Directional NAV Indicators and Orthogonal Routing for Smart Antenna Based Ad Hoc Networks

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Abstract

Smart antennas are expected to enhance scalability in ad hoc networks. This paper at first evaluates three directional MAC protocols, DMAC, MMAC and SWAMP as well as the omni-directional protocol IEEE 802.11 DCF in multi-hop transmission environment. The evaluations address the problem that the performance strongly depends on the topology of routes between sources and destinations, referred to as a directional hidden terminal problem. After analyzing the problem, we propose three MAC level solutions and one routing level solution. The MAC solutions are directional NAV indicators which are BRTS, RCTS and HCTS to indicate on-going communications to a directional hidden terminal to set directional NAV. On the other hand, the routing level solution is orthogonal routing protocol (ORP). ORP is a DSR based on-demand routing protocol and it prevents adjacent links to be in straight lines. As computer simulated results, we show that HCTS can improve the throughput performance.

1. Introduction

In recent years, wireless ad hoc networks attract attention. Wireless ad hoc networks do not need a fixed infrastructure. Omni-directional antennas result in low spatial utilization and poor performance because only single pair of nodes can communicate at a time[1].

Smart antennas[2] may potentially improve the performance of wireless ad hoc networks[1]. Smart antennas have advanced characteristics such as electrical adjustment of beam direction by signal processing. The directional MAC (Medium Access Control) protocols using smart antennas, such as SWAMP (Smart Antennas based Wider-range Access MAC Protocol)[3], DMAC (Directional MAC Protocol)[4], and MMAC (Multi-Hop RTS MAC Protocol)[4], are proposed for the purpose of efficient use of a radio medium in wireless ad hoc networks. As for the directional MAC protocols, improvement of the throughput performance are shown rather than omni-directional MAC protocols. However, comparison of directional MAC protocols has not been fully performed.

In this paper, we perform comparative evaluation about the characteristic in case of multi-hop transmission of IEEE 802.11 DCF[5] and three directional MAC protocols. We consider the validity of the directional MAC protocols and their problems. As the result, we show a suitable environment for using directional MAC protocols. Moreover, we also show that a directional hidden terminal problem is caused by using directional MAC protocol and causes performance degradation. The directional hidden terminal problem is a serious problem which should be solved. We propose three MAC level solutions and one routing level solution. The MAC solutions are DNAV indicators which are HCTS, BRTS and RCTS. On the other hand, the routing level solution is ORP. As computer simulated results, we show that HCTS can improve the throughput performance.

2. DIRECTIONAL MAC PROTOCOLS

In this paper, we evaluate the following four protocols.

2.1. IEEE 802.11 DCF

IEEE 802.11 DCF a MAC protocol which spreads widely. It uses an omni-directional antenna and communicates in the order of RTS/CTS/DATA/ACK. It is shown that spatial reuse of IEEE 802.11 DCF is low and cannot perform efficiently[6, 7].

2.2. SWAMP

SWAMP consists of two access modes, OC-mode (Omni-directional area Communication access mode) and EC-mode (Extend area Communication access mode).

OC-mode is selected when a destination terminal is located within the area of omni-directional transmission range

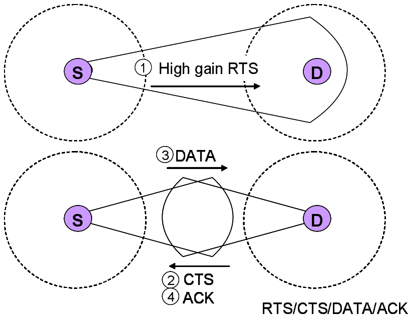


Figure 1. SWAMP (EC-mode).

or when the transmitter has no knowledge about the receiver node. A Communication pair exchanges RTS/CTS/SOF (Start of Frame)/DATA/ACK. RTS/CTS/SOF are transmitted omni-directional beam and DATA/ACK are transmitted with directional beam. By exchange of RTS/CTS/SOF, a communication partner's position information is acquired and the acquired position information is notified in the neighborhood. The neighboring terminal which received RTS/CTS/SOF postpones its own communication while Omni-NAV which is shorter than the conventional NAV.

In Fig. 1 to Fig. 3, a solid line shows the directional communicational range, and a dashed line shows an omni-directional receiving range. Note that a transceiver and a receiver can communicate each other if the transceiver's beam form overlaps the receiver's beam form.

EC-mode is selected when a destination terminal is in the two hops communication range by omni-directional beam. The flow of communication of SWAMP (EC-mode) is shown in Fig. 1. The direction of a beam is controlled by the terminal position information acquired from the neighborhood by OC-mode. RTS/CTS/DATA/ACK are transmitted with a directional beam. By transmitting RTS with a higher gain directional beam, it communicates with the terminal of the two hops position directly.

2.3. DMAC

The flow of communication of DMAC is shown in Fig. 2 RTS/CTS/DATA/ACK are transmitted with a directional beam. In DMAC, a communication pair exchange RTS/CTS/DATA/ACK transmitted with directional beam. The neighboring terminal which received RTS/CTS sets DNAV, and postpones the communication to the direction of the terminal which transmitted 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 to be used. In DMAC, the position information acquisition method required for directional control is not shown.

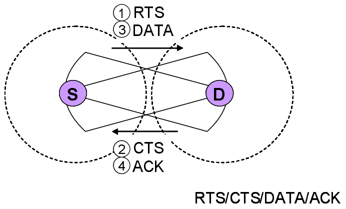


Figure 2. DMAC.

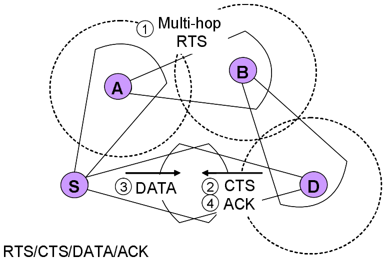


Figure 3. MMAC.

2.4. MMAC

The flow of communication of MMAC is shown in Fig. 3. MMAC is a protocol which is extended DMAC. It uses a directional antenna and communicates in the order of Multi-hop RTS/CTS/DATA/ACK. MMAC uses a multi-hop RTS which relays RTS at a neighboring terminal for extension of the communication area. In MMAC, the position information acquisition method is not shown such as DMAC. Furthermore, the construction method of the route of multi-hop RTS is not shown.

3. PERFORMANCE EVALUATION

Comparative evaluation of SWAMP, DMAC, MMAC and 802.11 is carried out in a multi-hop environment to find the dependency of the performance on the topology. As the result, we consider the relation of the directional MAC protocols, a multi-hop flow, and antenna beam form. Performance evaluation is performed by computer simulation. A simulation preface is shown in Table 1.

The maximum communication distance by the antenna beam used by each protocol is as follows. IEEE 802.11 DCF and SWAMP (OC-mode) assumed to 250m for the maximum communication distance. SWAMP (EC-mode) assumed to 500m. DMAC assumed to two kinds, 900m [4] and 250m. MMAC assumed to 900m [4]. The position information on a destination terminal assumed to be known. An evaluation route models are straight model and non-straight model. The evaluation index is the total end-to-end throughput of the four flows (Aggregate Through-

Table 1. Simulation Parameters

Topology	5x5 grid topology (interval 150m)
Number of flows	4 (fixed, 4hops) *SWAMP(EC-mode),MMAC: 2hops
Traffic	CBR traffic generation
Size of Data	512Bytes
Omni-directional communication range	250m
Directional beam width	45-degree
Wireless band	2Mbps

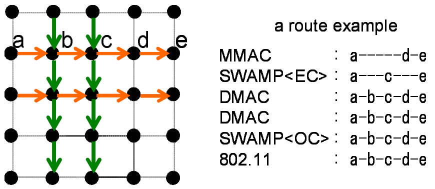


Figure 4. Straight model.

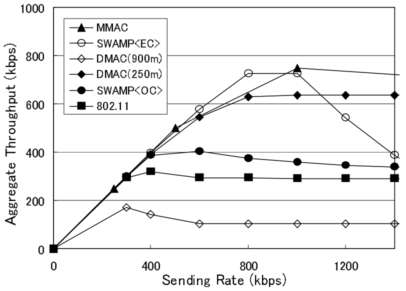


Figure 5. Straight model throughput.

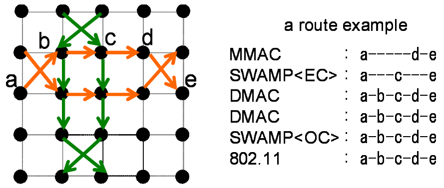


Figure 6. Non-Straight model.

put). The evaluation result in a straight model in Fig. 4 is shown in Fig. 5. The evaluation result in a non-straight model in Fig. 6 is shown in Fig. 7. In addition, routes are changed by communication distance. For example, routes in the flow between a-e, both a straight model and a non-straight model, are as follows. IEEE 802.11 DCF, SWAMP (OC-mode), and DMAC multi-hop with a-b-c-d-e, SWAMP (EC-mode) multi-hops with a-c-e, and MMAC multi-hops with a-d-e.

In Fig. 5, it is shown that MMAC and DMAC (250m) can achieve a high performance. MMAC needs a few hops to communicate between souse and destination. DMAC (250m) use the directional beam of the small transmitting range. In cases of SWAMP (EC-mode) and DMAC (900m), higher gain directional beam interferes in other links easily. Therefore, in the straight flow such as Fig. 5, SWAMP (EC-mode) and DMAC (900m) show low performance. In addition, SWAMP (OC-mode) achieves the higher performance compared with IEEE 802.11 DCF. However in order to use the control frame by the omni-directional beam, SWAMP (OC-mode) shows lower performance than DMAC (250m).

Fig. 7 shows that all directional MAC protocols can achieve better performance than IEEE 802.11 DCF. In particular, SWAMP (EC-mode) shows the highest performance in a low load situation. SWAMP (EC-mode) does not interfere by the directional beam in a low load situation. Moreover, SWAMP (EC-mode) does not need multi-hop RTS compared with MMAC.

Figs. 5 and 7 show that SWAMP (EC-mode) shows a high performance in a non-straight model rather than a straight model. Both in a straight and a non-straight model, the performance of DMAC (900m) is lower than DMAC (250m). In DMAC (900m), high gain beam interfere surrounding links in DMAC (900m).

By extension of communication area, SWAMP (EC-mode) and MMAC need only two hops for end-to-end communication. SWAMP (EC-mode) and MMAC obtain the high throughput. It is shown that extension of a communication area is effective in a multi-hop network. However, the performance of SWAMP (EC-mode) is lower than MMAC of the same number of the hops.

Moreover, we compare the three protocols which with the same number of hops. SWAMP (OC-mode) which transmits DATA/ACK with a directional beam shows higher throughput than IEEE 802.11 DCF. Furthermore, DMAC (250m) which transmits all frames with a directional beam shows the highest performance of the three protocols. However, solution of position information acquisition and not using a directional beam are required. In other words, it is ideal to transmit by a necessary minimum gain of the beam for every transmission. However, control the necessary minimum gain, reliable position information on a destination terminal is required.

In this performance evaluation, position information is assumed to be known. Therefore, this assumption is advantageous to DMAC and MMAC. For directional control of a beam, the position information of a destination terminal is essential. SWAMP solves acquisition of position information using an omni-directional beam in OC-mode. In EC-mode, sender communicates with a long distance terminal using position information acquired by OC-mode, and using high gain RTS. DMAC and MMAC assume on posi-

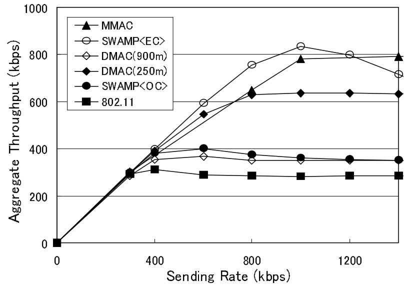


Figure 7. Non-Straight model throughput.

tion information given beforehand. Therefore, DMAC and MMAC do not function without additional mechanism for acquiring position information. DMAC and MMAC cannot avoid increasing the overhead for acquiring position information in the upper layer.

As mentioned above, directional MAC protocols improve the throughput performance by cutting down number of hops and limitation of the transmitting range. Too high gain beam degrades throughput performance. Moreover, a throughput performance depends on the route in case of using directional MAC protocols. A throughput performance improves by losing the straight nature in a self-route and by abolishing parallelism with neighboring links.

4. DIRECTIONAL HIDDEN TERMINAL PROBLEM

Fig. 5 shows that throughput performance of the SWAMP (EC-mode) becomes lower than MMAC and DMAC (250m) in the straight model. The reason of the performance degradation is a kind of hidden terminal problem which occurs in case the directional beam of a higher gain is used by the flow of more straight nature. This problem is called a directional hidden terminal problem. We explain how to happen a directional hidden terminal problem. After that, we propose three kinds of DNAV indicators to solve a directional hidden terminal problem. Additionally, we evaluate the throughput performance of the proposed DNAV indicator.

4.1. DIRECTIONAL HIDDEN TERMINAL PROBLEM

A directional hidden terminal problem occurs by using the directional beam of a higher gain. Fig. 8 shows the mechanism which a directional hidden terminal problem occurs. Note that a transceiver and a receiver can communicate each other if the transceiver's beam form overlaps the receiver's beam form.

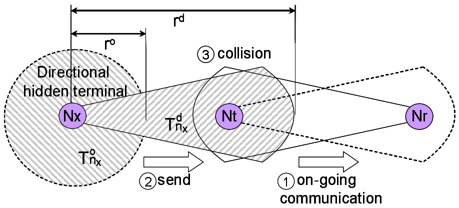


Figure 8. Directional hidden terminal problem.

We define N as a set of nodes in the network area ($N = \{n_1, n_2, \dots, n_K\}$). A set of directional hidden terminal is defined as $H(n_t, n_r)$, where $n_t \in N$ is a transmitter and $n_r \in N$ is a receiver. Omni-directional transmission area and omni-directional reception area of $n_i \in N$ with a range r^o are defined as $T^o_{n_i}$ and $R^o_{n_i}$, respectively. Also, directional transmission area and directional reception area of n_i with a range $r^d (\geq r^o)$ are defined as $T^d_{n_i}$ and $R^d_{n_i}$, respectively. If the transmission area of n_i and the reception area of n_j are overlapped, n_j will receive a message transmitted by n_i, which is defined as $\{T_{n_i} \cap R_{n_j} \neq \emptyset\}$. In directional case, a transmitting beam of n_i should be towards n_j, and vice versa. Then H is defined as follows. $H = \{n_x | n_x \in N, \{T^d_{n_t} \cap R^o_{n_x} = \emptyset\} \wedge \{T^d_{n_r} \cap R^o_{n_x} = \emptyset\} \wedge \{T^d_{n_x} \cap R^d_{n_r} \neq \emptyset\}\}$, where n_t is a transmiting node, n_r is a receiving node and n_x is a directional hidden terminal of n_r.

Directional hidden terminal problem not only suspends its communication, but also destroys the on-going communication. Therefore, directional hidden terminal problem is more serious than the exposed and deafness problems [4].

5. DIRECTIONAL NAV INDICATERS

The DNAV indicators are schemes to inform a directional hidden terminal of on-going communication. Then the directional hidden terminal sets DNAV. We propose three kinds of DNAV indicators which are HCTS, BRTS and RTS to solve a directional hidden terminal problem.

5.1. HIGH GAIN CTS (HCTS)

We propose a scheme that the destination terminal transmits CTS with higher gain to make a directional hidden terminal set DNAV. The situation that the HCTS prevents the directional hidden terminal is shown in Fig. 9. In this case, CTS needs to cover all the area in which a directional hidden terminal may exist. Therefore, an antenna gain must be enlarged. However, HCTS does not need to introduce a new flame.

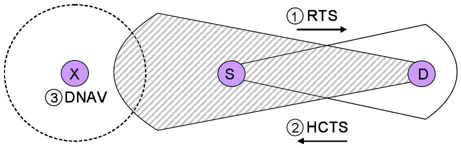


Figure 9. High gain CTS (HCTS).

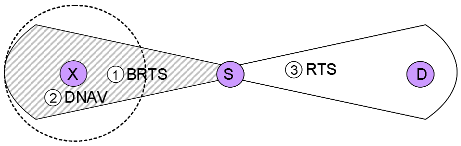


Figure 10. Backward RTS (BRTS).

5.2. BACKWARD RTS (BRTS)

The situation of the BRTS prevents the directional hidden terminal is shown in Fig. 10. Before terminal S transmits RTS to destination, it turns the direction of a transmitting antenna to 180-degree back toward destination, and transmits RTS. Directional hidden terminal X sets DNAV by BRTS. About extension of RTS, circular RTS[8] uses rotation transmission of RTS for prevention of the directional hidden terminal. The scheme which DNAV is made to set to the terminals of all the direction of surrounding of a transmitting terminal. However, in order to transmit RTS repeatedly, changing the direction of an antenna, an overhead arises. When a sender did not receive CTS from a destination terminal, terminal which received the BRTS sets DNAV and postpones own communication. Therefore, BRTS has potential for decline in spatial reuse.

5.3. RELAYED CTS (RCTS)

There is a problem in BRTS and circular RTS[8]. If a transmitting terminal cannot receive CTS from a communication partner, a terminal which received BRTS sets DNAV. Then the circumference terminal postpones its own communication. In order to solve the problem in BRTS, RCTS is introduced. The situation of the RCTS prevents the directional hidden terminal is shown in Fig. 11. The terminal S transmits RTS to the terminal D with a directional beam, and after receiving CTS from D, S transmits RCTS to 180-degree back. After that, DATA/ACK are transmitted and received. RCTS is introduced to notify behind terminal of own communication. The received terminal sets DNAV. When a sender received CTS from communication partner, sender transmits RCTS. The timing is not immediately after transmitting RTS. Therefore RCTS is more effective than BRTS. It is thought that RCTS is the same as SOF of SWAMP (OC-mode) with high gain and directionally.

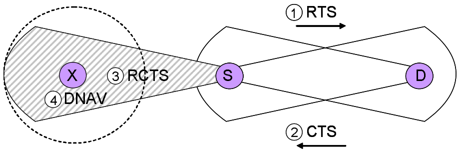


Figure 11. Relayed CTS (RCTS).

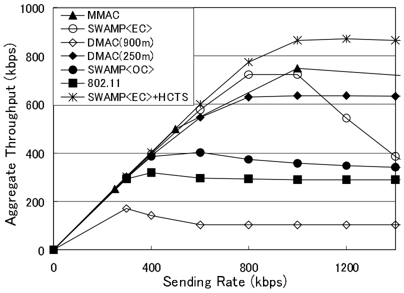


Figure 12. Throughput performance in straight model.

5.4. PERFORMANCE EVALUATION

Under the same conditions in Section 3, we evaluate proposed HCTS. Although the proposed schemes are able to apply to every directional MAC protocol, in this section we evaluate HCTS schemes extended SWAMP (EC-mode). The evaluation result in a straight model is shown in Fig. 12, and the evaluation result in a non-straight model is shown in Fig. 13.

Fig. 12 shows that HCTS improves the performance in a straight model. The throughput of SWAMP (EC-mode) with HCTS can achieve the highest performance in all protocols. Because HCTS scheme prevent almost all the directional hidden terminals.

Fig. 13 shows that HCTS deteriorates the performance rather than SWAMP (EC-mode). In a non-straight model, although a directional hidden terminal problem is solvable, however, the HCTS causes on the contrary more interference.

As mentioned above, whether HCTS can improve performance also depends on the shape of the flow. In a straight flow, it is considered that HCTS is effective. However, in a non-straight flow, in other words, in the situation that less occurrence of directional hidden terminal problem, proposed schemes lead to low performance. Nodes behind a receiver have a possibility destruction of receiver's ACK. A directional hidden terminal problem exists not only behind a sender but also behind a receiver. It is necessary to examine for the directional hidden terminal problem under variable

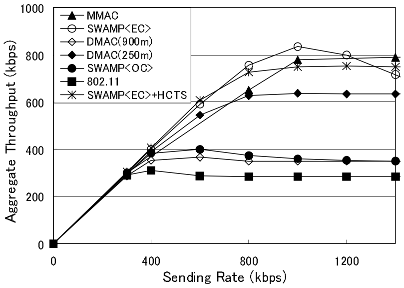


Figure 13. Throughput performance in non-straight model.

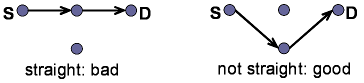


Figure 14. A route exists in a network.

situations.

6. ORTHOGONAL ROUTING

In this section, we propose a routing level solution. Fig. 14 shows a case that a route exists. In Fig. 14, if two adjacent links are not in a straight line, the directional hidden terminal problem does not occur. In Fig. 15, if two adjacent links in different routes are not parallel, the directional hidden terminal problem does not occur. Therefore, a solution to eliminate the directional hidden terminal problem is to avoid the following two cases.

- A route is straight.
- Two nearby routes are parallel.

In other words, route's orthogonality prevents the directional hidden terminal problem.

We propose an orthogonal routing protocol (ORP) which is the DSR[9] based on-demand routing protocol. Fig. 16 shows the operation of the ORP. In this figure, node S is the source and node D is the destination. Node A, B and C are intermediate nodes. In ORP, each node has a location table. The location table includes node's IDs and their location information. In the ORP, RREQ is extended. In addition to the node's list from the source node, RREQ includes location information of previously two nodes. For example, when a RREQ is originated from node S as shown in Fig. 16, the RREQ that sent from node B to node D include the location information of node A (X_a, Y_a) and B (X_b, Y_b). ORP algorithm is as follows.

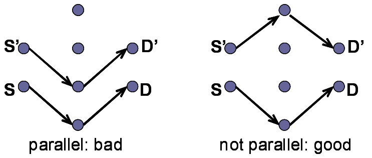
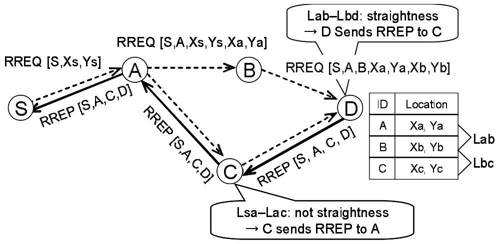


Figure 15. Two routes exist in a network.



* Each node gets location information of the nodes within 2-hops by RREQ(s).

Figure 16. ORP's operation.

i) RREQ transmission process: Node S sends RREQ including own ID (S) in routing information and location information (X_s, Y_s).

ii) RREQ reception process: When a node receives a RREQ, the node behaves as follows.

- A case that the node is not the destination such as node A (or B, C).

1. The node A gets S's location information (X_s, Y_s) from the RREQ and inserts the location information in own location table.
2. The node A adds own ID (A) and location information (X_a, Y_a) to the RREQ.
3. The node A forwards the RREQ.

- A case that the node is the destination node D.

1. The node gets location information from the RREQ and inserts the location information in own location table.
2. After the first RREQ (S-A-B-D) arrival, node D waits until Δt to acquire more information by other RREQs (such as S-A-C-D).
3. Node D prepared to send RREP to B because the first arrival RREQ through (S-A-B-D).
4. First, node D calculates inner product of two vectors I_{abd} by L_{ab} and L_{bd} in own location table. L_{ab} means the vector of the link between node A and B.
5. If $I_{abd} < threshold(Th)$, the route A-B-D is not straight.
6. Node D generates a RREP including own ID (S-A-B-D) and location information (X_d, Y_d).Then node D sends RREP to node B.

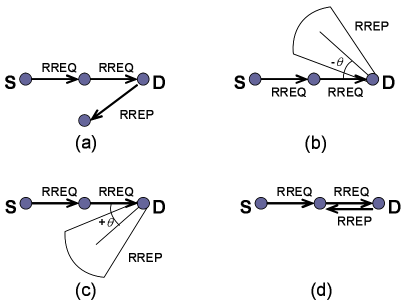


Figure 17. Four patterns of RREP transmission.

7. If $I_{abd} \geq Th$, the route A-B-D is straight. Node D checks its location table for suitable node instead of node B. If node D finds that C is suitable ($I_{acd} < Th$), node D sends RREP including own ID and location information (X_d, Y_d) to node C instead of node B. At that time, routing information in RREP (S-A-B-D) is changed to (S-A-C-D).

   - When $I \geq Th$, the node's detail behavior is as follow.

   (a) If there is a suitable node in the location table, the node sends RREP to the suitable node as shown in Fig. 17(a).
   (b) If there is no suitable node in the location table, the node shifts antenna direction to -θ and sends RREP as shown Fig. 17(b).
   (c) If there is no suitable node for direction of -θ, the node shifts antenna direction to +θ and sends RREP as shown in Fig. 17(c).
   (d) If there is no suitable node for both the directions -θ and +θ, the node sends RREP to RREQ's sender as shown Fig. 17(d).

iii) RREP reception process: When a node receives a RREP, the node behaves as follows. - A case that the node is not the RREP's destination node, such as C (or A).

1. The node C gets location information (X_d, Y_d) from the RREP and inserts the location information in own location table.
2. The node C calculates inner product of two vectorsI_{sac}, L_{sa} and L_{ac}, by using own location table.
3. If $I_{sac} < Th$, the route S-A-C is not straight. Then node C sends RREP (S-A-C-D) to node A.
4. If $I_{sac} \geq Th$, the route S-A-C is straight. Then node C sends RREP to a node that excepted node A.

- A case that the node is the source node S. An orthogonal route construction is completed.

In the future, we have a plan to evaluate performance of ORP. Moreover, we consider the situation that routes exist in a network.

7 Conclusions

In this paper, we have evaluated comparatively three directional MAC protocols, DMAC, MMAC and SWAMP as well as the omni-directional protocol IEEE 802.11 DCF in multi-hop transmission environment. The evaluations address the problem that the performance strongly depends on the topology of routes between sources and destinations, referred to as a directional hidden terminal problem.

After analyzing the problem, we have proposed three MAC level solutions and one routing level solution. The MAC solutions are DNAV indicators which are HCTS, BRTS and RCTS to indicate on-going communications to a directional hidden terminal to set DNAV. On the other hand, the routing level solution is ORP. ORP prevents adjacent links to be in straight lines. As computer simulated results, we show that HCTS can improve the throughput performance. For future work, we have a plan to evaluate more variable situations of the MAC solutions and performance of the ORP.

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