MAC Protocol for Ad Hoc Network Using Smart Antenna with Pulse/Tone Exchange

Jing Ma, Hiroo Sekiya, Nobuyoshi Komuro, Shiro Sakata
Graduate School of Advanced Integration Science, Chiba University
1-33, Yayoi-cho, Inage-ku, Chiba, 263-8522 Japan
Email: maggie@graduate.chiba-u.jp, sekiya@faculty.chiba-u.jp, kmr@faculty.chiba-u.jp, sakata@faculty.chiba-u.jp

***Abstract*—This paper proposes a MAC protocol for smart antenna used networks. The basic idea is that the Pulse/Tone exchange, instead of the RTS/CTS handshake, is applied prior to the data transmission. By only changing the transmission initiation method, we can obtain four advantages. First, collisions due to general hidden-node problem can be reduced. Second, the collision between the control frame and the DATA frame due to the directional hidden-node problem can be mitigated. Third, the transmission delay can be reduced by using the fixed contention window value. Finally, the overhead can be reduced because the duration of the Pulse/Tone exchange is much shorter than that of the RTS/CTS handshake. As a result, the higher network throughput can be achieved compared with previous protocols. Simulation results demonstrate the validity and effectiveness of the proposed protocol.**

***Keywords*-Smart antennas; ad hoc networks; Pulse/Tone.**

I. Introduction

Recently, wireless communication systems using a beamforming of the smart antenna have attracted many researchers‘ attention [2–6]. 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 used networks was proposed in [2], in which IEEE 802.11 with RTS/CTS is applied to smart antenna used 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 occurrence. Collisions often occur between two control frames due to general hidden-node problem. Additionally, collisions between the control frame and the DATA frame due to the directional hidden-node problem newly occur in smart antenna used networks. The other factor is the transmission delay due to the deafness problem. The deafness problem is a typical drawback for smart antenna used networks. When the transmission fails, the transmitter cannot understand the cause for transmission failure. The transmitter initiate the retransmission with doubled contention window value(CW) in all cases, because the effect of the transmission failure caused by the collision is larger than that due to the effect of the transmission failure caused by the deafness problem. The binary exponential increase in the CW value causes the transmission delay.

On the other hand, narrow-band and short-time in-band signals, called Pulse and Tone hereafter, are proposed in [7]. According to [7], it is sufficient for nodes to detect the Pulse or Tone signal in 5 μs, which is much shorter than the control frame length, e.g. RTS and CTS frames. Therefore, the simultaneous transmission of Pulse or Tone signals from multiple nodes rarely occurs. Additionally, the Pulse or Tone signal does not interfere with frames. The characteristics of Pulse and Tone signals are suitable to avoid collisions which occur between the control frame and the DATA frame due to the directional hidden-node problem.

This paper proposes a MAC protocol for smart antenna used networks. Each node has only one transceiver in the proposed system. The basic idea is that the Pulse/Tone exchange, instead of the RTS/CTS handshake, is applied to smart antenna used networks. By only changing the transmission initiation method, we can obtain four advantages. First, collisions due to general hidden-node problem can be reduced, because the simultaneous transmission of Pulse or Tone signals from multiple nodes rarely occurs. Second, the collision between the control frame and the DATA frame due to the directional hidden-node problem can be mitigated, because the Pulse or Tone signal does not interfere with DATA frames. Third, the transmission delay can be reduced by using the fixed contention window value. Because collisions due to the general or directional hidden-node problem rarely occur by using Pulse/Tone exchange, it can be stated that the reason for transmission initiation failure is the deafness problem. Therefore, the retransmission is conducted using the fixed CW, which can achieve the transmission delay reduction. Finally, the overhead can be reduced because the duration of the Pulse/Tone exchange is much shorter than that of the RTS/CTS handshake. As a result, the higher network throughput can be achieved compared with previous protocols. Simulation results demonstrate the validity and effectiveness of the proposed protocol.

The rest of the paper is organized as follows: The related work is discussed in Section 2. In Section 3, the details of the proposed protocol is introduced. Performance evaluations are presented in Section 4. Section 5 concludes.

 ISBN: 978-1-61208-245-5

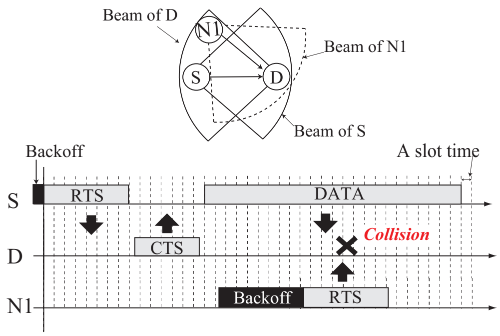

Fig. 1. An example scenario of the collision due to the directional hidden-node problem in the DMAC protocol.

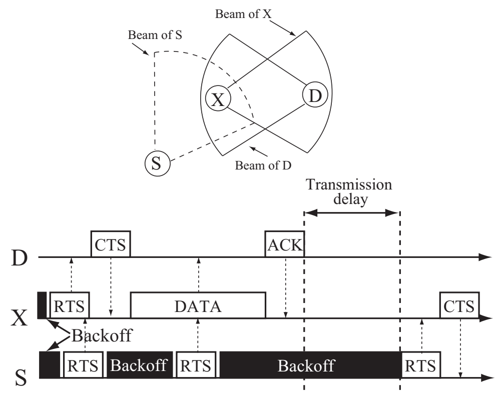

Fig. 2. The transmission failure example due to the deafness problem in the DMAC protocol.

II. Related Works

Wireless communications in smart antenna used networks can enhance the spatial reusability of the network [2–6]. The DMAC (Directional Medium Access Control) [2] protocol is a basic MAC protocol for smart antenna used networks. 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 the omni-directional antenna networks.

However, the network throughput is degraded because of two dominant factors in the DMAC protocol. One is the control frame collisions due to general hidden-node problem. This kind of collision often occurs when control frames are transmitted by multiple nodes simultaneously when the offered load is heavy. Additionally, collisions between the control frame and the DATA frame due to the directional hidden-node problem newly appear in the smart antenna used networks. Fig. 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 S 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 transmission delay according to [2]. The deafness problem is a typical drawback for smart antenna used networks. When a transmitter transmits an RTS frame to a receiver, which transmits or receives a frame to or from another node, the deafness problem occurs. Since the receiver is beamformed toward the direction away from the transmitter, the receiver is unable to hear the RTS frame transmission. Fig. 2 shows an example of transmission failure due to the deafness problem in the DMAC protocol. Since node X is beamforming toward node D, node X cannot comprehend the RTS frame transmission from node S. Accordingly, node S cannot receive the CTS frame for response. Then, node S retransmits the RTS frame after the BT decreases to 0. The initial BT value is set randomly in the range of 0 to CW. When the RTS frame transmission fails, the CW is doubled and the BT is reset. This kind of binary exponential increase in the CW can reduce the RTS frame collision probability. However, if the transmission failure is caused by the deafness problem, then the binary exponential increase in the CW causes wastage of channel resources, as shown in Fig. 2. In Fig. 2, node S fails in the RTS/CTS handshake process due to the deafness problem. It is not necessary to double the CW when the transmitter retransmits the RTS frame. In the DMAC protocol, the transmitter cannot understand the reason for the transmission failures. When an RTS frame retransmission is needed, the CW is doubled in all cases. This is because the throughput decrease due to the effect of the transmission failure caused by the hidden-node problem is larger than that due to the effect of the transmission failure caused by the deafness problem.

III. Proposed MAC protocol

In this paper, a MAC protocol for ad hoc networks with smart antennas is proposed. The basic idea is that the Pulse/Tone exchange, instead of the RTS/CTS handshake, is applied to smart antenna used 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, which is the same assumption as the smart-antenna systems [2], [5]. There are some techniques for identifying the node positions. GPS technique [3] is one of the methods which determine the location of a node in the network. Fig. 3 shows a flowchart of the proposed protocol for the transmitter. Compared with the DMAC protocol, the short-duration Pulse/Tone exchange is conducted prior

 ISBN: 978-1-61208-245-5

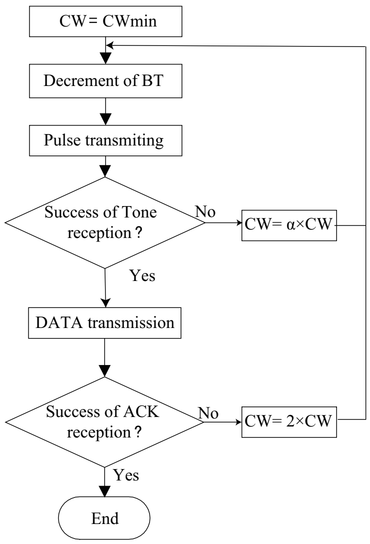

Fig. 3. Flowchart of the proposed protocol.

to the DATA-frame transmission instead of the RTS/CTS handshakes in the proposed protocol.

Pulse and Tone are narrow-band and short-time in-band signals [7]. According to [7], it is sufficient for nodes to detect the Pulse or Tone signal in 5 μs, which is much shorter than the control frame length, e.g. RTS and CTS frames. Therefore, the simultaneous transmission of Pulse or Tone signals from multiple nodes rarely occurs. Additionally, the Pulse or Tone signal does not interfere with frames. Because of the characteristic of Pulse and Tone signals, Pulse and Tone signals can be exchanged within only one time slot [8]. In the proposed protocol, Pulse/Tone exchange, instead of RTS/CTS handshake, is conducted at the final count of the backoff timer (BT).

A. The proposed protocol design

A node, which has no transmission frame, is in the idle state with omni-mode. When a node has a transmission frame, it sets the BT and senses the channel in omni-mode. If the transmitter confirms that the channel is idle, it transfers to directional mode, requests the physical layer to beamform toward the receiver, and sends a Pulse signal. After that, the transmitter sets a Tone-wait timer and waits for the Tone signal in the directional mode. If the transmitter detects the Tone signal, it starts transmitting a DATA frame. Inversely, if the transmitter cannot detect the Tone signal during the Tone-wait timer duration, it transfers to the omni-mode and sets the BT again with the fixed CW, namely α=1 in Fig. 3. After transmitting the DATA-frame, the transmitter sets an ACK-frame-wait timer. If the transmitter receives an ACK-frame from the receiver successfully, the transmission process is finished successfully. If the transmitter cannot receive the ACK-frame from the receiver, it sets the BT again after doubling the CW value as shown in Fig. 3.

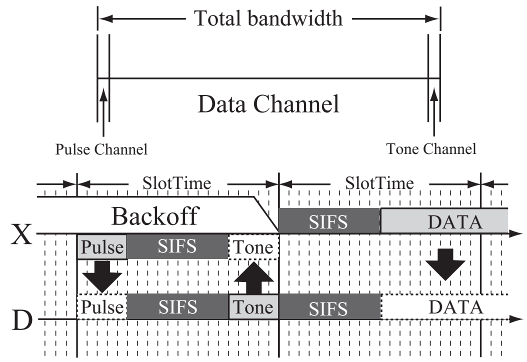

Fig. 4. Pulse/Tone exchange process.

Nodes, which detect the Pulse signal, reply a Tone signal and prepare to receive a DATA frame in directional mode. Nodes, which only detect the Tone signal, will freeze their transmissions of the Tone detected direction.

B. Features of the proposed protocol

In the proposed protocol, each node is only required to have one transceiver. The Pulse/Tone exchange, instead of the RTS/CTS handshake, is applied prior to the DATA frame transmission in smart antenna used networks. By only changing the transmission initiation method, we can obtain four advantages. First, collisions due to general hidden-node problem can be reduced. Second, the collision between the control frame and DATA frame due to the directional hidden-node problem can be mitigated. Third, the transmission delay can be reduced by using the fixed CW. Finally, the overhead can be largely reduced. As a result, the network throughput can be effectively improved.

1) Reduction of frame collisions due to the general hidden-node problem.: Fig. 4 shows the Pulse/Tone exchange process in the proposed protocol. In Fig. 4, the transmitter X sends a Pulse to the receiver D prior to the DATA frame transmission. The duration of the Pulse/Tone exchange is only one slot time, which is 20 μs in IEEE 802.11b, as shown in Fig. 4. The probability that multiple Pulses are sent simultaneously is much lower than the probability of DATA frame collisions. As a result, DATA frame collisions due to the general hidden-node problem are effectively inhibited.

2) Mitigation of directional hidden-node problem: By using Pulse/Tone exchanges, collisions between the control frame and the DATA frame due to the directional hidden-node problem can be mitigated. Fig. 5 shows an example for avoiding the collision due to the directional hidden-node in the proposed protocol. As shown in Fig. 5, the Pulse/Tone exchanges are carried out 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. In the shown scenario in 5, when the node N1 finishes the previous communication and wants to

 ISBN: 978-1-61208-245-5

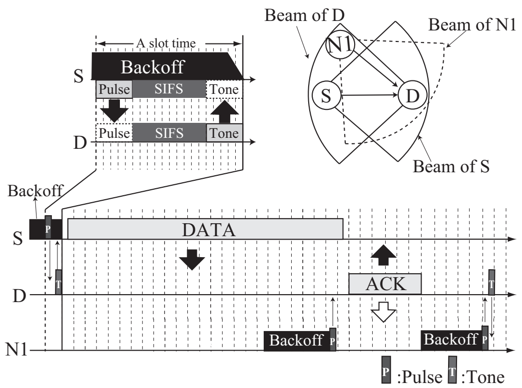

Fig. 5. An example of mitigating the directional hidden-node problem in the proposed protocol.

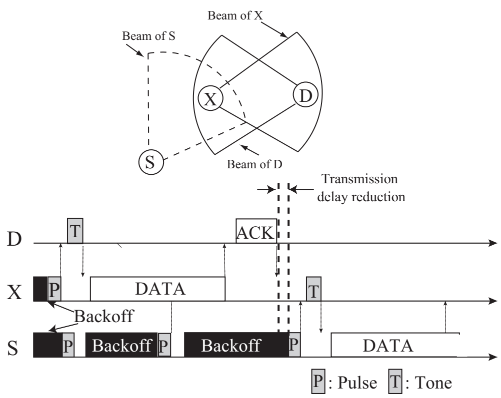

Fig. 6. An example of reducing the transmission delay due to the deafness problem in the proposed protocol.

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 the frame, 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.

3) The transmission delay reduction: Fig. 6 shows an example of reducing the transmission delay due to the deafness problem in the proposed protocol. Node S transmits a Pulse to node X, as shown in Fig. 6. Since node X communicates with node D, node S cannot detect a Tone for response. Thus, node S recognizes that node X is busy communicating with another node in another direction. This is because the probability of Pulse-transmission overlapping due to the hidden-node problem is very low. Therefore, node S retransmits a Pulse with the fixed CW, namely $\alpha = 1$ in Fig. 3. As a result, the network throughput can be improved by applying the Pulse/Tone exchange due to the transmission delay reduction.

4) The overhead reduction: In the proposed protocol, the Pulse/Tone exchange is conducted prior to the DATA frame transmission instead of RTS/CTS frame handshake. Because the duration of the Pulse/Tone exchange is much shorter than that of the RTS/CTS handshake [1], [7], the overhead can be largely reduced by using Pulse/Tone exchange instead of RTS/CTS handshake.

By the way, because Pulse and Tone signals do not contain any information, the all nodes, which only detect the Tone signal, freeze their transmission processes in the proposed protocol. It seems that many exposed node will appear in this proposed protocol. Smart antennas are, however, applied in the proposed system. By using smart antennas, the transmission range can be squeezed. Therefore, exposed nodes appearance is limited. The exposed nodes appearance due to the Pulse/Tone exchange is not a serious problem in the proposed protocol.

IV. Performance Evaluations

In order to evaluate the performance of the proposed protocol, we have simulated ad hoc networks implementing the proposed protocol and other conventional protocols using a simulation program written in C. In order to confirm the credibility of our simulator, the throughputs of the IEEE 802.11 DCF obtained using our simulator were verified to be the same as those obtained using the NS-2 simulator. The effects of PHY and upper layer are not included in the results of this paper. Additionally, it is assumed that the bandwidth consumption of the in-band Pulse and Tone signals is negligible compared to the bandwidth of the data channel. This assumption is the same as assumptions in [7], [8]. 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 would like to 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 direction by receiving frames and the sensing Pulse or 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 simulation parameters are given in Table I, which basically follow those in IEEE 802.11b standard [1]. 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 [7]. Nodes are placed in the 300 m $\times$ 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, MAC protocol using smart antennas

Table I
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/ACK-frame length	14 bytes
Pulse/Tone tx time	5 μs
Simulation area	300 m × 300 m
Simulation time	20 s

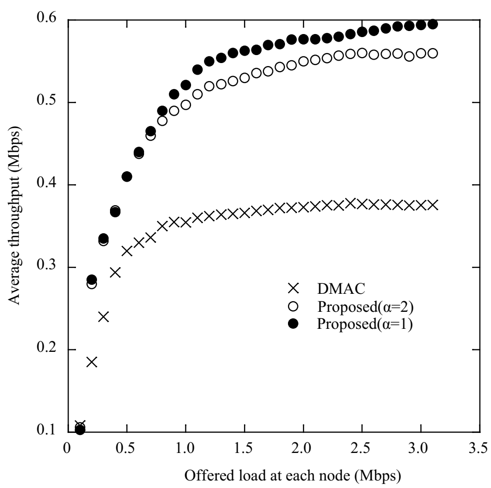

Fig. 7. Average throughput as a function of the offered load at each node.

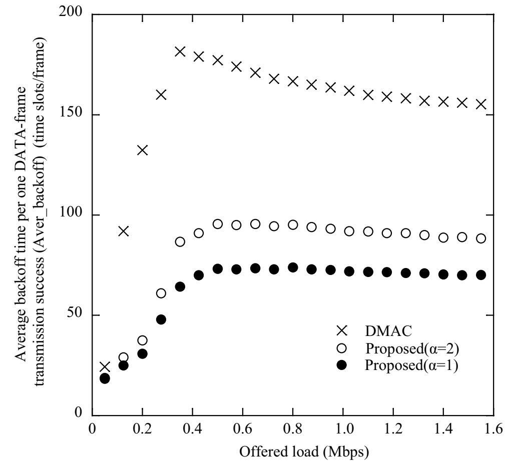

Fig. 8. The average backoff periods per successful frame transmission at each node.

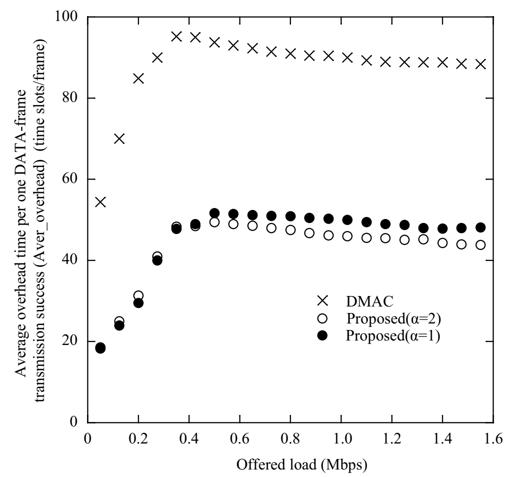

Fig. 9. The average overhead per successful frame transmission at each node.

(DMAC) [2] and the proposed protocol (Proposed) are investigated. Additionally, the proposed protocol is evaluated for α=1 and 2, where α is defined as shown in Fig. 3.

Fig. 7 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, Figs. 8 and 9 show the average of backoff time (Aver_backoff) and overhead time (Aver_overhead) per one DATA-frame transmission success as functions of offered load at each node. Aver_backoff, and Aver_overhead are defined as 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 total control-frame-transmission duration includes RTS-, CTS-, and ACK-frame transmission periods. 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. 7 that the proposed protocol provides the higher throughput than DMAC. This is because the collisions due to the general and directional hidden-node problem are reduced by applying the Pulse/Tone exchanges, as well as the overhead is largely reduced in the proposed protocol. DMAC suffers from frame collisions and the deafness problem. It can be confirmed from Fig. 8 that DMAC achieves the highest Aver_backoff. This is because collisions cause many retransmission, as well as the deafness problem causes the transmission delay. In the proposed protocol, by using the Pulse/Tone exchange, collisions can be reduced. Therefore, it can be confirmed from Fig. 8 that Aver_backoff of the proposed protocol is much lower than that of DMAC. Additionally, the overhead is reduced compared with DMAC. It can be confirmed in Fig. 9 that Aver_overhead of the proposed protocol is lower than that of DMAC. As a result, the proposed protocol achieves the higher throughput compared with DMAC.

In addition, it is seen from Fig. 7 that the throughput

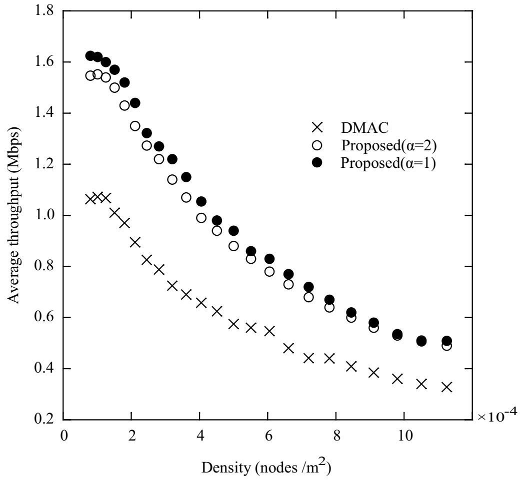

Fig. 10. Average throughput as a function of the node density

of the proposed protocol for α=1 is higher than that for α=2. This is because transmission delay induced by the deafness problem is reduced by retransmitting with the fixed CW in the proposed protocol for α=1. It can be confirmed from Fig. 8 that the proposed protocol for α=1 shows lower Aver_backoff than that for α=2. Therefore, the transmission delay reduction enhances the network throughput by using the fixed CW value. By the way, it is seen from Fig. 9 that the Aver_overhead of the proposed protocol for α=1 is a little higher than that of the proposed protocol for α=2. This is because fixing the CW increases the retransmission probability in the proposed protocol for α=1. Note that the positive factor of the transmission delay reduction can overcome the negative factor of the increase in retransmissions, which can be confirmed in Figs. 8 and 9.

Fig. 10 shows the average throughput as a function of the node density for 2.5 Mbps of offered load. It is seen from Fig. 10 that the throughput decreases as the node density increases for all the protocols. When the node density is high, it is inevitable that the network throughput is degraded due to collisions. However, it is seen from Fig. 10 that the proposed protocol for α=1 achieves the highest throughput regardless of the node density. In the proposed protocol, the positive factor of the collision reduction, the transmission delay reduction, and the overhead reduction improves the network throughput even if the node density is high.

Additionally, it is seen from Fig. 10 that the throughput difference between the proposed protocol for α=1 and that for α=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 used networks. Therefore, most of the Pulse/Tone exchanges are in success. Therefore, the behavior of the proposed protocol for α=1 is almost the same as that for α=2 as the node density increases. In this case, the DATA-frame collisions due to the directional-hidden node problem occur.

V. Conclusions

This paper has proposed a MAC protocol for smart antenna used networks. The basic idea is that the Pulse and Tone signals are exchanged, instead of the RTS/CTS handshake, prior to the data transmission. In the proposed protocol, first, collisions due to general hidden-node problem can be reduced. Second, the collision between the control frame and the DATA frame due to the directional hidden-node problem can be mitigated. Third, the transmission delay can be reduced by using the fixed contention window value. Finally, the overhead can be reduced because the duration of the Pulse/Tone exchange is much shorter than that of the RTS/CTS handshake. As a result, the higher network throughput can be achieved compared with previous protocols. Simulation results demonstrate the validity and effectiveness of the proposed protocol.

References

[1] *IEEE 802.11 Standard: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification*, IEEE, 1999.

[2] R. R. Choudhury, X. Yang, R. Ramanathan, and N. H. Vaidya, “Using Directional Antennas for Medium Access Control in Ad Hoc Networks,” *Proc. ACM MobiCom*, Atlanta, Georgia, USA, pp.59-70, Sept. 2002.

[3] S. Motegi, H. Sekiya, J. Ma, K. Sanada, and S. Sakata, “A directional MAC protocol with the DATA-frame fragmentation and short busy advertisement signal for mitigating the directional hidden node problem, “ *Proc. PIMRC‘ 12*, Sydney, Australia, Sept. 2012.

[4] J. L. Bordim, K. Nakano, ”Deafness Resilient MAC Protocol for Directional Communications,” *IEICE TRANSACTIONS on Information and Systems*, Vol.E93-D, No.12, pp.3243-3250, 2010.

[5] K. Sundaresan, R. Sivakumar, “Cooperating with smartness: using heterogeneous smart antennas in multihop wireless networks,” *Mobile Computing, IEEE Transactions on*, vol.10, no.12, pp.1666-1680, Dec. 2011.

[6] K. Takano, S. Shiokawa, ”Fairness aware back-off control scheme in wireless network using directional MAC protocol”, IEICE Tech. Rep., vol.110, no.449, IN2010-187, pp.259-264, March 2011. (in Japanese)

[7] Fouad A. Tobagi and L. Kleinrock, ”Packet switching in radio channels: part II- the hidden terminal problem in carrier sense multiple-access and the busy-tone solution, “ *IEEE Transactions on Communications*, COM-23(12), Dec. 1975.

[8] K. P. Shih, W. H. Liao, H. C. Chen, and C. M. Chou, “On avoiding RTS collisions for IEEE 802.11-based wireless ad hoc networks,” *Computer Communications*, vol.32, no.1, pp.69-77, Jan. 2009.