MAC Protocol for Smart-antenna Used Ad Hoc Networks with RTS/CTS Overhead Reduction

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***Abstract*—This paper proposes a MAC protocol for ad hoc networks with smart antennas. In the proposed protocol, pulse/tone exchange mechanism is applied to smart-antenna networks. The mechanism significantly reduces collisions caused by the hidden-node problem. Further throughput enhancement is achieved because of the compatibility between the pulse/tone exchange and the smart-antenna networks. The directional hidden-node problem is mitigated by the pulse/tone exchange. Additionally, the number of exposed nodes due to pulse/tone exchanges is limited because of the smart-antenna usage. Therefore, it is unnecessary to use RTS/CTS handshakes after pulse/tone exchanges, while RTS/CTS handshakes are necessary for omni-directional antenna system. This overhead reduction enhances the network throughput. As a result, the network throughput can be effectively improved. Simulation results show the validity and effectiveness of the proposed protocol.**

***Index Terms*—Ad hoc networks, smart antenna, pulse/tone, overhead reduction.**

I. Introduction

Ad hoc networks are next-generation networks without centralized control. IEEE 802.11 Distributed Coordination Function (DCF) [1] provides a request to send/clear to send (RTS/CTS) handshake protocol for reducing DATA frame collisions caused by hidden-nodes. Because RTS/CTS frames are shorter than DATA frames, RTS/CTS handshakes can effectively decrease the DATA frame collisions. RTS/CTS handshakes, however, increase the network overhead. In addition, there is a possibility that an RTS frame collides with other RTS frames transmitted by neighbor nodes. The IEEE 802.11 DCF is originally designed for nodes with omni-directional antennas. However, the omni-directional antenna usage limits the spatial-reusability of the network.

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Recently, wireless communication systems using a beamforming of the smart antenna have attracted many researchers' attention [2–11]. Smart antennas provide two separate modes. One is the omni-mode, where the antenna radiates in omni-directions. The other is the directional mode, where the antenna can point its main lobe towards any specified direction. A MAC protocol for smart antenna networks was proposed in [3], in which IEEE 802.11 with RTS/CTS is applied to smart antenna networks. Because the spatial-reusability efficiency is enhanced by using smart antennas, the network throughput can be improved. However, there are two dominant factors for degrading the network throughput. One is the collision due to the hidden-node problem, which is called the hidden-node collision in this paper. The hidden-node problem includes the directional hidden-node problem, which newly arises in smart antenna networks. The other is the time wastage due to the deafness problem. When the deafness problem occurs, multiple retransmissions could happen. The contention window (CW) value increases exponentially as the number of retransmissions increases. The increase in the CW value causes the time wastage in the deafness problem.

On the other hand, an RTS collision avoidance (RCA) protocol was proposed to reduce RTS frame collisions in [13]. Pulse and tone, which are very short-time and narrow-band signals, are exchanged prior to the RTS/CTS handshake [13]. By applying the pulse/tone exchange, RTS frame collisions are reduced drastically [13]. Pulse and tone exchange, however, increases exposed nodes. In the RCA protocol [13], RTS/CTS handshakes are needed after pulse/tone exchanges for releasing exposed nodes from the frozen state in short duration and for recognizing the occurrence of the unexpected tone-detection. However, the large increase of exposed nodes still seriously limits the throughput, especially in networks with high node density and heavy offered load.

This paper proposes a MAC protocol for ad hoc networks with smart antennas. The proposed protocol requires each node to have only one transceiver. In the proposed protocol, the pulse/tone exchange mechanism is applied to smart antenna networks. Hidden-node collisions can be reduced by applying pulse/tone exchanges. Additional throughput improvement can be achieved because of the compatibility between the pulse/tone exchange and the smart-antenna network. The directional

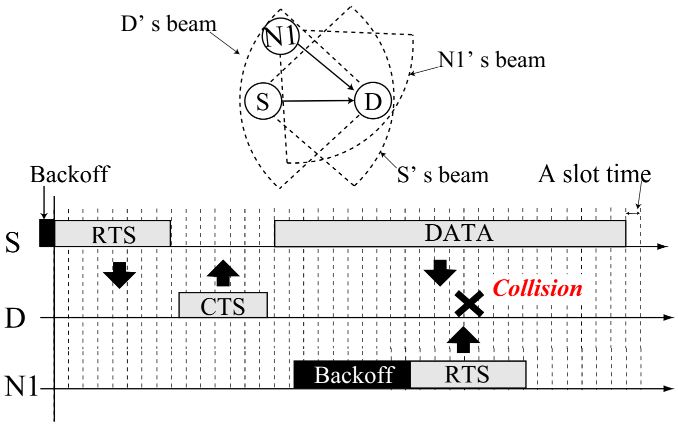

Fig. 1. An example scenario of the collision due to the directional hidden-node problem in the DMAC protocol.

hidden-node problem is mitigated by the pulse/tone exchange. Additionally, the number of exposed nodes due to pulse/tone exchanges is limited because of the smart-antenna usage. Therefore, it is unnecessary to use RTS/CTS handshakes after pulse/tone exchanges. This overhead reduction enhances the network throughput. As a result, the network throughput can be effectively improved. Simulation results show the validity and effectiveness of the proposed protocol.

II. Related Works

A. The hidden-node collisions and the deafness problem in smart antenna networks

Wireless communications in smart antenna networks can enhance the spatial reusability of the network [2–11]. The DMAC protocol (Directional Medium Access Control) [3] protocol is a basic MAC protocol for smart antenna networks. Figure 3(a) shows a flowchart of the DMAC protocol. In the DMAC protocol, a channel is reserved by using RTS/CTS handshakes. Because all frames are transmitted in the directional mode, the network spatial-reusability efficiency is high. Therefore, the throughput can be improved compared with omni-directional antenna networks.

However, the network throughput is degraded because of two dominant factors in the DMAC protocol. One is the hidden-node collision. The hidden-node collision often occurs when RTS frames are transmitted by multiple nodes simultaneously when the offered load is heavy. Additionally, collisions due to the directional hidden-node problem newly appear in smart antenna networks. Figure 1 shows an example scenario of a collision due to the directional hidden-node problem. In Fig. 1, we consider the case that the node N1 communicates with a certain node, which is in the opposite direction of the node S. In this case, the node N1 cannot hear the RTS/CTS handshake between the nodes S and D. There is a possibility that the node N1 transmits an RTS frame to the node D after the previous communication. Therefore, the RTS frame transmission of the node N1 interferes with the DATA frame transmission of the node S. In this case, the frame transmissions from both the nodes S and N1 are in failure. In Fig. 1, the node N1 is a hidden node of the node S due to the smart-antenna usage. Therefore, this collision problem is called "directional hidden-node problem". The other factor is the deafness problem, which causes the unnecessary time wastage according to [3].

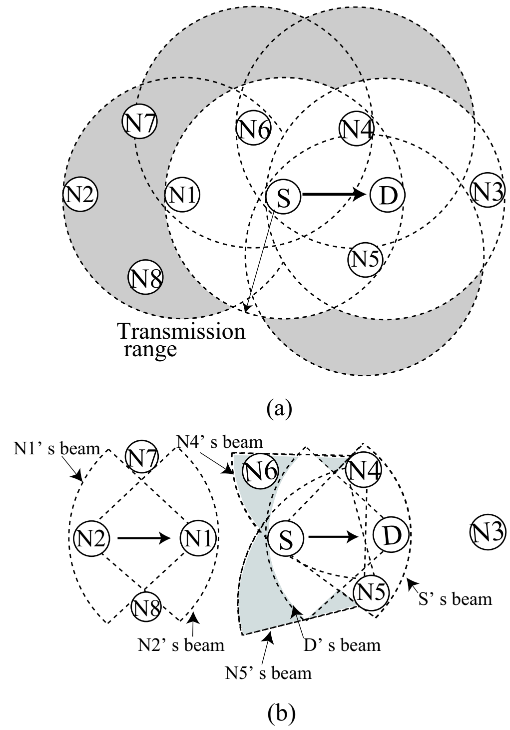

Fig. 2. Examples for exposed node increasing in the RCA and proposed protocols. (a) the RCA protocol (b) The proposed protocol.

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B. MAC protocol using pulse and tone

The RCA protocol was proposed in [13]. In this protocol, two narrow-band signals, which are called "pulse" and "tone", are used prior to RTS/CTS handshakes. According to [12], [13], it is sufficient for nodes to detect the pulse/tone signal in 5μs, which is much shorter than the RTS frame length. Figures 2(a) and 3(b) show an example scenario and a flowchart of the RCA protocol, respectively. The transmitter S transmits a pulse signal prior to the RTS frame transmission to inform its transmission to neighbor nodes. The pulse/tone exchange is carried out only one time slot at the final count of the backoff timer (BT). Because pulse and tone signals do not contain any information, all the nodes, which detect the pulse signal, reply tone signals, for example, Node D, N1, N4, N5, and N6 in Fig. 2(a). The pulse/tone signals do not collide with other pulse/tone signals. The pulse/tone exchanges do not interfere with other frame transmissions because the time durations of pulse and tone are very short. When the node S can detect the tone signals, it prepares to transmit an RTS frame to the node D. The simultaneous-transmission probability of pulse signals from multiple nodes is much lower than that of RTS frames because of the short durations of the pulse and tone signals. Therefore, the RTS frame collisions can be reduced by applying the

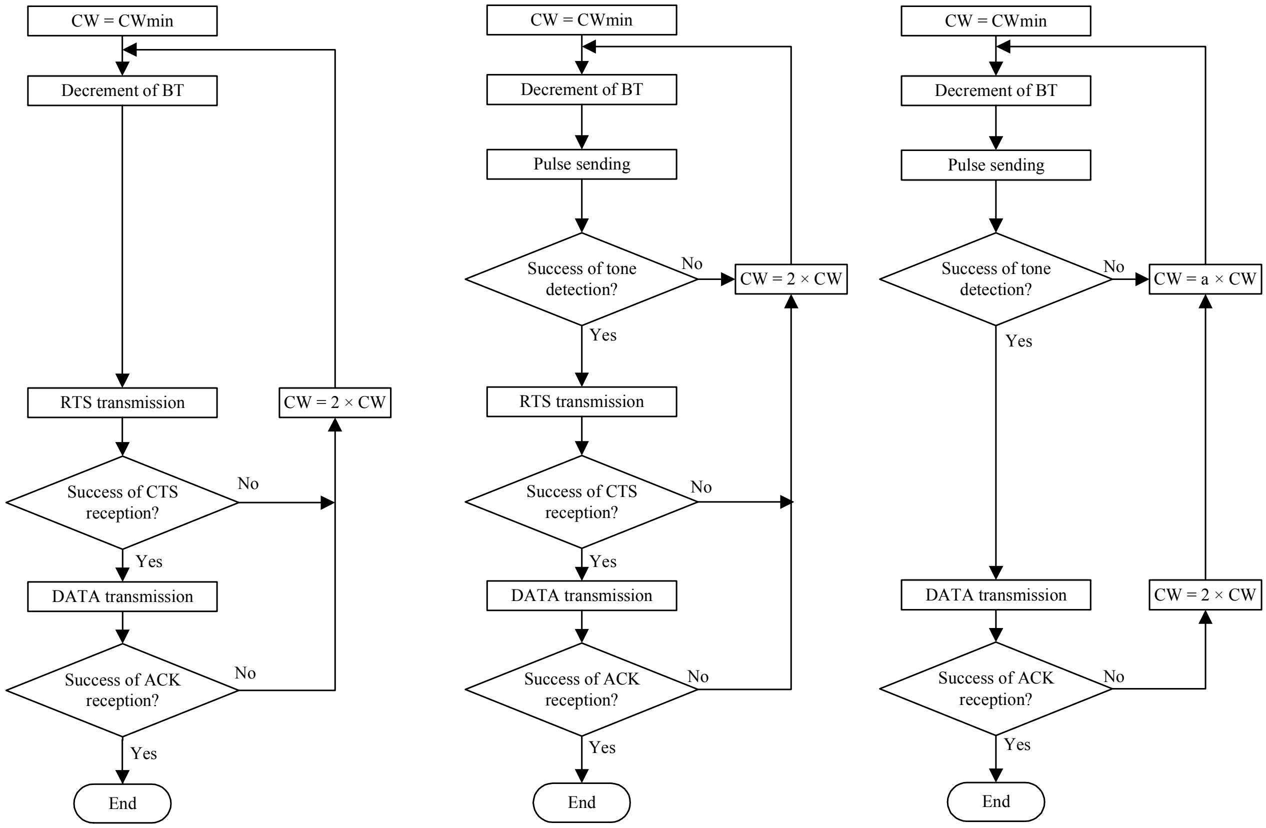

Fig. 3. Flowcharts of DMAC, RCA and the proposed protocols. (a) The DMAC protocol. (b) The RCA protocol. (c) The proposed protocol.

pulse/tone exchange. All the nodes, which are in the two-hop range from the transmitter, also detect the tone signals. The nodes, which detect only the tone signal, freeze their transmission process for the RTS frame transmission duration and the double Short Inter Frame Space (SIFS) duration by setting their Network Allocation Vector (NAV).

In the IEEE 802.11 with RTS/CTS, all the one-hop neighbor nodes of the transmitter and the receiver freeze their transmission process by receiving the RTS and CTS frames. In the RCA protocol, however, all nodes, which are in the two-hop range of the transmitter, freeze their transmissions by detecting the pulse/tone signals. Therefore, the number of exposed nodes increases compared with the IEEE 802.11 with RTS/CTS as shown in Fig. 2(a). In Fig. 2(a), the nodes within the gray area are the extra exposed nodes due to the pulse/tone exchange. In the RCA protocol in [13], an RTS/CTS handshake process is included. There is no description about the reason why the RTS/CTS handshake is needed. We suppose that the RTS/CTS handshake is included in the RCA protocol because the extra exposed nodes due to pulse/tone exchanges can be released from the frozen state in a short duration. Additionally, it is also possible to recognize the occurrence of the unexpected tone-detection by the RTS/CTS handshakes. The unexpected tone-detection occurs when the transmitter detects the tone signal as a response from the neighbor nodes. Any of these neighbor nodes is not a target receiver. Because the tone signal has no information in it, the transmitter cannot understand whether the tone signal was transmitted by the target receiver or not. The RTS/CTS handshake helps the transmitter to recognize the occurrence of the unexpected tone-detection because the RTS and CTS frames include transmitter and receiver information. The RCA protocol, however, still suffers from the increase in the exposed nodes, especially for high node density and heavy offered load conditions.

III. Proposed MAC protocol

In this paper, a MAC protocol for ad hoc networks with smart antennas is proposed. The basic idea of the proposed MAC protocol is that pulse/tone exchanges are applied to smart antenna networks. In the proposed protocol, we only focus on the MAC protocol design. It is assumed that each node knows all the neighbor nodes and their directions. This is the same assumption as the smart-antenna systems [3], [4], [7], [8], [11]. There are some techniques for identifying the node positions. GPS technique [5] is one of the methods which determine the location of a node in the network. Figure 3(c) shows a flowchart of the proposed protocol for the transmitter. Compared with the DMAC protocol, the short-duration pulse/tone signal exchanges are conducted prior to the DATA frame transmission in the proposed protocol instead of RTS/CTS frame handshakes.

A. Details of the proposed MAC protocol

Table I gives triggers and operations of each node when the

TABLE I
UNITS FOR MAGNETIC PROPERTIES

ID	Triggers	Operations
T1	A node has a data frame.	The node sets BT.
T2	A node confirms that the channel is idle in omni-mode until the final 1 time slot of the backoff stage is left.	The node prepares to send a pulse signal toward the destination direction.
T3	A node sends the pulse/tone signal or transmits the DATA/ACK frame completely.	The node sets a wait-timer for the tone signal, the DATA/ACK frame, respectively.
T4	A node detects a tone signal or receives a DATA frame.	The node prepares to send the relevant frame in directional mode, i.e. DATA or ACK.
T5	A node fails to detect a tone signal or receives the DATA/ACK frame within the preset wait-timer duration.	If it is failed to detect a tone signal the node retransmits a pulse signal with setting the BT again after multiplying CW by α, which equals 1. If it is failed to receive the ACK frame, the node retransmits a pulse signal with doubled CW value. If a DATA frame is failed to receive, the node returns to the previous state, i.e. the IDLE state or the *CONTEND* state.
T6	A node senses the channel in the directional mode and confirms that the channel is idle for a SIFS duration.	The node starts to send the pulse/tone signal or transmits the DATA/ACK frame in directional mode.
T7	A node senses the channel in directional mode. However, the node confirms that the channel is busy within a SIFS duration.	If the node prepares to transmit a DATA frame, it retransmits a pulse signal with the doubled CW value. If the node prepares to send the tone signal or transmit the ACK frame, it cancels the pending transmission and returns to the previous *IDLE* or *CONTEND* state.
T8	A node receives an ACK frame.	The transmission succeeds.
T9	A node detects a pulse signal when it is in the *IDLE* state or the *CONTEND* state.	The node prepares to send a tone signal in directional mode.
T10	A node detects only the tone signal when it is in the *IDLE* state or *CONTEND* state.	If the node is in the *IDLE* state, it sets the DNAV. If the node is in the *CONTEND* state, it freezes the BT countdown and sets the DNAV.
T11	The DNAV timer expires.	The node returns to the previous state, i.e. the *IDLE* state or the *CONTEND* state.

proposed protocol is applied to networks. Figure 4 shows the state transition diagram of the proposed protocol. In Fig. 4, a node changes the state when the trigger events occur. The trigger events are given in Table I. The number written on each arrow corresponds to the ID in Table I. All nodes start at the *IDLE* state in the omni mode, where the node has no transmission frame. When an IDLE node has a transmission frame, it sets the BT and moves to the *CONTEND* state following T1. In the *CONTEND* state, the transmitter senses the channel in the omni mode. After the transmitter confirms that the channel is idle, it requests the physical layer to beamform toward the receiver. Then the transmitter transits to the *TRANSMISSION* state and sends a pulse signal. After that, the transmitter sets a tone-wait timer and moves to the *WAIT_REPLY* state following T3.

When a node detects a pulse signal, it beamforms towards the transmitter following T9. In addition, when the node detects multiple pulses from different directions in the omni mode, it beamforms to the first pulse-detecting direction in the proposed protocol. When the node detects multiple pulses in the same direction, it beamforms to the pulse-detecting direction because a pulse signal does not collide with other pulse signals. Then the node confirms whether the channel is idle or not in a SIFS duration in the *WAIT_SIFS* state. If the node confirms that the channel is idle, it sends a tone signal and sets a DATA-wait timer. The node transfers to the *WAIT_REPLY* state as following T3. Inversely, if the node detects that the channel is busy in the *WAIT_SIFS* state, it does not send the tone signal and returns to the previous *IDLE* or *CONTEND* state following T5.

If the transmitter detects the tone signal, it transits to the *WAIT_SIFS* state following T4. After confirming that the channel is idle for the SIFS duration, the transmitter moves to the *TRANSMISSION* state following T6, and starts to transmit a DATA frame in the directional mode. Inversely, if the tone signal cannot be detected within the predefined tone-wait timer duration, the transmitter transits to the *CONTEND* state following T5 to set the BT again after multiplying CW by α shown in Fig. 3(c). In the proposed protocol, the α equals to 1 for reducing the unnecessary time wastage as explained in section III-B. The neighbor nodes, which detect only the tone signal, would freeze their transmission process in the tone-detecting direction for the DATA and ACK frame transmission duration and the double SIFS duration by setting their Directional Network Allocation Vector (DNAV) [4].

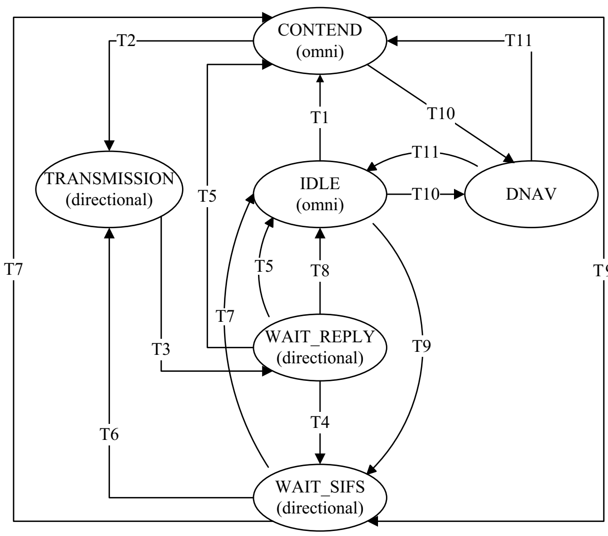

Fig. 4. State transition diagram of proposed MAC protocol.

After the DATA frame is received successfully, the receiver

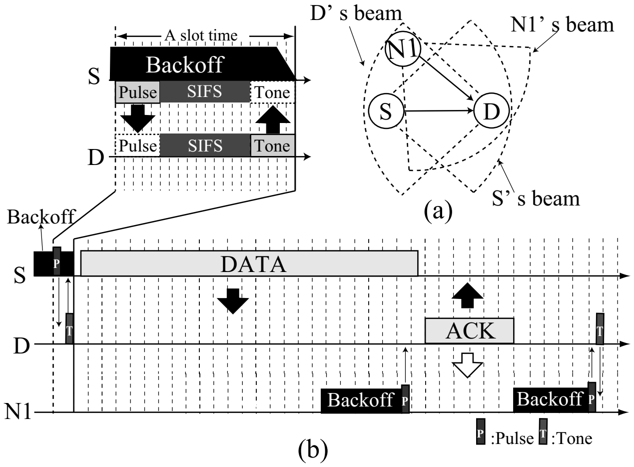

Fig. 5. An example of mitigating the directional hidden-node problem in the proposed protocol. (a) An scenario. (b) Time-domain expression.

transits to the *WAIT_SIFS* state following T4. Then the receiver transmits an ACK frame in directional mode following T6, after confirming that the channel is idle for the SIFS duration. When the transmitter receives the ACK frame successfully from the receiver following T8, the frame transmission is finished successfully. On the contrary, if the transmitter cannot receive the ACK frame, it transits to the *CONTEND* state following T5 and sets the BT again with the doubled CW value.

B. Hidden-node collision reduction

By using pulse/tone exchanges, not only general hidden-node collisions but also directional hidden-node collisions can be reduced. Figure 5 shows an example for avoiding the hidden-node collisions in the proposed protocol. As shown in Fig. 5(b), the pulse/tone exchanges are carried out in only one time slot at the final count of the BT. Therefore, the probability of the concurrent transmission of the pulse signals from multiple nodes is very low. Figure 5(a) shows a scenario in the proposed protocol. This scenario is the same as Fig. 1. When the node N1 finishes the previous communication and wants to transmit a new frame to the node D, the node N1 is unaware of the communication between the nodes S and D. In this case, the node N1 sends a pulse signal as shown in Fig. 5. Because the pulse signal does not interfere with other frame transmissions, the node D can receive the DATA frame from the node S successfully. This means that the directional hidden-node problem is solved by using pulse/tone exchanges. From the node N1 point of view, it cannot detect the tone signal for response and prepares retransmission. This means that the directional-hidden-node problem of the node N1 is converted to the deafness problem. From the above discussion, the transmitter can recognize that the deafness problem occurs when the pulse/tone exchange is in failure. Therefore, it is possible to set 1 to the α. This means that the CW value is fixed for reducing the unnecessary time wastage [3], when the transmitter cannot receive the tone signal and prepares a retransmission as shown in Fig. 5.

TABLE II
SIMULATION PARAMETERS.

Antenna type	Adaptive antenna array antenna
Angle of antenna beam	$\pi/2$
Node density	9.11×10^{-4} nodes/m ^{2}
Transmission range	135 m
PHY layer	IEEE 802.11b
Data channel rate	11 Mbps
Control channel rate	1 Mbps
Slot time	20 µs
DIFS time	50 µs
SIFS time	10 µs
Minimum CW size	31 slot
Max CW size	1023 slot
Frame payload	1024 bytes
RTS frame length	20 bytes
CTS frame length	14 bytes
ACK frame length	14 bytes
Pulse tx time	5 µs
Tone tx time	5µs
PC R	130 mJ
PC T	136 mJ
PC I/C	120 mJ
Simulation area	300 m × 300 m
Simulation time	20 s

C. The overhead reduction

The increase in exposed nodes due to pulse/tone exchanges can be limited by using smart antennas. Figure 2(b) shows an example of the exposed node reduction in the proposed protocol. The scenario of the Fig. 2(b) is the same as that of Fig. 2(a). The transmitter S sends a pulse signal to the receiver D prior to the DATA frame transmission. In the proposed protocol, the nodes, which detect the pulse signal, decrease compared with the RCA protocol because the transmission range is narrowed by applying smart antennas. Because the tone signal is also sent using the smart antenna, the nodes, which detect the tone signal, also decrease. It is seen from Figs 2(a) and (b) that the extra exposed nodes due to pulse/tone exchanges are reduced drastically. Therefore, we propose that the RTS/CTS handshake after the pulse/tone exchange is skipped for achieving the network overhead reduction.

As a result, there are three factors for improving the network throughput in the proposed protocol: it is possible to avoid the hidden-node collisions including the directional-hidden-node collisions. The time wastage is reduced by retransmitting with the fixed CW value, and the overhead can be reduced because RTS/CTS handshakes are not conducted after pulse/tone exchanges.

IV. PERFORMANCE EVALUATIONS

We evaluated the proposed protocol using numerical-simulation programs in C language written by ourselves. We confirmed that the throughputs of the IEEE 802.11 DCF obtained from our program showed the complete agreement with those obtained from the NS-2 simulator. The effects of the layers except the MAC layer are not included in the results in this paper. Additionally, it is

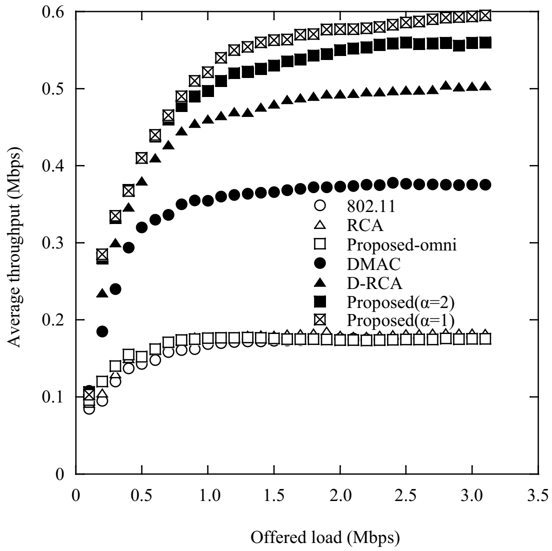

Fig. 6. Average throughput as a function of the offered load at each node.

assumed that the bandwidth consumption of the in-band pulse/tone signal is negligible compared to the bandwidth of the data channel. This assumption is the same as assumptions in [6], [13]. Each node has both the omni mode and the directional mode with an adaptive array antenna. Generally, directional transmissions have larger transmission range than omni-directional transmissions. Therefore, the directional beamforming may potentially interfere with communications taking place far away. In this paper, however, we focus on the gains from spatial reuse exclusively. Therefore, it is assumed that the transmission range of the directional antenna is the same as that of the omni-directional antenna. Each node can know all neighbor nodes and their directions. Receivers can know the transmitter's direction by receiving frames and detecting pulse/tone signals in the omni-mode. It is possible for the nodes to transmit only one frame or one signal at a time.

A. Simulation parameters and results

The parameters of the simulation in Table II basically follow those of IEEE 802.11b standard [1]. The receiving power consumption, the power consumption for *TRANSMISSION* state, and the power consumption for *IDLE* or *CONTEND* states are abbreviated to PC_R, PC_T, and PC_I/C in Table II, respectively. Data-channel and control-channel rates are 11 Mbps and 1 Mbps, respectively. Both the pulse and tone signals are sent for 5 μs duration [13]. Nodes are placed in the 300 m × 300 m square area at random. Each node randomly selects one of the neighbor nodes as a receiver. The traffic model follows the Poisson arrival. The node mobility is not considered in this paper. The angle of the antenna beam is set to $\pi/2$.

In this paper, IEEE 802.11 with RTS/CTS (802.11) and MAC protocol using smart antennas (DMAC) [3] are regarded as conventional protocols. DMAC indicates the MAC protocol in which IEEE 802.11 with RTS/CTS is applied to smart antenna networks. The RCA protocol (RCA) [13] is also regarded as a conventional protocol. Additionally, the protocol, called D-RCA, is also investigated as a smart-antenna network version of the RCA protocol. For the comparison, the proposed protocol is applied to omni-directional networks. This is regarded as an omni-directional-antenna network version of the proposed protocol, called Proposed-omni. Furthermore, the proposed protocol is evaluated for $\alpha = 1$ and 2, where α is defined as shown in Fig. 3(c).

Figure 6 shows the average throughput as a function of offered load at each node for 9.11×10^{-4} nodes/m ^{2} of node density. Additionally, Fig. 7 shows the average of blocking time (Aver block), backoff time (Aver backoff), and overhead time (Aver overhead) per one DATA frame transmission success as functions of offered load at each node. Aver block, Aver backoff, and Aver overhead are defined as ratio of amount of the prohibiting duration of non-target receivers to the number of the DATA frame transmission success, ratio of the total backoff time to the number of the DATA frame transmission success, and ratio of the total control-frame-transmission duration to the number of the DATA frame transmission successes, respectively. Here, the control-frame-transmission duration includes RTS, CTS, and ACK frame transmission durations. Pulse and tone signal durations are not included in the overhead time since pulse/tone exchanges are conducted in the final time slot in the backoff stage.

It is seen from Fig. 6 that the average throughput of Proposed-omni is almost the same as that of 802.11 and RCA. Because the pulse/tone exchanges prohibit the neighbor nodes of the transmitter from transmitting, the hidden-node collisions can be reduced as shown in Fig. 7(b). However, exposed nodes increase in RCA and Proposed-omni. Figure 7(d) shows the sum of the Aver block, Aver backoff, and Aver overhead as functions of offered load at each node. Compared with Figs. 7(a) and (d), the sum of the Aver block, Aver backoff, and Aver overhead is almost the same as the Aver block for all the three omni-directional-antenna protocols. Therefore, it can be stated that the reduction of Aver block has a dominant impact on the network throughput enhancement for omni-directional-antenna protocols.

It is seen from Fig. 7(a) that Aver block of both RCA and Proposed-omni are higher than that of 802.11. Additionally, it is seen that Aver block of RCA is lower than that of Proposed-omni. This is because some exposed nodes due to pulse/tone exchanges can escape from the frozen state in a short duration due to the RTS/CTS handshake process. In Proposed-omni, only pulse/tone exchanges are conducted prior to the DATA frame transmission. Therefore, all exposed nodes, which detect tone signals, should freeze their operations during the DATA frame transmission. Because the DATA frame is longer than the RTS frame, the network throughput of Proposed-omni is lower than those of 802.11 and RCA for heavy offered load as shown in Fig. 6. It can be stated that the RTS/CTS handshakes after pulse/tone exchanges are necessary for alleviating the freezing durations of exposed nodes in omni-directional-antenna networks. It is also seen from Fig. 6

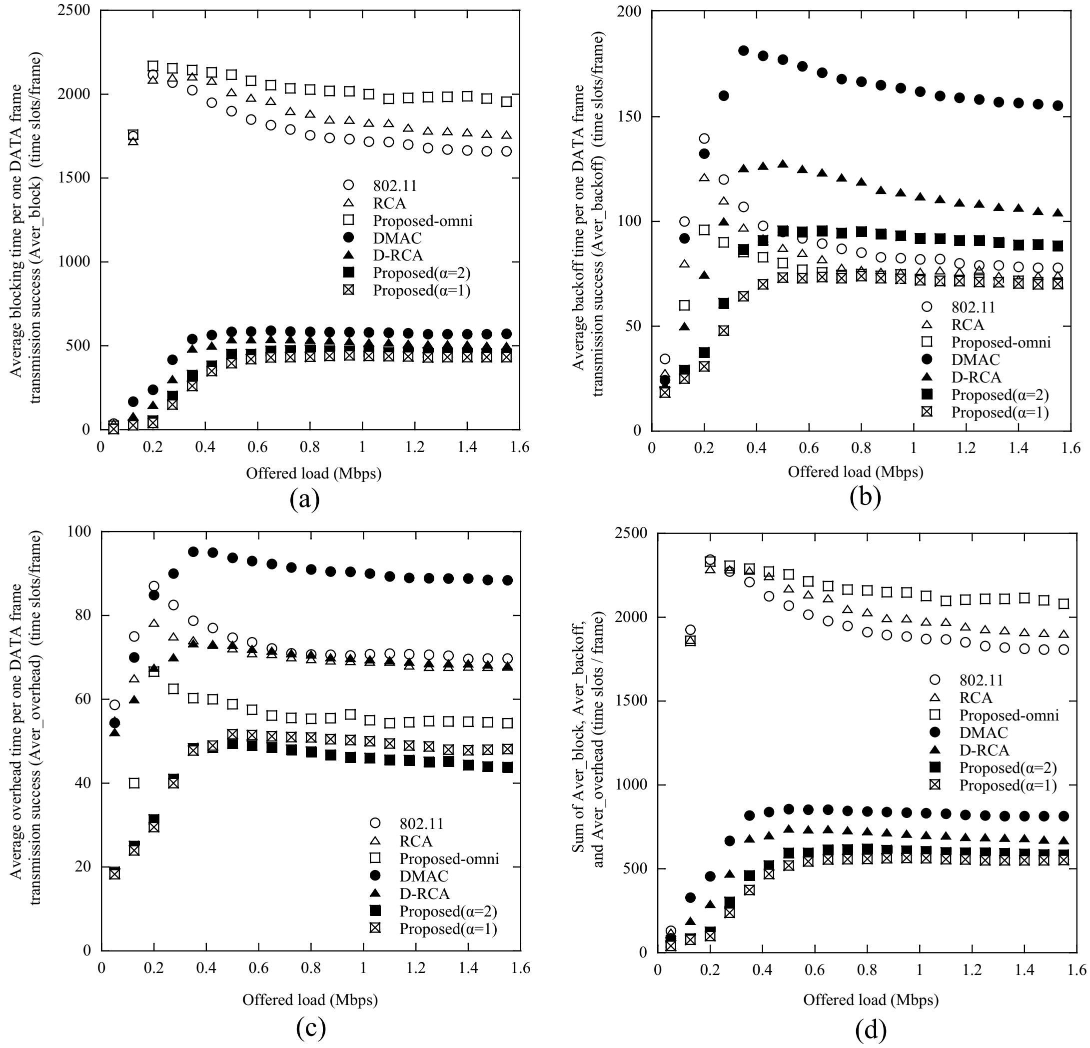

Fig. 7. The average block, backoff, and overhead periods per successful frame transmission at each node. (a) Aver backoff period. (b) Aver block period. (c) Aver overhead period. (d) Sum.

that the throughputs of DMAC, D-RCA, and the proposed protocol are higher than those of 802.11, RCA, and Proposed-omni respectively, since the smart-antenna utilization enhances the network spatial-reusability efficiency. Additionally, the relationships among the three protocols for smart-antenna networks are completely different from those among omni-directional-antenna networks. It is seen from Fig. 6 that the proposed protocol provides the highest throughput and difference of throughputs between the proposed protocol and DMAC is much larger than that between the Proposed-omni and 802.11. In the three smart-antenna protocols, the number of exposed nodes is smaller than that of the omni-directional-antenna protocols because of the smart-antenna utilization. It can be confirmed from Fig. 7(a) that the Aver blocks of the three smart-antenna protocols are much lower than those of the omni-directional-antenna protocols. This indicates the enhanced network spatial reusage efficiency in smart-antenna protocols.

In the proposed protocol and D-RCA, hidden-node collisions are reduced by applying pulse/tone exchanges. Because DMAC suffers from much backoff durations due to the deafness and the hidden-node problems, DMAC shows the highest Aver backoff in Fig. 7(b). By using pulse/tone exchanges, both the general and directional hidden-node collisions can be reduced. Therefore, it can be confirmed from Fig. 7(b) that Aver backoffs of the proposed protocol and D-RCA are much lower than that of DMAC. The hidden-node-collision reduction of both the proposed protocol and D-RCA effectively enhances the network throughput compared with the omni-directional-antenna protocols, since the exposed-node increase is limited by using smart antennas. This can be confirmed from Fig. 7(a), (b), and (c). Therefore, the throughput enhancement of the pulse/tone exchange in the smart-antenna system is higher than that in omni-directional-antenna system as shown in Fig. 6.

It is also seen from Fig. 6 that throughput of the proposed rotocol is higher than that of D-RCA. This is because RTS/CTS handshakes are skipped in the proposed protocol and the overhead can be reduced compared with D-RCA as shown in Fig. 7(c). Because the overhead can be reduced with the slight increase in exposed nodes, the throughput of the proposed

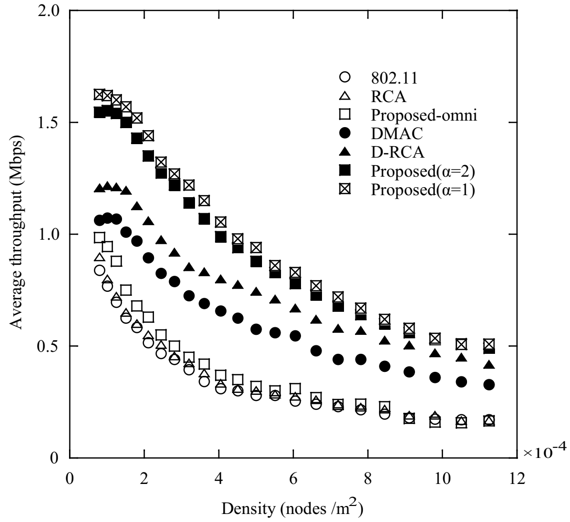

Fig. 8. Average throughput as a function of the node density.

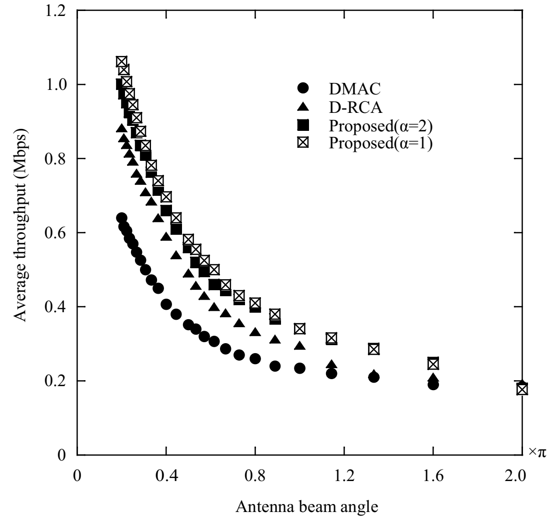

Fig. 9. Average throughput as a function of the antenna beam angle.

protocol is higher than that of D-RCA. As a result, the proposed protocol can obviously enhance the network throughput because not only the hidden-node collisions but also overhead can be reduced with a little increase of the exposed nodes.

Additionally, it is seen from Fig. 6 that the throughput of the proposed protocol for $\alpha = 1$ is higher than that for $\alpha = 2$. This is because that time wastage induced by the deafness problem is reduced by retransmitting with the fixed CW value in the proposed protocol for $\alpha = 1$. It can be confirmed from Fig. 7(a) and (b) that the proposed protocol for $\alpha = 1$ show lower Aver backoff and Aver block than that for $\alpha = 2$. Therefore, the time-wastage reduction enhances the network throughput by using the fixed CW value.

Figure 8 shows the average throughput as a function of the node density for 2.5 Mbps of offered load. It is seen from Fig. 8 that the throughput decreases as the node density increases for all the protocols. The increase in both hidden-node collisions and exposed nodes degrades the network throughput as the node density increases. In Fig. 8, Proposed-omni shows the lowest throughput when the node density is high as shown in Fig. 8. When the node density is high, the transmitter takes high probability for detecting a tone signal from unexpected neighbor nodes even if the target receiver communicates with another node. Therefore, DATA frame collisions due to the hidden-node problem often occur in Proposed-omni for high node density. In Proposed-omni, the negative factor of the DATA frame collisions is stronger than the positive factor of the overhead reduction. As a result, throughput of Proposed-omni is lower than those of 802.11 and RCA for high node density, as shown in Fig. 8.

Inversely, the throughput of the proposed protocol is higher than those of D-RCA and DMAC even if the node density is high. In the proposed protocol, exposed nodes decrease by using the smart antenna, and unexpected tone detection can be suppressed compared with Proposed-omni. Therefore, the positive factor of the overhead reduction overcomes the negative factor of the DATA frame collisions, and the proposed protocol keeps high throughput compared with the other protocols.

Additionally, it is seen from Fig. 8 that the throughput difference between the proposed protocol for $\alpha = 1$ and that for $\alpha = 2$ becomes small as the node density increases. As the node density increases, the possibility that the transmitter detects the unexpected tone signals becomes high in spite of the smart-antenna system networks. Therefore, most of the pulse/tone exchanges are in success. Therefore, the behavior of the proposed protocol for $\alpha = 1$ is almost the same as that for $\alpha = 2$ as the node density increases. In this case, the DATA frame collisions due to the directional-hidden node problem occur.

Figure 9 shows the average throughput as a function of the antenna-beam angle. It is seen from Fig. 9 that the throughput decreases as the antenna-beam angle increases. As the antenna-beam angle becomes wide, the neighbor nodes located in the antenna-beam range increases. Therefore, the increase in both hidden nodes and exposed nodes degrades the network throughput as shown in Fig. 9. Of course, the system with very narrow antenna angle has a weakness against the node-location error and node mobility. In this sense, there is a trade-off relationship between the throughput enhancement and the system robustness. It is also seen in Fig. 9 that the throughput difference between the proposed protocol for $\alpha = 1$ and that for $\alpha = 2$ becomes small as the antenna-beam angle increases. These characteristics can be explained by discussions similar to the node-density case, because narrow antenna angle yields the decrease in the neighbor nodes. Note that the throughput of the proposed protocol for $\alpha = 1$ is always the highest among all the protocols. These results show the validity and effectiveness of the proposed protocol.

Figure 10 shows the power consumption for one frame transmission as a function of the offered load at each node. It is seen from Fig. 10 that the power consumptions decrease as the offered load increases for all the protocols. This is because that the differences of the consumed power in *IDLE* state, *CONTEND* state, and *TRANSMISSION* state are small as shown in Table II. When the offered load is low, nodes take a long time to stay in the *IDLE* state, where consumed power never

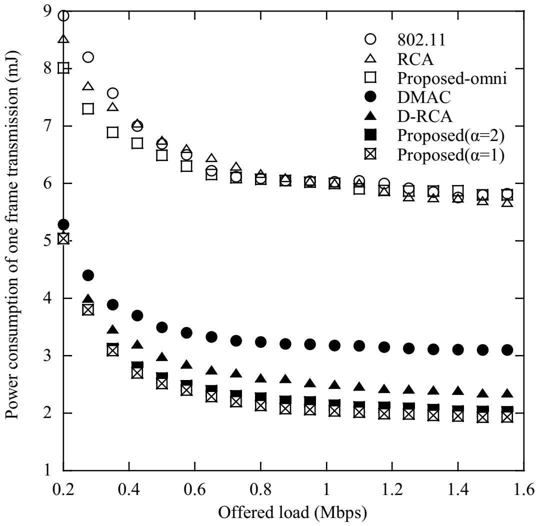

Fig. 10. Power consumption for one frame transmission as a function of the offered load at each node.

TABLE II
EXACT POWER CONSUMPTION FOR TRANSMISSION TAKING INTO ACCOUNT PHYSICAL LAYER CONVERGENCE PROTOCOL PREAMBLE (PLCP) AND PLCP HEADER.

Pulse/tone	RTS frame	CTS/ACK frame	DATA frame
0.68 μJ	47.8 μJ	41.3 μJ	130.8 μJ

contributes to frame transmissions. It is seen from Fig. 10 that three omni-directional-antenna protocols show almost the same power consumption when the offered load increases. The exposed-node increase causes that large number of nodes stay in the *CONTEND* state, in which power consumption never contributes to frame transmissions. Because three omni-directional-antenna protocols suffer from the the exposed-node-increase problem when the offered load increases, their power consumption results show almost the same in Fig. 10. It is also seen from Fig. 10 that three smart-antenna protocols show lower power consumption than omni-directional-antenna protocols, because exposed nodes decrease by applying smart antennas in the smart-antenna protocols. As a result, both of D-RCA and the proposed protocol achieve lower power consumption than DMAC due to the collision reduction, as shown in Fig. 10. Additionally, because the overhead is reduced further in the proposed protocol, the power consumption shows the lowest among three smart-antenna protocols as shown in Fig. 10.

V. CONCLUSIONS

This paper has proposed a MAC protocol for ad hoc networks with smart antennas. In the proposed protocol, pulse/tone exchange mechanism is applied to the smart-antenna network. This mechanism significantly reduces collisions caused by the hidden-node problem. Further throughput enhancement is achieved because of the compatibility between the pulse/tone exchange and the smart-antenna networks. The directional hidden-node problem is mitigated by the pulse/tone exchange. Additionally, the number of exposed nodes due to pulse/tone exchanges is limited because of the smart-antenna usage. Therefore, it is unnecessary to use RTS/CTS handshakes after pulse/tone exchanges. This overhead reduction enhances the network throughput. As a result, the network throughput can be effectively improved. Simulation results show the validity and effectiveness of the proposed protocol.

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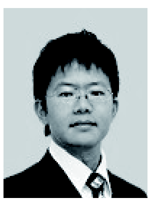

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