An Extended Directional MAC for Location Information Staleness in Ad Hoc Networks

Masanori Takata
Graduate School of Science and Engineering
Shizuoka University, Japan
takata@aurum.cs.inf.shizuoka.ac.jp

Masaki Bandai   Takashi Watanabe
Faculty of Informatics
Shizuoka University, Japan
{bandai, watanabe}@cs.inf.shizuoka.ac.jp

Abstract

Recently, several directional MAC protocols using smart antennas or directional antennas have been proposed for wireless ad hoc networks including our proposed MAC protocol called SWAMP (Smart antennas based Wider-range Access MAC Protocol). This paper first outlines issues of directional MAC protocols and investigates different factors which reduce the probability of successful transmissions, such as location information staleness, deafness and hidden- and exposed-terminal problems arisen due to directional transmissions. In addition, this paper proposes solutions of location information staleness and exposed-terminal problems. The experimental results show that the optimization of parameters associated with location information staleness, such as the beamwidth, retry limit and lifetime of the table information improves the reliability of the transmission and the overall network performance.

Keywords-Ad Hoc Networks; Smart Antennas; Directional Antennas; Medium Access Control; IEEE 802.11 DCF; Location Information

1. Introduction

The previous works on wireless ad hoc networks assume the use of omni-directional antennas that radiate or detect signal strength equally well in all directions. Traditional MAC protocols such as IEEE 802.11 [1] cannot achieve high throughput in wireless ad hoc networks because that waste a large portion of the network capacity by reserving the wireless media over a large area as discussed in [2]. To deal with this problem, smart antenna technology may have various potentials [3]. In particular, it can improve spatial reuse of the wireless channel, which allows nodes to communicate simultaneously without interference. Furthermore, the directional transmission concentrates signal power to the receiver, which enlarges the transmission range. Thus, it can potentially establish links between nodes far away from each other, and it prevents network partitions and the number of routing hops can be fewer than that of omni-directional antennas.

However these potentials smart antennas may have, a sophisticated MAC is required to take 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.

This paper first outlines some common issues of directional MAC protocols and investigates different factors which reduce the probability of successful transmissions on directional MAC protocols, such as location information staleness, deafness and hidden- and exposed-terminal problems arisen due to directional transmissions, and confirms its negative impact on network performance through computer simulations. In addition, this paper proposes solutions of these issues, especially for location information staleness and exposed-terminal problems. The experimental results show that the optimization of parameters associated with location information staleness, such as the beamwidth, retry limit and lifetime of the table information, mitigates location information staleness and improves the overall network performance.

2. Related work

IEEE 802.11 DCF (Distributed Coordination Function) [1] 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), however, it wastes a large portion of the network capacity by reserving the wireless media over a large area.

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.

Ko et al. [4] propose a MAC protocol called DMAC (Directional MAC) in which all frames are transmitted directionally except for the CTS. Choudhury et al. [5] propose a derived MAC from DMAC, called MMAC (Multi-hop RTS MAC), which involves the multi-hop RTS to take advantage of the higher gain obtained by directional antennas. They, however, assume that each node knows the location of other nodes a priori. Therefore, these protocols need various additional mechanisms to provide the location information and to forward the RTS.

In [6] [7] [8] and [9], RTS is transmitted omni-directionally in order to find the receiver in case location information is not available. Each node estimates the direction of neighboring nodes for pointing the beam with AOA (Angle of Arrival) when it hears any signal. Because these protocols employ at least one omni-directional control frame transmission, it limits the coverage area provided by directional transmissions and do not exploit one of the main benefits of directional antennas, i.e., the increase of the transmission range, either.

Ramanathan [10] proposes circular directional transmission of periodic hello packets to obtain node information that is located farther away than the omni-directional transmission range, and the neighbor nodes could determine the direction of the sender by tracking the received AOA. Korakis et al. [11] propose circular RTS, which scans all the area around the transmitter to find the addressed receiver and to tackle the hidden-terminal problem and the deafness problem arisen from directional transmissions. Bandyopadhyay et al. [12] develops additional frames in order to determine the neighbor topology by recording the angle and signal strength. Although these schemes attempt communication range extension, circular transmission increases the delay and incurs large control overhead.

3. SWAMP

In this section, we illustrate our proposed MAC protocol called SWAMP (Smart antennas based Wider-range Access MAC Protocol) [13]. SWAMP is a MAC protocol for ad hoc networks using smart antennas based on IEEE 802.11 DCF, which enables the both high spatial reuse of the wireless channel and communication range extension in order to improve the throughput performance by providing two access modes. It also incorporates the mechanism to acquire the neighbors' location information farther away than the omni-directional transmission range with less overhead.

3.1. Antenna models

SWAMP provides four antenna beam forms. Fig. 1 illustrates four beam forms and each transmission range. Note that in the figure nodes can communicate when the transmitting beam and the receiving beam are at least tangential to each other. OB (omni-directional beam form) and DL (directional low gain beam form) are for the regular link communication, while DM (directional middle gain beam form) and DH (directional high gain beam form) for the extended link communication.

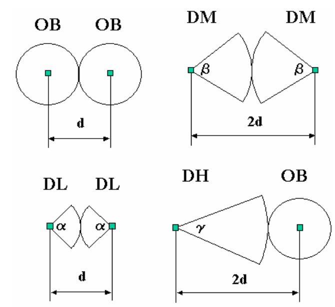

Figure 1. Smart antenna beamforming.
Left side: Transmitting beamforming
Right side: Receiving beam forming

3.2. OC-mode

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

OC-mode is selected when the receiver node is located within the area of omni-directional transmission range (d in Fig. 1) or when the transmitter has no knowledge about the receiver node. Fig. 2 illustrates the OC-mode frame sequence with the corresponding beams. The RTS/CTS handshaking tries to reserve the wireless channel and to exchange the location information between the transmitter and the receiver. Then, these nodes forward the location information that is obtained by the reception of the RTS or CTS to neighbors using an omni-directional beam. As a result, neighbors can obtain the location information of nodes located within an area at most two times farther away than that of the omni-directional beam. We refer to this information that neighbors obtain as NHDI (Next Hop Direction Information). In Fig 2, node B transmits SOF (Start of

Frame) after receiving CTS. SOF contains the NHDI of node C. Also, node C includes the NHDI of node B in CTS. Nodes A and D can recognize C and B respectively by receiving the NHDI. NHDI is registered to the NHDI table of each node and this information is used in EC-mode. DATA and ACK are sent by DLs that point beams towards each other. Omni-NAV shorter than ordinal NAV is used to increase simultaneous communications and the spatial reuse of the wireless channel.

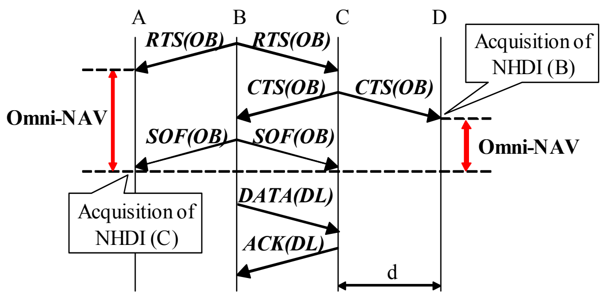

Figure 2. OC-mode frame sequence (B to C).

3.3. EC-mode

EC-mode is selected when the receiver node has been already registered in the transmitter's NHDI table. Fig. 3 illustrates the EC-mode frame sequence with the corresponding beam. Because the transmitter has the prior knowledge of the direction of the intended receiver, the transmitter can determine the direction to point the beam towards the receiver. To perform communications between nodes at a distance of 2d, RTS is required to use the high gain beam form (DH) because the receiver node waits for signals with the omni-directional beam form (OB) in an idle state. After it sends RTS, the transmitter switches the beam form from DH to DM. After the receiver receives RTS, it also switches the beam form from OB to DM and points the beam towards the transmitter. When the transmitter fails EC-mode access over the EC-retry limit, the transmitter deletes the receiver information from its own NHDI table. In EC-mode, DNAV (Directional NAV) [8] is used instead of NAV for virtual carrier sensing. DNAVs are set up towards the specific directions where on-going communication nodes exist. This allows nodes to initiate an EC-mode transmission if DNAVs are not set in the desired direction and it improves performance by allowing simultaneous transmissions.

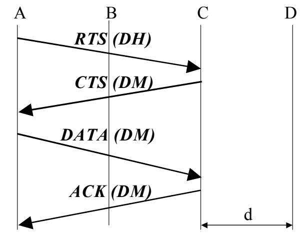

Figure 3. EC-mode frame sequence (A to C).

4. Issues of directional MAC protocols

This section discusses some common issues of directional MAC protocols such as location information staleness, deafness and directional hidden- and exposed-terminal problems. Among these issues, location information staleness and exposed-terminal problems are critical. We propose the optimization of the beamwidth and the lifetime of the table information to deal with location information staleness, and propose the mechanism of interference suppression to mitigate the exposed-terminal problem.

4.1. Location information staleness

The transmitter must know and maintain the location of the intended receiver to point the beam in the appropriate direction while network topology changes dynamically. Especially, when the transmitter uses the directional transmission based on the table information recorded in advance to point the beam towards the specific node, a gap between the table information and the actual location is arisen due to the lapse of time and the mobility of nodes. This gap deteriorates the reliability of the transmission because the direction of transmission becomes inaccurate. We refer to this phenomenon as location information staleness.

In [7] and [8], AOA tables are used at each node from which it maintains records of the AOA for each node in which it successfully receives. If the transmitter fails to get the CTS response back from the receiver after 4 consecutive directional transmissions of the RTS frame, it is assumed that the corresponding AOA information is out-of-date and subsequent RTS frames are sent omni-directionally to deal with location information staleness. These schemes, however, are only available for communications within the omni-directional transmission range.

In [11], multiple directional RTS frames are transmitted consecutively in a circular way for each transmitted data frame to handle location information staleness but it has high control overhead. In [14], if the transmitter does not receive a reply from the receiver, the transmitter sends hello packets using adjacent beams to update the location information of the receiver. It also incurs large control overhead.

To handle the issue of location information staleness without large control overhead and to improve the reliability of the table based directional transmission, we investigate the optimization of parameters related to location information staleness, such as the beamwidth, retry-limit and lifetime of the table information (Time to Live) in section 5.

4.2. Deafness and hidden-terminal problem

Directional transmission of RTS/CTS, which is usually used in directional MAC protocols, introduces new kind of problems. One problem is *deafness* [5]. Deafness is caused when a transmitter repeatedly attempts to communicate with a receiver, but it fails to communicate because the receiver has its beam pointed towards a direction away from the transmitter and cannot hear the signal from the transmitter. This problem leads to the wastage of the wireless channel, excessive packet drops, and channel access unfairness.

The other problem is *hidden-terminal due to asymmetry in gain* [5], referred to as the directional hidden-terminal problem in this paper. Assume that node T is communicating with node R. Directional hidden-terminal problem is caused by the neighboring node of the on-going communication, say X, which is far enough from node R not to hear the CTS pointed towards node T (and also node X). If X transmits the RTS directionally towards the direction of node R, it may interfere with the on-going communication because node R is receiving DATA with a beam pointed towards nodes T and X.

Although [5] studies deafness and the directional hidden-terminal problem, they do not solve these problems. Mitigating deafness and the hidden-terminal problem is our future work.

4.3. Exposed-terminal problem

In most of directional MAC protocols, each node waits for signals with the omni-directional mode in an idle state. Therefore, in Fig. 4, node B becomes an exposed-terminal during the data transmission between A and C. If node D sends RTS to B, it will result in collision at node B. We refer to this type of exposed-terminal problem as the directional exposed-terminal problem.

We propose the mechanism to reduce such RTS collisions due to the directional exposed-terminal using

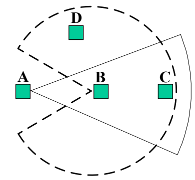

Figure 4. Interference suppression.
Solid line: Transmitting beamforming of node A
Dotted line: Receiving beamforming of node B

interference suppression. Because data from node A is meaningless for node B, it needs not receive the signal from node A. In our mechanism, node B is beamformed in the direction away from the A's direction for duration of the on-going communication between A and C after the receipt of the RTS from node A. Therefore, if node D sends RTS to B, node B can reply and communicate simultaneously. This mechanism may mitigate the directional exposed-terminal problem and improve the number of simultaneous communications.

5. Performance evaluation

In this section, we investigate different factors which reduce the probability of successful transmissions, such as location information staleness, deafness and hidden- and exposed-terminal problems arisen due to directional transmissions, and confirm its negative impact on network performance through computer simulations. In addition, we investigate the effects of the different values of parameters related to location information staleness, such as the beamwidth, retry-limit and lifetime of the table information, to handle the issue of location information staleness.

We make the following assumptions. A hundred nodes are arranged at random in a square area with dimensions of 1500 m and move independently according to the random way point mobility model with a maximum speed of 40 km/h and a pause time of zero. Packets arrive at every node according to Poisson distribution with mean value of λ (packet/s). Destination node for each packet is chosen at random from two hop neighbors. A packet size is 512 bytes and an omni-directional transmission range (d in Fig. 1) is 250 m. The beamwidth of DL, DM and DH are 45 degrees. The data rate is 2 Mbps. Among directional MAC protocols, SWAMP is used to investigate the effects of issues mentioned in section 4.

5.1. Performance of protocols

The throughput versus the offered load is shown in Fig. 5. The throughput of SWAMP (OC), which is the case using only OC-mode for all communication, is roughly 2 times against IEEE 802.11 DCF. This is because OC-mode improves the spatial reuse of the wireless channel due to omni-NAV, and consequently more node pairs can communicate simultaneously. As shown in Fig. 5, SWAMP (OC+EC) outperforms others because packets are delivered to the destination in fewer hops in EC-mode, and the consumption of the wireless channel and store-and-forward overhead are reduced.

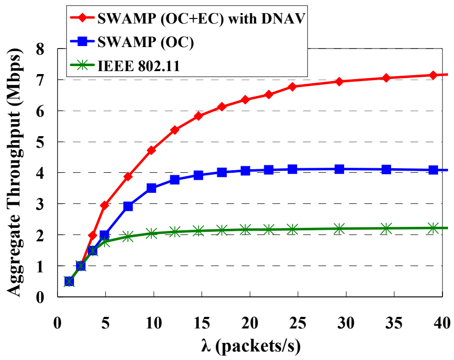

Figure 5. End-to-End throughput.

5.2. Analysis of communication failures

Fig. 6 shows the RTS failure ratio. RTS failure ratio is calculated as follows:

*RTS failure ratio = (number of not received CTS / number of transmitted RTS) * 100*

Fig. 7 shows the communication failure factors of SWAMP (OC+EC). Each failure factor in Fig 7 is represented below.

- *Out of range*: The addressed receiver node moves out of range of the transmitter's communication range (it almost 0 % in Fig. 7).
- *CTS collision*: The receiver node sends CTS, however the transmitter cannot receive it because of collision (it almost 0 % in Fig. 7).
- *Location information staleness*: The gap between the NHDI and actual location of the addressed node becomes larger than the beamwidth.
- *NAV blocking*: The receiver node receives RTS correctly, but cannot send CTS because of NAV.
- *RTS collision*: RTS is not received correctly by the receiver since other nodes are transmitting (i.e. the receiver node is an exposed-terminal, or two or more nodes transmit control frames concurrently).
- *Deafness*: The receiver node cannot receive RTS because the receiver is beamformed towards the direction away from the transmitter.
- *Directional hidden-terminal problem*: Hidden-terminal due to asymmetry in gain or hidden-terminal due to unheard RTS/CTS [5].

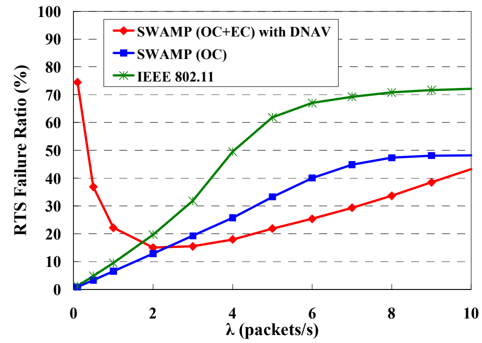

Figure 6. RTS failure ratio.

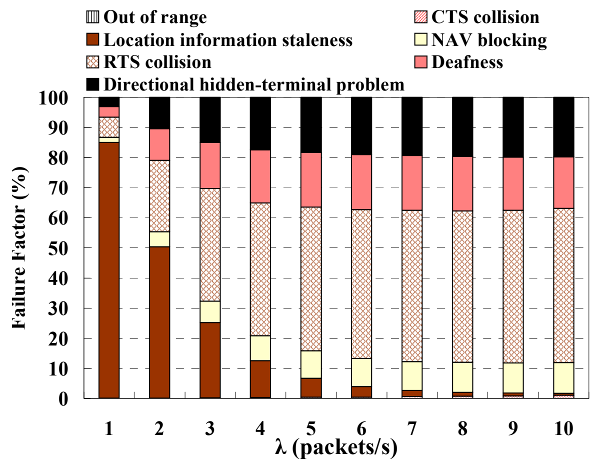

Figure 7. Communication failure factors.

As shown in Figs. 6 and 7, SWAMP increases the communication failure due to location information staleness especially when offered load is low. This is because the gap between the NHDI and actual location of the neighbor node is large when the frequency of update of the NHDI is low, and nodes try to communicate frequently and attempts multiple retransmissions under such situations. Therefore, handling issue of location information staleness is critical in directional MAC protocols.

Another main factor of communication failure is RTS collision. Since RTS collisions mainly occur due to congestion, it may not be possible to completely get rid of RTS collisions. However, our proposed interference suppression mechanism can mitigate the directional exposed-terminal problem. Evaluating the effects of interference suppression mechanism is our future work.

Deafness and directional hidden-terminal problems are also reduce the probability of successful transmissions, which may not arise in the case of omni-directional transmissions. Therefore, there is a tradeoff between spatial reuse of the wireless channel using directional transmissions and collision avoidance using omni-directional transmissions.

There are communication failure factors of SWAMP, but that may arise with other directional MAC protocols as well.

5.3. Optimization of parameters

In OC-mode, the transmitter gets the location information of the addressed receiver node on demand to point the beam in the appropriate direction. In EC-mode, on the other hand, the transmitter refers to the NHDI table information recorded by overhearing the previous OC-mode communication between neighboring nodes. Therefore, a gap between the table information and actual location is arisen due to the lapse of time and the mobility of nodes. To handle the issue of location information staleness and to improve the reliability of the table based directional transmission, dynamic adaptation of parameters related to location information staleness, such as the beamwidth, retry-limit and lifetime of the table information (Time to Live), can be available.

We confirm the effects of the different values of these parameters on the performance of our proposed MAC protocol.

Fig. 8 shows the effects of the beamwidth. SWAMP uses three kinds of directional beam (i.e., DL, DM and DH). We set up five different sets of angle while the transmission range of each beam is kept according to Fig. 1. When λ is low, the cases using wider angle-set have better performance. This is because that the frequency of update of the NHDI table entry is low and the gap between the NHDI and actual location of the neighbor nodes is large. Under these situations, the wider beamwidth is suitable for struggling with the node mobility. When λ is high, to the contrary, narrower angle-sets have better performance. SWAMP uses the data flow not the periodic control frame to inform the location information. If the network traffic is high, each node can acquire the NHDI frequently by overhearing the communication between neighboring nodes and the NHDI is maintained fresh and accurate. Therefore, the narrower beam can reduce the interference and contention among nodes and improve the spatial reuse when the NHDI is sufficiently accurate and reliable. It implies that the optimization of the beamwidth based on the network traffic or the freshness of the table information improves the reliability of the transmission and the efficiency of spatial reuse. We have confirmed that the adaptation of the beamwidth requires not only the surrounding traffic information but also the mobility of nodes.

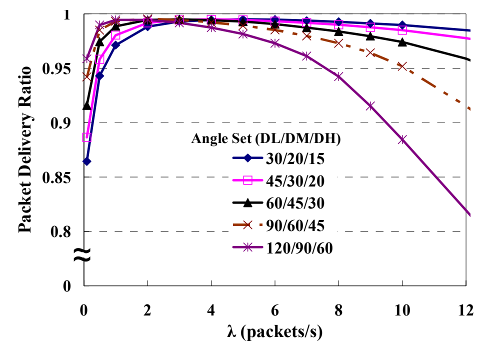

Figure 8. Effects of the beamwidth (degrees).

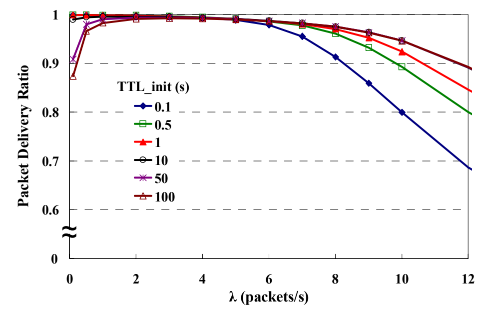

Figure 9. Effects of the TTL.

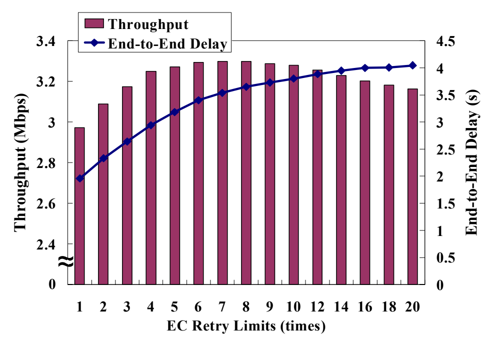

Figure 10. Effects of the retry limits.

Fig. 9 shows the effects of the lifetime of NHDI table information. Each node maintains an NHDI table with one record for every node that receives NHDI in SWAMP. In the NHDI table, the TTL (Time to Live) represents the lifetime of the entry and it is related to the reliability of the transmission. TTL is decreased during the progress of time. If the TTL expires, the corresponding record is deleted. When the NHDI is obtained that is already registered, it is updated and the TTL is initialized (TTL_init).

As shown in Fig. 9, the cases using the large TTL_init are unsuitable compared with the cases using small one when λ is small because the transmission based on the obsolete table information deteriorates the reliability. As λ becomes larger, however, the cases using the small TTL_init grow rapidly worse. This is because that the NHDI entry is deleted frequently although it is sufficiently accurate and reliable. In this case, each node cannot gain the benefits of EC-mode. Therefore, the reliability of the transmission and the overall network performance have the relation of a trade-off. To adapt the TTL_init dynamically, we must consider the network load, mobility of node, and QoS (Quality of Service) requirement.

Fig. 10 shows the throughput and End-to-End delay with the different values of the maximum EC-retry limit. As shown in Fig. 10, although an increase in the allowable number of retransmissions can increase the probability of a successful transmission and improve the throughput, excess retransmissions lead to degradation of the throughput and delay performance. This is because that excess retransmissions influence the neighbor nodes and waste the wireless channel, and the backoff time (the contention window size) is also increased.

6. Conclusion

This paper has discussed the issues of directional MAC protocols, such as location information staleness, deafness and hidden- and exposed-terminal problems arisen due to directional transmissions. We have investigated different factors which reduce the probability of successful transmissions, and confirmed its negative impact on network performance through computer simulations. Results show that RTS collision and location information staleness are critical issues among these communication failure factors. We have also proposed the mechanism of interference suppression using directional beamforming in an idle state in order to mitigate the directional exposed-terminal problem, and have investigated the optimization of parameters associated with location information staleness, such as the beamwidth, retry limit and lifetime of the table information.

The experimental results show that the different values of the beamwidth, retry limit and lifetime of the table information have an impact on the performance of protocol and these parameters should be optimized based on the network traffic, the freshness of the table information, the mobility of nodes and the QoS requirement to improve the reliability of the transmission and the overall network performance.

References

[1] ANSI/IEEE Std 802.11, “Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications”, 1999.

[2] S. Xu and T. Saadawi, “Does the IEEE 802.11 MAC Protocol Work Well in Multihop Wireless Ad Hoc Networks?”, IEEE Commun. Mag., vol.39, no.6, pp.130-137, June 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] Y. –B. Ko, V. Shankarkumar and N. H. Vaidya, “Medium Access Control Protocols Using Directional Antennas in Ad Hoc Networks”, Proc. IEEE INFOCOM, pp.13-21, March 2000.

[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 Network (MobiCom), pp.59-70, Sep. 2002.

[6] N. S. Fahmy, T. D. Todd and V. Kezys, “Ad Hoc Networks with Smart Antennas using IEEE 802.11-Based Protocols”, Proc. IEEE International Conference on Communications (ICC), pp.3144-3148, April 2002.

[7] A. Nasipuri, K. Li and U. R. Sappidi, “Power Consumption and Throughput in Mobile Ad Hoc Networks using Directional Antennas”, Proc. IEEE International Conference on Computer Communications and Networking (ICCCN), pp.620-626, Oct. 2002.

[8] M. Takai, J. Martin, A. Ren and R. Bagrodia, “Directional Virtual Carrier Sensing for Directional Antennas in Mobile Ad Hoc Networks”, Proc. ACM Mobile Ad Hoc Networking and Computing (MOBIHOC), pp.183-193, June 2002.

[9] M. Takai, J. Zhou and R. Bagrodia, “Adaptive Range Control Using Directional Antennas in Mobile Ad Hoc Networks”, Proc. ACM International Workshop on Modeling and Simulation of Wireless and Mobile (MSWiM), pp.92-99, Sep. 2003.

[10] R. Ramanathan, “On the Performance of Ad Hoc Networks with Beamforming Antennas”, Proc. ACM Mobile Ad Hoc Networking and Computing (MOBIHOC), pp.95-105, Oct. 2001.

[11] 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, June 2003.

[12] S. Bandyopadhyay, K. Hasuike, S. Horisawa and S. Tawara, “An Adaptive MAC Protocol for Wireless Ad Hoc Community Network (WACNet) Using Electronically Steerable Passive Array Radiator Antenna”, Proc. IEEE Global Communications Conference (GLOBECOM), pp.2896-2900, Nov. 2001.

[13] M. Takata, K. Nagashima and T. Watanabe, “A Dual Access Mode MAC Protocol for Ad Hoc Networks Using Smart Antennas”, Proc. IEEE International Conference on Communications (ICC), pp.4182-4186, June 2004.

[14] R. R. Choudhury and N. H. Vaidya, “Impact of Directional Antennas on Ad Hoc Routing”, Proc. International Conference on Personal Wireless Communications (PWC), pp.590-600, Sep. 2003.