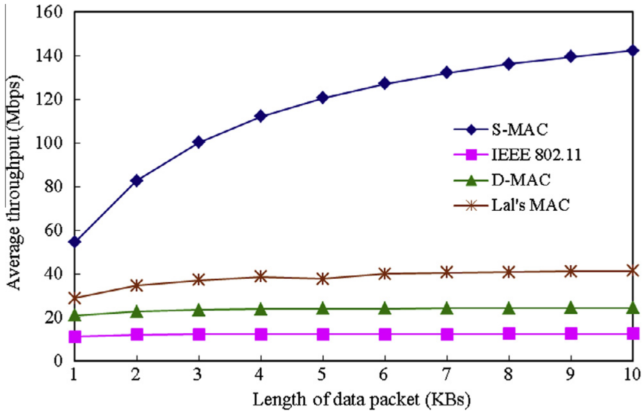

Fig. 15. Average throughput vs. length of data packets.

Fig. 15 illustrates the average throughput with data packets of different lengths. The throughput of S-MAC was roughly 980% of IEEE 802.11, 500% of D-MAC, and 320% of Lal's MAC. As can be seen in the figure, the throughput of S-MAC increased as the size of data packets increased. The throughputs of IEEE 802.11, D-MAC, and Lal's MAC did not increase as the size of data packets increased. The throughput of S-MAC clearly outperformed IEEE 802.11, D-MAC, and Lal's MAC. This simulation results confirmed that S-MAC effectively improved the spatial reuse of the wireless channel.

Fig. 16 illustrates the packet transmission time for different lengths of data packets in the network. The packet transmission time in IEEE 802.11 substantially increased when the size of data packets increased. The packet transmission time in D-MAC gradually increased as the size of data packets increased. In this simulation, the proposed S-MAC scheme slightly increased the packet transmission time when the size of data packets increased. Because S-MAC prevented collision, its performance clearly outperformed IEEE 802.11, D-MAC, and Lal's MAC.

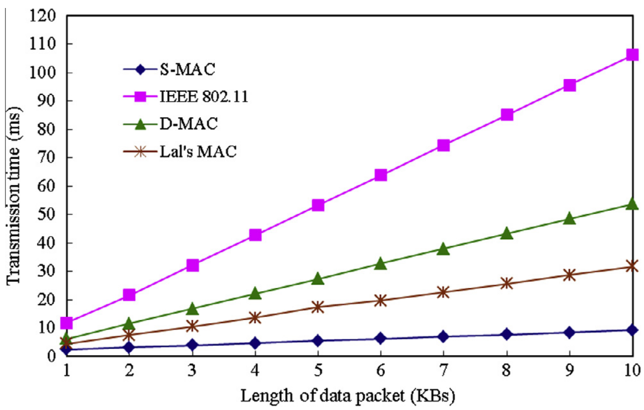

Fig. 16. Transmission time vs. length of data packet.

5. Conclusions

This paper proposed an SDMA-based MAC protocol, called S-MAC, for wireless ad hoc networks using smart antennas. The proposed S-MAC exploits the creation of spatial channels to effectively enhance network capacity. This protocol utilizes the broadcasting of RTS to find the location of a receiver, and employs a directional beam to increase spatial reuse of the wireless channel and extend the transmission range. This protocol does not assume any knowledge of the location of neighboring nodes. S-MAC exploits beam information by transmitting CTS and BDTS frames to find the beam being used by the communicating nodes. Each node uses a beam table to determine the direction of the busy beam and to prevent collision and congestion in the network. Simulation results showed that the performance of the proposed S-MAC substantially improves throughput and spatial channel reuse.

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Neng-Chung Wang received the Ph.D. degree in Computer Science and Information Engineering from National Cheng Kung University, Taiwan, in June 2002. He is a Professor at the Department of Computer Science and Information Engineering, National United University, Taiwan. His research interests include wireless and mobile networks, wireless communications, mobile computing, and cloud computing. He is a member of the IEEE.

Yu-Chun Huang received the B.S. degree in Business Administration from Dayeh University, Taiwan, in June 2000, and the M.S. degree in Computer Science and Information Engineering from Chaoyang University of Technology, Taiwan, in June 2006. Her research interests include mobile computing and wireless networks.