A Directional Hidden Terminal Problem in Ad hoc Network MAC Protocols with Smart Antennas and its Solutions

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***Abstract*— Smart antennas are expected to enhance scalability in ad hoc networks. This paper describes the evaluations of three directional MAC protocols, DMAC, MMAC, and SWAMP, as well as the IEEE 802.11 DCF omni-directional protocol in a multi-hop transmission environment. These evaluations address the problem that performance strongly depends on the route topology between the source and destination, referred to as the directional hidden terminal problem. After analyzing this problem, we propose three MAC level solutions. The MAC solutions are NAV indicators, i.e. HCTS, BRTS, and RCTS, which indicate on-going communications to a directional hidden terminal to set NAV. Based on simulated results, we show that all the proposed MAC solutions could improve the throughput performance.**

I. Introduction

Recently, wireless ad hoc networks have been attracting attention. Since wireless ad hoc networks do not need a fixed infrastructure. Omni-directional antennas result in low spatial utilization and poor performance because only a single pair of nodes can communicate at one time[1], [2]. Smart antennas[3] could potentially improve the performance of wireless ad hoc networks[1]. They have advanced characteristics, such as electrical adjustment of beam direction using signal processing. Directional medium access control (MAC) protocols using smart antennas, such as smart antennas based wider-range access MAC protocol (SWAMP)[4], directional MAC protocol (DMAC)[5], and multi-hop RTS MAC Protocol (MMAC)[5], have recently been proposed to efficiently use radio media in wireless ad hoc networks. They showed the improvement of the throughput performance against the omni-directional MAC protocols.

In this paper, we describe a comparative evaluation of the characteristics of IEEE 802.11 DCF[6] multi-hop transmissions and the three-directional MAC protocols. We consider the validity of the directional MAC protocols and their problems. As a result, we obtained a suitable environment for using directional MAC protocols. Moreover, we also find that the directional hidden terminal problem is caused by using directional MAC protocol, which degrades performance. Then, we propose three MAC-level solutions. The solutions are NAV indicators[7], which are HCTS, BRTS, and RCTS. The simulation results verify that all the proposed MAC solutions improve the throughput performance.

II. Directional MAC Protocols

In this paper, we evaluate the following four protocols.

A. IEEE 802.11 DCF

This is a popular and widely used MAC protocol that uses an omni-directional antenna and communicates in the order of RTS/CTS/DATA/ACK. In addition to a physical carrier sense, a virtual carrier sense is also used to ameliorate the hidden terminal problem.

B. SWAMP

Smart antennas based wider-range access MAC protocol consists of two access modes, omni-directional area communication access mode (OC-mode) and extend area communication access mode (EC-mode).

OC-mode is selected when the destination terminal is located within the omni-directional transmission range 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 using an omni-directional beam and DATA/ACK are transmitted using a directional beam. Through the RTS/CTS/SOF exchange, the communication peer's position information is acquired and the position information is relayed to the neighborhood. The neighbor terminal that receives RTS/CTS/SOF temporarily suspends its communication activities, while Omni-NAV, which is shorter than the conventional NAV, is active.

On the other hand, EC-mode is selected when the destination terminal is located out of the transmitter's omni-directional range and in the twice of the omni-directional range. The beam direction is controlled by the terminal position information acquired from the neighborhood by the OC-mode. Then, RTS/CTS/DATA/ACK are transmitted using a directional beam. By transmitting RTS using a higher gain directional beam, EC mode can directly communicate with the two-hop position terminals.

C. DMAC

In DMAC, communication pair exchanges RTS/CTS/DATA/ACK transmitted using a directional beam. The neighboring terminal that receives the RTS/CTS sets NAV, temporarily suspends communication to the RTS/CTS transmitting terminal. During this time, it is possible to communicate towards area in which NAV is not set. The communication area depends on the distance of the directional beam used. In DMAC, the position information acquisition method required for directional control is not shown.

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TABLE I
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

D. MMAC

MMAC is a protocol used to extend DMAC's transmission area. It uses a directional antenna and communicates in RTS/CTS/DATA/ACK. MMAC order using a multi-hop RTS that relays the RTS to a neighboring terminal to extend the communication area. In MMAC, the position information acquisition method is not shown as it is in DMAC. Furthermore, the construction method of the multi-hop RTS route is not shown.

III. PERFORMANCE EVALUATION

We carry out a comparative evaluation of SWAMP, DMAC, MMAC and 802.11 standards in a multi-hop environment to find the degree to which performance depends on the topology. As a result, we consider the relationship of the directional MAC protocols, the multi-hop flow, and the form of the antenna beam. We conduct a performance evaluation using a computer simulation. The simulation parameters are shown in Table 1.

The maximum communication distance of the antenna beam used by each protocol is as follows: - IEEE 802.11 DCF and SWAMP (OC-mode) assumes 250 m for the maximum communication distance, - SWAMP (EC-mode) assumes 500 m. - DMAC assumes 900 m [5] and 250 m, and - MMAC assumes 900 m [5]. The position information for the destination terminal is assumed to be known. We use both straight and non-straight evaluation route models. The evaluation index is the total end-to-end throughput of the four flows (aggregate throughput). The evaluation results of the straight model in Fig. 1 are shown in Fig. 2. The evaluation results of the non-straight model in Fig. 3 are shown in Fig. 4. In addition, the routes are changed, depending on the communication distance. For example, the routes in the flow between a-e for both the straight and the non-straight models, 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.

As seen in Fig. 2, MMAC and DMAC (250m) achieve a high performance. However, MMAC need a few hops to communicate between the source and destination. The 250-m DMAC uses the directional beam in a short transmitting range. For SWAMP (EC-mode) and DMAC (900 m), the higher gain directional beam interfered with the other links. Therefore, in straight flows, such as seen in Fig. 2, SWAMP (EC-mode) and DMAC (900 m) show a poor performance. In

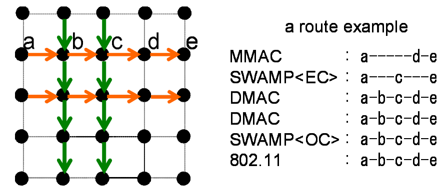

Fig. 1. Straight model.

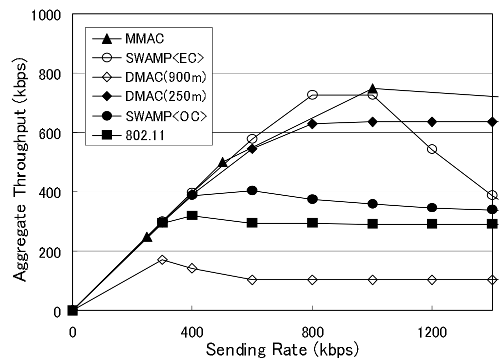

Fig. 2. Straight model throughput.

addition, SWAMP (OC-mode) achieves a better performance than IEEE 802.11 DCF. However, to use the omni-directional beam control frame, SWAMP (OC-mode) shows a poorer performance than the 250-m DMAC.

Figure 4 shows that all directional MAC protocols achieve a better performance than IEEE 802.11 DCF. In particular, SWAMP (EC-mode) showes the highest performance in low-load situations and does not interfere with the directional beam. Moreover, it does not need multi-hop RTS that MMAC does.

Figures 2 and 4 show that SWAMP (EC-mode) had a higher performance in the non-straight model than the straight model. In both straight and non-straight models, the 900-m DMAC performance is lower than the 250 m. In the 900-m DMAC, the high gain beam interferes with the surrounding links.

By extending the communication area, SWAMP (EC-mode) and MMAC only need two hops for end-to-end communication and a high throughput. Thus, extending the communication area is effective in multi-hop networks. However, the SWAMP (EC-mode) performance is lower than MMAC with the same number of the hops.

We then compare the three protocols with the same number of hops. SWAMP (OC-mode), which transmits DATA/ACK using a directional beam, we obtain a higher throughput than for IEEE 802.11 DCF. Furthermore, the 250-m DMAC, which transmits all frames using a directional beam, shows the highest performance of the three protocols. However, a solution is still required to acquire position information without using a directional beam. In other words, ideally we should transmit using the minimum necessary beam gain for

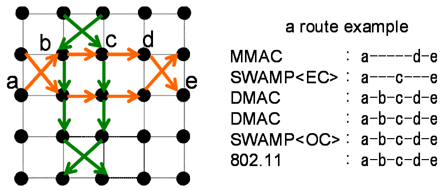

Fig. 3. Non-Straight model.

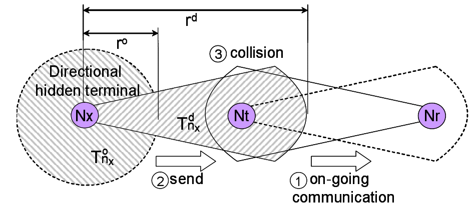

Fig. 5. Directional hidden terminal problem.

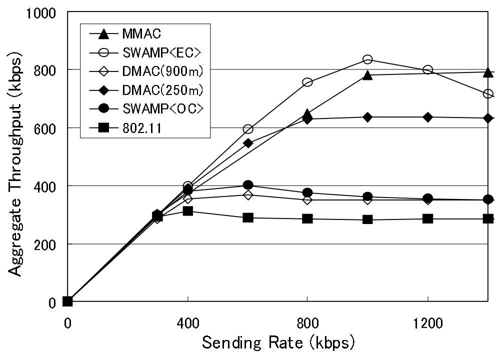

Fig. 4. Non-Straight model throughput.

every transmission. However, to control this gain, we need reliable position information about the destination terminal.

In this performance evaluation, we assume the position information was known. Therefore, this assumption is advantageous to DMAC and MMAC. For directional control of the beam, the position information about the destination terminal is essential. To solve the problem of acquiring position information, SWAMP uses an omni-directional beam in OC-mode. In EC-mode, the sender communicates with the long distance terminal using the position information acquired in OC-mode, and the high gain assumed for RTS. DMAC and MMAC are based on the position information given beforehand. Therefore, DMAC and MMAC cannot function without the additional mechanism for acquiring position information. To acquire position information in the upper layer, DMAC and MMAC cannot avoid increasing the overhead.

Thus, directional MAC protocols improve the throughput performance by reducing the number of hops and limiting the transmission range. Too high a gain beam degrades throughput performance. Moreover, throughput performance depends on the route when directional MAC protocols are used. The throughput performance is improved by avoiding the straight nature in self-routes and abolishing parallelism with neighboring links.

IV. Directional Hidden Terminal Problem

Figure 2 shows that the throughput performance in SWAMP (EC-mode) is lower than for the 250-m MMAC and DMAC in straight model. The reason for the degraded performance is the kind of hidden terminal problem that occurs when the directional beam of the higher gain is used by straighter flows. This problem is called the directional hidden terminal problem. We will now explain how directional hidden terminal problems occur. After that, we propose three NAV indicators to solve the directional hidden terminal problem. Additionally, we evaluate the throughput performance of the proposed NAV indicators.

A. Directional Hidden Terminal Problem

A directional hidden terminal problem occurs when the directional beam of a higher gain is used. Figure 5 shows the mechanism by which directional hidden terminal problems occur. Note that the transceiver and receiver can communicate with each other if the transceiver's beam form overlaps that of the receiver.

We define N as a set of nodes in the network area ($N = \{n_1, n_2, \ldots, n_K\}$). A set of directional hidden terminals is defined as $H(n_t, n_r)$, where $n_t \in N$ is a transmitter, and $n_r \in N$ is a receiver. The omni-directional transmission and reception areas of $n_i \in N$ with a range r^o are defined as $T^o_{n_i}$ and $R^o_{n_i}$, respectively. Also, the directional transmission and reception areas 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 overlap, n_j will receive a message transmitted by n_i, which is defined as $\{T_{n_i} \cap R_{n_j} \neq \emptyset\}$. In the directional case, the transmitting beam of n_i should be pointed 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 the transmitting node, n_r is the receiving node, and n_x is n_r's directional hidden terminal.

The directional hidden terminal problem not only suspends communication, but also prevents any on-going communication, and is therefore more serious than the exposure and deafness problems [5].

V. Directional NAV Indicators

The NAV indicators are schemes that inform directional hidden terminals about on-going communication. Then the directional hidden terminal sets NAV. We propose three kinds of NAV indicators HCTS, BRTS, and RCTS to solve the directional hidden terminal problem.

A. High gain CTS (HCTS)

We propose a scheme in which the destination terminal transmits CTS with higher gain to make the directional hidden terminal set NAV. A situation in which the HCTS blocks the directional hidden terminal is shown in Fig. 6. In this case,

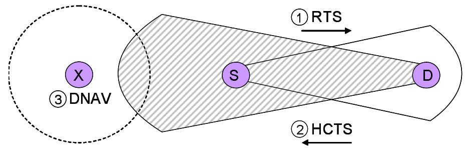

Fig. 6. High gain CTS (HCTS).

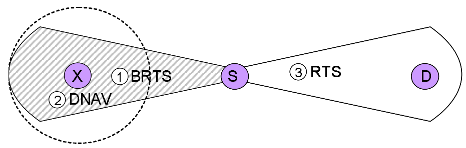

Fig. 7. Backward RTS (BRTS).

CTS needs to cover all areas in which directional hidden terminals might exist. Therefore, the antenna gain must be enlarged. However, HCTS does not need to introduce a new flame.

B. Backward RTS (BRTS)

A situation in which BRTS blocks the directional hidden terminal is shown in Fig. 7. Before terminal S can transmit RTS to its destination, it must be turned in the direction of the transmitting antenna 180-degrees back towards the destination. The directional hidden terminal X sets NAV using BRTS. Regarding the extension of RTS, a circular RTS[8] uses the rotation transmission to avoid the directional hidden terminal. We developed a scheme in which NAV sets the terminals in the direction of the surrounding transmitting terminals. However, to repeatedly transmit RTS, we must change the direction of the antenna, which raises the overhead. When the sender does not receive CTS from the destination terminal, the terminal that receives the BRTS sets the NAV and postpones its own communication. Consequently, BRTS has the potential to deteriorate during spatial reuse.

C. Relayed CTS (RCTS)

Both BRTS and circular RTS[8] have the following problem. When the transmitting terminal cannot receive CTS from its communication partner, the terminal that received BRTS sets the NAV. Then the circumference terminals postpone their communications. We introduced RCTS to solve the problem in BRTS. The arrangement in RCTS prevents the directional hidden terminal, as shown in Fig. 8, in which terminal S transmits RTS to the terminal D using a directional beam. Then after receiving CTS from D, S transmits RCTS 180-degrees back. After that, DATA/ACK can be transmitted and received. RCTS was introduced to notify the rear terminal about communication. The receiving terminal sets the NAV. After the sender receives CTS from their communication partner, they transmit RCTS. The timing is slightly delayed. 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.

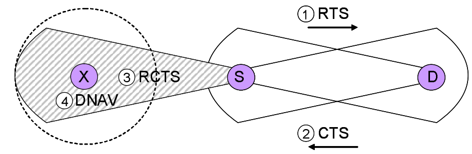

Fig. 8. Relayed CTS (RCTS).

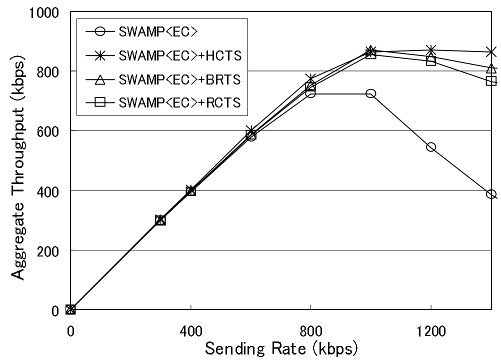

Fig. 9. Throughput performance in straight model.

D. Performance Evaluation

Under the same conditions described in Section 3, we evaluate the proposed HCTS, BRTS, and RCTS. Although the proposed schemes could be applied to every directional MAC protocol, we evaluate the three schemes extended SWAMP (EC-mode) in order. The evaluation results for the straight model are shown in Fig. 9, and the evaluation results for the non-straight model are shown in Fig. 10.

Figure 9 shows that all three proposed schemes improve the performance in the straight model. The SWAMP (EC-mode) throughput with HCTS in particular, is able to achieve the highest performance of all protocols, because the HCTS scheme avoids almost all the directional hidden terminals.

Figure 10 shows that all three proposed schemes deteriorate performances. In the non-straight model, although there is a directional hidden terminal behind the sender, BRTS and RCTS can not cover all the directional hidden terminals.

Moreover, when the proposed schemes are used in situations where the directional hidden terminal problem does not exist, they cause unnecessary interference with the surrounding terminals. However HCTS is able to achieve the highest performance of all three proposed schemes.

BRTS and RCTS deteriorate the performance compared with HCTS, because BRTS and RCTS can not solve the directional hidden terminal problem completely.

In Figures 9 and 10, we find that HCTS solves the directional hidden terminal problem for both straight and non-straight models. This is because of the position of the hidden terminal. Figure 11 shows a hidden terminal area where the destination node can receive transmissions from the directional hidden terminals. In this figure, we assume the beamwidth of

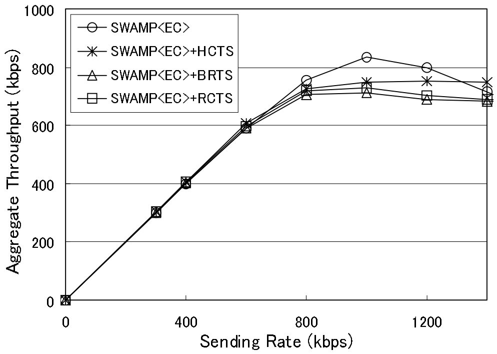

Fig. 10. Throughput performance in non-straight model.

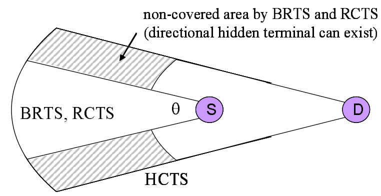

Fig. 11. Non-cover Area by BRTS, RCTS.

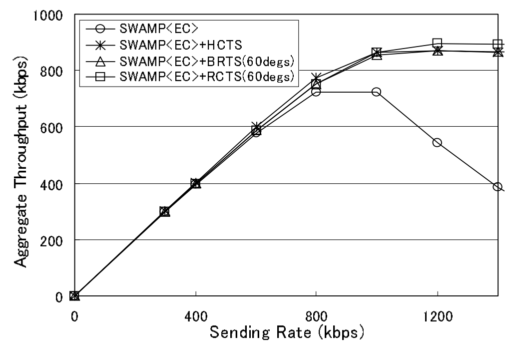

Fig. 12. Throughput performance in straight model (60-degrees).

BRTS and RCTS is θ. It is highly feasible to use HCTS to avoid directional hidden terminals. HCTS uses a beam at the same angle as the original CTS with high gain. Accordingly, HCTS can prevent all directional hidden terminal problems. On the other hand, BRTS and RCTS cannot cover all of the areas in which the directional hidden terminal can exist, as shown in Fig. 11. In the previous simulations, we assume all of the directional beamwidth 45-degrees. Then, we widen the directional beamwidth θ from 45-degrees to 60-degrees. In Figures 9 and 12, we find that in case θ is 60-degrees, BRTS and RCTS achieve high performance even in high-load situations, as well as HCTS. This is because that BRTS and RCTS solve the directional hidden terminal problem for the straight model. Thus, it is considered that widen the directional beam of BRTS and RCTS is effective for performance improvement. However, if we set excessive wide beamwidth, performance of BRTS and RCTS degrades. This is because that exposed terminal problem occurs. Therefore, it is consider that throughput performance depends on the route topology between the sources and the destinations.

As mentioned earlier, whether HCTS can improve performance depends on the shape of the flow. In a straight flow, it is considered that HCTS is effective. BRTS and RCTS using the wider beam also show high performance. However, in a non-straight flow, in other words, in which there is less possibility for directional hidden terminal problems, the proposed schemes degrade performance. Nodes behind the receiver can possibly destroy the receiver's ACK. The directional hidden terminal problem does not only exist behind the sender, but also behind the receiver. Therefore, we need to further examine the directional hidden terminal problem under various situations.

VI. Conclusions

We described a comparative evaluation of three directional MAC protocols, DMAC, MMAC, and SWAMP, as well as the IEEE 802.11 DCF omni-directional protocol in multi-hop transmission environments. The evaluations addressed the problem in which performance strongly depends on the route topology between the sources and the destinations, referred to as the directional hidden terminal problem.

After analyzing the problem, we proposed three MAC level solutions. They are NAV indicators, which are HCTS, BRTS, and RCTS to indicate on-going communications to a directional hidden terminal to set NAV. In the simulation results, we showed that all the proposed MAC solutions could improve the throughput performance. In the future, we plan to evaluate various MAC solutions. Moreover, we will consider situations in which routes exist on actual networks.

References

[1] Z. Huang, C. Shen: A Comparison Study of Omnidirectional and Directional MAC Protocols for Ad hoc Networks, Globecom (2002)

[2] J. Li, C. Blake, D. S. J. D. Couto, H. I. Lee, R. Morris: Capacity of Ad Hoc Wireless Networks, Proc. ACM/IEEE Mobile Computing and Networks (MobiCom) (2001).

[3] P. H. Lehne and M. Pettersen: An Overview of Smart Antenna Technology for Mobile Communications Systems, IEEE Communications Surveys and Tutorials, Vol.2, No.4, Fourth Quarter (1999).

[4] M. Takata, K. Nagashima, T. Watanabe: A Dual Access Mode MAC Protocol for Ad Hoc Networks Using Smart Antennas, IEEE International Conference on Communications (ICC), pp4182-4186 (2004).

[5] R. R. Choudhury, X. Yang, R. Ramanathan and N. H. Vaidya: Using Directional Antennas for Medium Access Control in Ad Hoc Networks, Proc. ACM Mobile Computing and Networking (MobiCom), pp.59-70 (2002).

[6] ANSI/IEEE Std 802.11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications (1999).

[7] M. Sekido, M. Takata, M. Bandai, T. Watanabe: Directional NAV Indicators for Smart Antenna Based Ad Hoc Networks, Second International Conference on Mobile Computing and Ubiquitous Networking (ICMU) (2005).

[8] T. Korakis, G. Jakllari and L. Tassiulas: A MAC protocol for full exploitation of Directional Antennas in Ad-hoc Wireless Networks, Proc. ACM Mobile Ad Hoc Networking and Computing (MobiHoc), pp.98-107 (2003).