A Directional MAC Protocol for Practical Smart Antennas

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Abstract **- Recently, several MAC protocols using directional antennas, typically referred to as directional MAC protocols, have been proposed for wireless ad hoc networks. However, the MAC protocols in the previous studies were evaluated using simulation with ideal antenna forms. When using practical antenna beam forms, side lobes and back lobes exist which may cause new problems. In this paper, we evaluate the performance of the directional MAC protocol in the previous studies with practical antenna beam forms. In addition, we propose a directional MAC protocol that assumes practical antenna beam forms. The proposed MAC protocol mitigates data collisions due to the effects of minor lobes by the following two schemes. First, the nodes rotate directional receiving antenna beams in an idle state. Second, nodes transmit NAV (Network Allocation Vector) request frames to avoid collisions from neighboring nodes. By controlling the transmitting power, our protocol allows nodes to communicate with nodes beyond the omni-directional transmission range. The simulation results show that the proposed directional MAC protocol improves throughput performance compared to existing directional MAC protocol when using practical antenna beam forms.**

I. INTRODUCTON

In recent years, wireless ad hoc networks [1] have attracted a significant amount of attention. These networks do not need a fixed infrastructure. Previous works dealing with wireless ad hoc networks assumed the use of omni-directional antennas that radiate or detect signal strength equally well in all directions. However, IEEE 802.11 [2] which assumes using omni-directional antennas cannot achieve high throughput in wireless ad hoc networks because they waste a large portion of the network capacity by extending the wireless media over a large area as discussed in [3] [4] [5]. To deal with this problem, smart antenna technology may have various potentials [6] [7]. These antennas improve spatial reuse of the wireless channel and extend communication range.

However, regardless of the potentials of smart antennas, a sophisticated MAC is required to take full advantage of these benefits. Recently, several MAC protocols using smart antennas or directional antennas, typically referred to as directional MAC protocols, have been proposed for wireless ad hoc networks.

The directional MAC protocols in the previous studies were evaluated using simulation with ideal antenna beam forms. An ideal antenna beam form has a constant gain in all directions within the transmission area, and has no radiated power towards other directions, although no physical antenna can provide equality gain for a given angle. The shape of the form the including those of the side lobes and back lobes has non-negligible effects on the interference among network nodes.

In this paper, we evaluate the performance of the directional MAC protocol in the previous studies that assume the use of ideal antenna beam forms with practical antenna beam forms. We also point out the problems resulting from the practical antenna beam forms. In addition, this paper proposes a directional MAC protocol which deals with problems of the practical antenna beam forms. The experimental results show that the proposed directional MAC protocol improves throughput performance compared to that of the directional MAC protocol examined in the previous studies.

II. RELATED WORKS

IEEE 802.11 DCF (Distributed Coordination Function) [2] is a contention-based MAC protocol of CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) and assumes the use of omni-directional antennas at the physical layer. The RTS (Request To Send) and CTS (Clear To Send) control frames relieve the hidden-terminal problem through the NAV (Network Allocation Vector), but the exposed-terminal problem remains. Therefore, a large portion of the network capacity is wasted using this protocol.

Recently, several MAC protocols that use smart antennas or directional antennas, typically referred to as directional MAC protocols, have been proposed for wireless ad hoc networks.

In DMAC (Directional MAC) [8], a communication pair exchanges RTS/CTS/DATA/ACK and all frames are transmitted with the directional beam. The neighboring nodes which received the RTS/CTS set up directional NAV (DNAV), and postpone the communication to the direction of the node which transmitted the RTS/CTS. At this time, the communication to the direction where DNAV is not set is possible. The communication area depends on the communication distance of the directional beam used. In DMAC, the position information acquisition method required for directional control is not shown.

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MMAC (Multi-hop RTS MAC) [8] is a protocol which extends DMAC. It uses directional antennas and exchanges control frames in the order of multi-hop RTS/CTS/DATA/ACK. MMAC uses multi-hop RTS to perform a wider transmission range for communication. In MMAC, the position information acquisition method required for directional control is not shown which is the same for DMAC. Furthermore, the construction method of the route of multi-hop RTS is not shown.

SWAMP (Smart Antennas Based Wider-range Access MAC Protocol) [9] based on IEEE 802.11 DCF is composed of two access modes, OC-mode (Omni-directional area Communication access mode) and EC-mode (Extend area Communication access mode).

The OC-mode is selected when the transmitter node has no knowledge of location information of the destination node or when the destination node is located in the one hop communication area by omni-directional beam form. The OC-mode is shown in Fig. 1. A communication pair exchanges control frames in the order of RTS/CTS/SOF (Start Of Frame)/DATA/ACK. RTS/CTS/SOF are transmitted and received with the omni-directional beam form and adds the location information. Therefore, neighboring nodes which receive RTS/CTS/SOF obtain the location information. DATA/ACK are transmitted and received with a directional beam form. The OC-mode uses the Omni-NAV which is shorter than conventional NAV. The Omni-NAV is shown in Fig 2. The Omni-NAV is set to the neighboring nodes that receive either RTS (and SOF) only or CTS only. The nodes which are set to Omni-NAV postpone the communication until the completion of SOF. The Omni-NAV improves spatial reuse of the wireless channel.

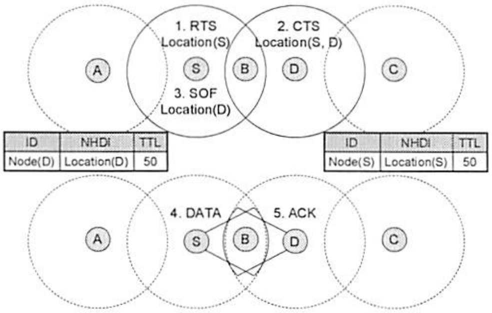


Figure 1 OC-mode

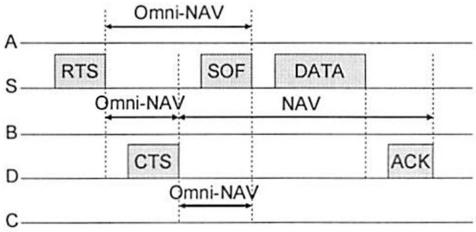


Figure 2. Omni-NAV

The EC-mode is selected when the transmitter node has knowledge of location information of the destination node by OC-mode communications. The EC-mode is shown in Fig. 3. A communication pair communicates in the order of RTS/CTS/DATA/ACK. To perform communication between the nodes which are separated at a distance between the two hops position directly by the omni-directional beam form, RTS is transmitted with a high gain beam form and received with the omni-directional beam form. CTS/DATA/ACK are transmitted and received with the directional beam form. The EC-mode improves spatial reuse and reduces the number of routing hops.

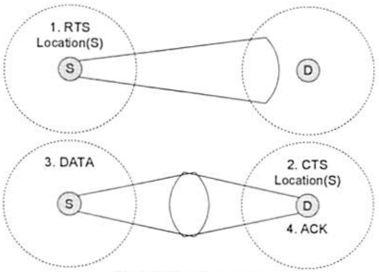


Figure 3 EC-mode

One of the smart antennas, ESPAR (Electronically Steerable Passive Array Radiator) antenna [10] which can control the directivity electronically is proposed. The ESPAR antenna is shown in Fig. 4. It is composed a vertical monopole radiator #0 and in the passive radiators #1 to #6. #0 radiator is used for transmission and receiving. #1 to #6 radiators control the directivity by applying voltage. Some antenna beam forms of ESPAR are shown in Fig 5.

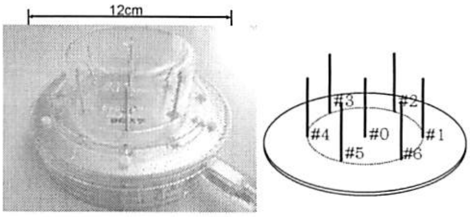
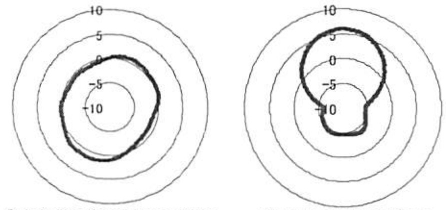


Figure 4.ESPAR antenna



Omni-directional beam form Directional beam form

Figure 5. Beam forms of the ESPAR antenna

III. BASIC EVALUATION

In this section, we evaluate the basic performance and point out the problems of using practical antenna beam forms.

A. Simulation parameters

We make the following assumption. A hundred nodes are arranged at random in a square area with dimensions of

1500 m. The nodes are fixed. Packets arrive at every node according to Poisson distribution with a mean value of λ (packet/sec). The destination node for each packet is chosen at random from two hop communication neighbors. The packet size is 1460 bytes and the omni-directional range is 250 m. The data rate is 2 Mbps.

The evaluated protocols are IEEE 802.11 DCF, SWAMP with ideal antenna beam forms and SWAMP with practical antenna beam forms.

B. Performance of protocols

The aggregate throughput versus the packet arrival rate is shown in Fig. 6. SWAMP with ideal antenna beam forms can achieve high throughput performance compared with IEEE 802.11 DCF. This is because SWAMP improves spatial reuse of the wireless channel due to omni-NAV in the OC-mode, and it reduces the number of routing hops due to an extend communication range in the EC-mode. However, SWAMP with practical antenna beam forms decreases throughput performance compared with SWAMP with ideal antenna beam forms.

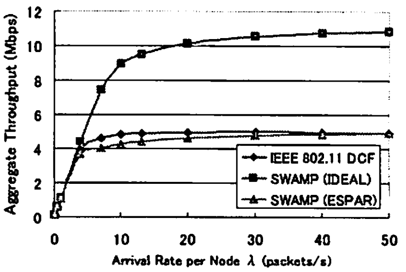


Figure 6. Aggregate throughput

The reason for the degradation in throughput performance is due to collisions of receivers when receiving DATA packets. The number of DATA communications which are successful and errorless in OC-mode and EC-mode versus the packet arrival rates is shown in Fig. 7 and in Fig. 8. The number of successful attempts for the practical antenna beam forms is fewer than that for ideal antenna beam forms. The number of errorless attempts for the practical antenna beam forms is more than that for ideal antenna beam forms.

The number of interference packets during DATA receiving versus the packet arrival rate is shown in Fig. 9 and in Fig. 10. In both the OC-mode and EC-mode, the leading factors that interfere with the DATA packet are RTS in both the OC-mode and EC-mode. It is considered that NAVs are not set adequately. The next, we describe the causes of the degrading throughput performance.

IV. CAUSES OF INTERFERENCE

In this section, we describe the four causes of interferences.

A. Interference by transmission after Omni-NAV

The neighboring nodes which are set in omni-NAV are permitted to transmit after completion of SOF communication. This improves spatial reuse of the wireless channel. The transmission does not interfere with DATA receiving in the ideal antenna beam forms which is shown in Fig. 11 (a), however, it does interfere with the practical antenna beam forms as shown in Fig. 11 (b). This problem is solved by setting the DNAV to the direction of the receiver node.

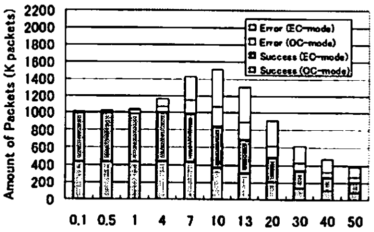


Figure 7. The number of successes and errors (Ideal antenna)

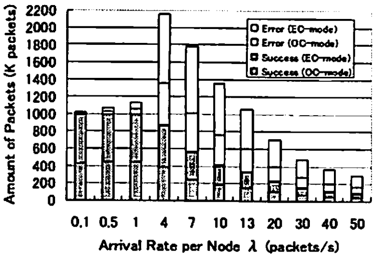


Figure 8. The number of successes and errors (Practical antenna)

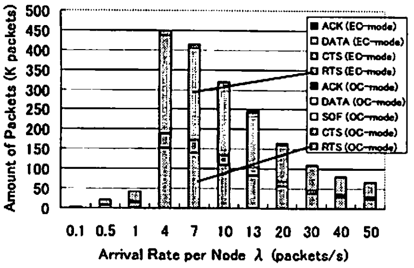


Figure 9. The number of interference packets during DATA receiving in OC-mode

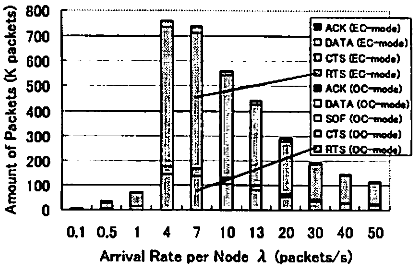
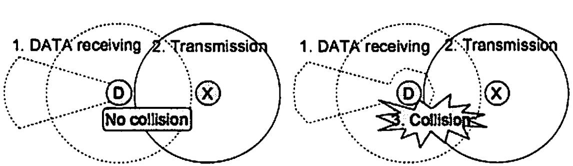


Figure 10. The number of interference packets during DATA receiving in EC-mode



(a) Ideal antenna (b) Practical antenna

Figure 11. Interference by transmission after Omni-NAV

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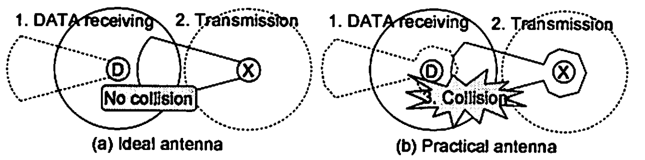
B. *Interference by transmission from the hidden terminals in OC-mode*

The neighboring nodes which are not located in the omni-directional range can not receive control frames. Therefore, these nodes can transmit at any time. In the ideal antenna beam forms, if these nodes transmit the packets with directional antenna beam forms to the receiving node from the back, it causes deafness as shown in Fig. 12 (a). However, deafness does not cause collisions. In the practical antenna beam forms, however, the transmission from hidden terminals from the back cause collision as is shown in Fig. 12 (b). This problem is solved by proposing the rotation of the directionally received antenna beams.

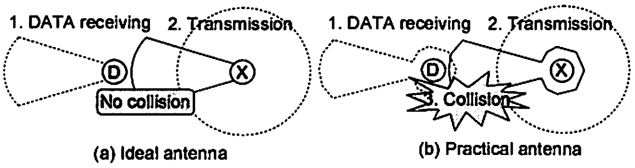


(a) Ideal antenna (b) Practical antenna

Figure 12. Interference by transmission from the hidden terminals in OC-mode

C. *Interference by transmission from the hidden terminals in EC-mode*

All frames are transmitted with the directional antenna beam forms. Thus, it is difficult to receive control frames with omni-directional receive antenna beam forms for the neighboring nodes which are located outside of the main lobe. In the ideal antenna beam forms, if these nodes transmit the packets with directional antenna beam forms to the receiving node from the back, it causes deafness as is shown in Fig. 13 (a). In the practical antenna beam forms, however, the transmission from hidden terminal from the back cause collision as is shown in Fig. 13 (b). This problem is solved by proposing the rotation of the directionally received antenna beams.



(a) Ideal antenna (b) Practical antenna

Figure 13. Interference by transmission from the hidden terminals in EC-mode

D. *Interference by directional hidden terminal problem*

In the EC-mode, RTS is transmitted with the directional antenna beam forms by high transmission power to extend the communication range. It assumes that the receiving node receives with omni-directional antenna beam forms. If the neighboring nodes direct their directional receive antenna beam forms to the transmitter, the interference range extends to more than two hops communication range with omni-directional beam is shown in Fig. 14. This problem is solved by proposing the NAV request frame.

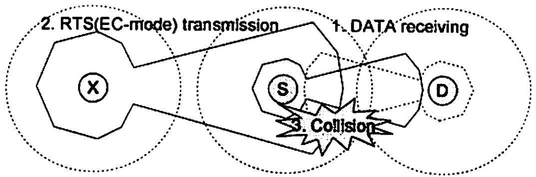


Figure 14. Interference by transmission from the hidden terminals in EC-mode

V. PROPOSED MAC PROTOCOL

In this section, we propose a directional MAC protocol which assumes the use of practical directional antennas. The proposed MAC protocol is based on SWAMP. It deals with influences of side and back lobes and the directional hidden terminal problem by rotating the directional receive antenna beams and transmitting NAV request frame. The MAC protocol is composed of two access modes like SWAMP, and improves spatial reuse of the wireless channel and extends the communication range. The location information required for directional control is obtained in the MAC protocol itself.

A. *Rotation of the directionally received antenna beams*

To solve the problems of B and C in the section IV, we propose rotation of received beams. In an idle state, each node rotates the directional receive antenna beam as shown in Fig. 15. This requires about 200 microseconds to measure the level of received signal and to rotate the directional receiving beam through 360 degrees [11]. Therefore, in order to enable the receiver to receive the signal, each control packet is transmitted with a preceding tone of about 200 microseconds. The node which receives the preceding tone stops the rotation and receives packets. The directions in which the node receives SOF (OC-mode) and RTS (EC-mode) from neighboring nodes are masked until their DATA transmission is completed. After SOF and RTS transmission, the transmitter transmits the DATA packet. Since the duration of DATA transmission is long, if the neighbor nodes receive a DATA packet for another node, it degrades spatial reuse. Receiving with a directional beam enables the nodes to receive control frames which are not received with the omni-directional beam.

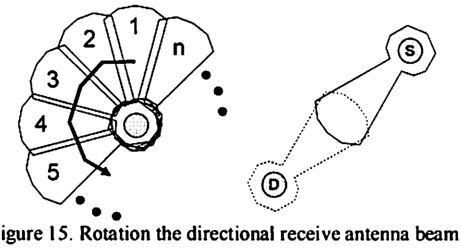


Figure 15. Rotation the directional receive antenna beams

B. *NAV request frame*

For the problem in the section IV D, a NAV request frame is transmitted before receiving the DATA packet by the receiver node. The NAV request frames consist of RTR (Ready To Receive) in the OC-mode and CTS in the EC-mode. RTR is a new control frame incorporated to the original SWAMP. The NAV request frame has effects with rotation of the directionally received antenna beams. The possibility of the most interference for neighboring nodes is RTS in the EC-mode. Therefore, the receiver node transmits the NAV request frame with a directional beam form which is the same as the receiving beam, and transmission power is the same as RTS in the EC-mode as shown in Fig. 16. The NAV request frame is transmitted with the directional beam and also received it. If the nodes which receive the NAV request frame transmit with directional beam in the same way as receiving the NAV request frame and transmission power is the same, its transmitted packet will interfere with DATA reception. The nodes which receive the NAV request frame postpone the communication to the direction of the node which transmits the NAV request frame. By transmitting the NAV request frame, it can set DNAV to the directional hidden terminals.

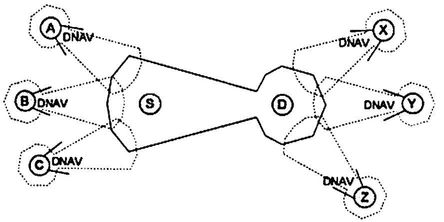


Figure 16. NAV Request frame

C. *Transmission power control*

Three transmission power controls are available for the proposed MAC protocol. The transmission power levels, transmission beam forms, receiving beam forms, and communication ranges are shown in Table 1. Each node rotates the directional receive antenna beams in an idle state, so that receiving beam is not omni-directional but only directional. The communication range is the maximum range when the transmitter's and receiver's antenna main lobe face each other.

TABLE 1
TRANSMISSION POWER

Transmission power	Transmitter beam form	Receiver beam form	Communication range
P_tO	Omni-directional	Directional	d
P_tD_1	Directional	Directional	2d
P_tD_2	Directional	Directional	d

D. *OC-mode*

The sequence for OC-mode is shown in Fig. 17 (a). It is selected when the transmitter node has no location information of the destination node or when the destination node is located in the one hop communication area by omni-directional beam. The maximum communication range is d in the OC-mode. The proposed protocol incorporates the control frame RTR as the NAV request frame to the original SWAMP. A transmitter transmits RTS with the omni-directional beam and transmission power P_tO. RTS includes the transmitter's location information. The receiver receives RTS and obtains transmitter location. It transmits CTS with the omni-directional beam and transmission power P_tO. CTS includes the transmitter location as NHDI (Next Hop Direction Information) and its own location information. The neighboring nodes which receive CTS register NHDI to the NHDI table. The transmitter receives CTS and obtains receiver location information. It transmits SOF with the omni-directional beam form and transmission power P_tO. SOF includes receiver location information as NHDI. The neighboring nodes which receive SOF register NHDI to the NHDI table. After the completion of SOF, the receiver transmits RTR as a NAV request frame with a directional beam and transmission power P_tD_2. RTR includes its own location as NHDI. The neighboring nodes that receive RTS/CTS/SOF and RTR are set to DNAV until completion of RTR and ACK, respectively. The location information in the NHDI table is used in the EC-mode.

DATA and ACK are transmitted with directional beam forms that point the beam form towards each other and transmission power P_tD_1.

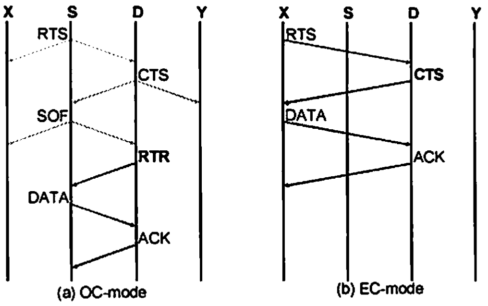
The OC-mode improves spatial reuse and solves location information required for directional control in the EC-mode.

E. *EC-mode*

The EC-mode is shown in Fig. 17 (b). It is selected when a transmitter has location information of the destination node in the NHDI table by OC-mode communications. The maximum communication range is 2d in the EC-mode because the NHDI table has location information of the nodes which are located two hops far. A communication pair exchanges RTS/CTS/DATA/ACK. All frames are transmitted with the directional beam and transmission power P_tD_2.

In the NHDI table, nodes register location information of destination nodes which are in the two hop range by omni-directional beam. Therefore, the EC-mode permits one hop communication with the nodes which are located in the two hops position directly by directional beam and transmission power control.

EC-mode improves spatial reuse and reduces the number of routing hops by extending communication range.



(a) OC-mode (b) EC-mode

Figure 17. Proposed MAC protocol

VI. PERFORMANCE EVALUATIONS

In this section, we evaluate the proposed MAC protocol. The simulation parameters and comparative protocols are the same as those of the basic evaluation.

A. The number of successes or errors

The number of DATA communications which are successes or errors in the OC-mode and EC-mode versus the packet arrival rates is shown in Fig. 18. Compared with SWAMP with practical antenna beam forms as shown in Fig. 8, the proposed MAC protocol increases the number of successes and decreases the number of errors. Because it reduces the collision with DATA and other control frames by rotating the directional receive antenna beams and transmitting the NAV request frame. However the neighbor nodes can not receive the NAV request frame when they receive other frames. Therefore, the collision of RTS with these nodes transmission can not be avoided.

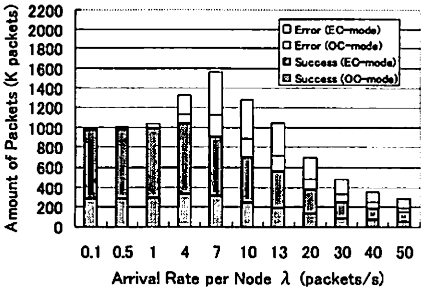


Figure 18. The number of success and error

B. Throughput evaluation

The aggregate throughput versus the packet arrival rate is shown in Fig. 19. Compared with SWAMP with practical antenna beam forms, the proposed MAC protocol improves throughput by about 2 Mbps.

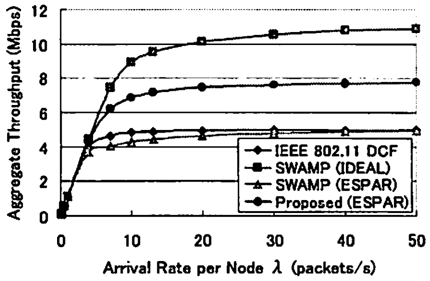


Figure 19. Aggregate throughput

The aggregate throughput versus the data size is shown in Fig 20. Poisson distribution λ is fixed to 10 (packets/s). The proposed MAC protocol has higher throughput as the data size is setting large. SWAMP with practical antenna beam forms can be easily interfered with by the neighbor node transmission during DATA reception. The communication period is longer due to the large data size. Consequently, the long period is wasted which is caused by collision and it decreases throughput of the original SWAMP with practical antenna beam forms. On the other hand, the proposed protocol reduces influence with collisions by rotating the directional receive antenna beams and transmitting the NAV request frames. Therefore, the proposed protocol can transmit the large size packet without collisions compared with the original SWAMP.

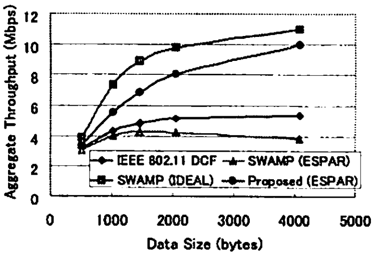


Figure 20. Aggregate throughput

VII. CONCLUSIONS

In this paper, at first, we have evaluated throughput of the directional MAC protocol in the previous studies with practical antenna beam forms and pointed out interference problems caused by transmission after Omni-NAV, by transmission from the hidden terminals in OC-mode, by transmission from the hidden terminals in EC-mode and by directional hidden terminals. After analyzing the problems, we have proposed the directional MAC protocol that deals with these problems by rotating the directional receive antenna beams and transmitting the NAV request frame. The simulated results show that the throughput of the proposed protocol has improved compared with that of the directional MAC protocol in the previous studies with practical antenna beam forms. And the results also show that the proposed MAC protocol is more effectives than the previous directional MAC protocol with a practical antenna when the data size is large.

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