A Receiver-Initiated Directional MAC Protocol for Handling Deafness in Ad Hoc Networks

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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. Although directional transmissions are expected to provide significant improvements, directional MAC protocols introduce new kinds of problems. One such problem is deafness. Deafness is caused when a transmitter repeatedly attempts to communicate with its intended receiver, but it fails because the receiver has its beam pointed towards a direction away from the transmitter. This paper proposes RI-DMAC (Receiver-Initiated Directional MAC) to address the issue of deafness in directional MAC protocols. RI-DMAC is a combination of sender- initiated and receiver-initiated operations. The sender-initiated mode is the default mode and the receiver-initiated mode is triggered when the transmitter experiences deafness. In RI-DMAC, each node maintains a polling table and polls a potential deafness node using the RTR (Ready To Receive) frame after the completion of every dialog. The experimental results show that RI-DMAC improves throughput and fairness performance compared to existing directional MAC protocols.**

I. Introduction

Wireless ad hoc networks [1] are the autonomous system of mobile nodes which share a single wireless channel to communicate with one another. The previous works on wireless ad hoc networks assume the use of omni-directional antennas that radiate or receive power equally well in all directions. Traditional MAC protocols using omni-directional antennas such as IEEE 802.11 DCF (Distributed Coordination Function) [2] cannot achieve high throughput in ad hoc networks because that waste a large portion of the network capacity as discussed in [3]. Directional antennas have great potentials to deal with this problem, such as high spatial reuse and range extension, and several MAC protocols using directional antennas for ad hoc networks have been proposed recently.

Directional MAC protocols, however, introduce new kinds of problems related to directional transmissions as identified in [4]. One such problem is deafness. Fig. 1 illustrates deafness situations. We consider DMAC (Directional MAC) [4] in which all frames are transmitted and received directionally, and physical and virtual carrier sense functions are performed directionally. In Fig. 1, node A is unaware of the communication between node B and node C because A does not overhear the directional signals between B and C. While B is communicating with C, A attempts to communicate with B, but it fails because B has its beam pointed towards C, and B is deaf with respect to A. In this paper, the transmitter, which suffers from deafness, is referred to as deafness node. Then, deafness node A backs off and repeatedly attempts to communicate. Even though B completes packet delivery to C, B keeps its beam towards C during backoff periods to deliver the next packet, and remains deaf to A. It may result in a packet drop at A after unproductive retransmissions. Another problem of deafness is the wastage of the wireless channel. After the communication between node and D, C is ready to receive the next packet from B. Node B, however, cannot initiate a transmission immediately because it has a longer backoff time due to the fact that the contention window is doubled for each retransmission, in a fashion similar to IEEE 802.11, and the wireless channel remains idle during this period. As mentioned above, deafness problem leads to excessive packet drops, longer delay, wastage of the wireless channel and channel access unfairness.

This paper proposes RI-DMAC (Receiver-Initiated Directional MAC) to address the issue of deafness in directional MAC protocols for wireless ad hoc networks. RI-DMAC handles deafness problem reactively using a polling scheme. RI-DMAC is a combination of sender-initiated and receiver-initiated operations. The sender-initiated mode is used as the default mode and the receiver-initiated mode is triggered when the transmitter may suffer from deafness. In RI-DMAC, each node maintains a polling table and polls a potential deafness node (potential transmitter) using the RTR (Ready To Receive) frame after the completion of every dialog. The potential deafness node can recognize that the intended receiver becomes idle, and deliver a packet immediately after receiving RTR. Among potential deafness nodes in the polling table, the least recently transmitted node is selected as a polled node to improve fairness. Simulation results show that RI-DMAC performs better than existing directional MAC protocols in terms of throughput and fairness.

II. Related Work

IEEE 802.11 DCF [2] is a contention-based 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

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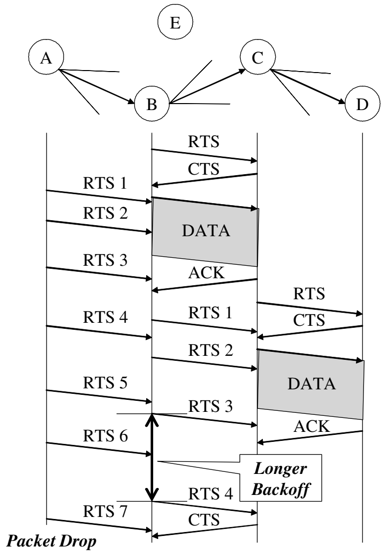

Fig. 1. Deafness Situations.

reserving the wireless media over a large area.

Recently, several MAC protocols using directional antennas, typically referred to as directional MAC protocols, have been proposed for wireless ad hoc networks. Ko et al. [5] propose DMAC (Directional MAC) in which all frames are transmitted directionally expect for the CTS. In [4], Choudhury et al. propose MMAC (Multi-hop RTS MAC) which involves multi-hop RTS to take advantage of the higher antenna gain obtained by directional antennas, and the issues of directional MAC protocols including deafness are discussed but no solution is provided.

In [6], [7], the RTS and CTS frames are transmitted omni-directionally for each data frame and directional capabilities are utilized only for Data/ACK frames. In [8], [9], RTS is transmitted omni-directionally in order to find the receiver in case location information is not available. Because these protocols employ at least one omni-directional transmission, it limits the coverage range provided by directional transmissions. Although omni-directional RTS/CTS is one simple solution to avoid deafness by notifying the on-going communication to neighbors, it cannot initiate any transmissions until the whole area around the transmitter and the receiver becomes idle. This may reduce the benefits of spatial reuse, a key advantage of directional antennas.

In [10–12], circular directional transmissions of periodic hello packets are utilized to obtain node information that is located farther away from the omni-directional transmission range. Takata et al. [13] propose SWAMP (Smart antennas based Wider-range Access MAC Protocol), which provides both spatial reuse and range extension by two types of access modes. The issue of deafness remains unsolved in these protocols. Korakis et al. [14] propose circular RTS, which scans all the area around the transmitter to find the addressed receiver and to tackle deafness and hidden-terminal problems arisen from directional transmissions. By informing neighboring nodes of imminent communication, deafness at the transmitting node can be alleviated. However, deafness at the receiving node appears due to the transmission of single directional CTS. Jakllari et al. [15] propose Circular RTS and CTS MAC (CRCM) protocol, in which multiple directional CTS frames are also transmitted consecutively in a circular way to handle deafness at the receiver side. Circular transmission, however, increases the delay and incurs large control overhead. In [16], Gossain et al. propose MDA (MAC protocol for Directional Antennas). In MDA, multiple directional RTS and CTS frames are transmitted simultaneously in diametrically opposite directions only through the antenna beams with neighbors to reduce overheads of circular transmission. In [17], Gossain et al. address the issue of deafness proactively by estimating the state of the intended receiver. These schemes require circular transmissions of RTS/CTS for each transmitted data packet to acquire the on-going transmission information of neighborhoods, which may incur large control overhead.

Choudhury et al. [18] propose ToneDMAC, tone-based mechanism to handle deafness reactively. They first propose the omni-directional physical carrier sensing during backoff periods, called omni-directional backing off. It prevents "persistent deafness", which occurs because the intended receiver remains in directional mode for a continued period of time (such as node A in Fig. 1). They then propose the tone-based feedback mechanism to neighbors of communicating node in order to distinguish deafness from congestion as the reason for communication failure. The protocol needs a dedicated control channel to transmit tones as well as a data channel, and it may be relatively complex.

Wang et al. [19] propose SYN-DMAC to address the issues of directional MAC protocols including deafness for ad hoc networks with clock synchronization. However, this scheme requires that nodes are synchronized to identify the timing structure, which is a challenging task in ad hoc networks.

Solutions of directional MAC problems other than deafness such as location information staleness and directional hidden- and exposed-terminal problems are proposed in [20], [21].

This paper proposes a receiver-initiated approach to handle deafness. Various receiver-initiated MAC protocols using omni-directional antennas are proposed for ad hoc networks. In [22], the RTR (Ready To Receive) frame is transmitted by the receiver node for inviting the transmitter node to transmit its packet. Lal et al. [23] propose the receiver-initiated approach to perform multiple simultaneous receptions using a five-way handshake (i.e., RTR/RTS/CTS/Data/ACK) in multi-beam smart antenna systems. However, most of receiver-initiated MAC protocols need a good traffic estimator at each node to perform well. Unlike these protocols, RI-DMAC eliminates the need for a traffic estimator by using a combination of sender-initiated and receiver-initiated operations.

III. Antenna Model

We assume that each node is equipped with a switched beam antenna system which is comprised of fixed beam patterns. The antenna system possesses two separate modes, i.e., Omni and Directional. In Omni mode, a node receives signals from all directions with gain G^o. An idle node waits for signals in Omni mode. After a signal is sensed in Omni mode, the antenna detects the beam (direction) on which the signal power is strongest and goes into the Directional mode. In Directional mode, a node can point its beam towards a specific direction with gain $G^d(> G^o)$. Most of existing research assumes the same antenna model. In RI-DMAC, the Omni mode is used for receiving signals, while the Directional mode is used for transmission as well as reception.

IV. RI-DMAC

In this Section, we propose RI-DMAC protocol, a novel receiver-initiated mechanism to overcome deafness problem in directional MAC protocols. As described in Section II, existing research exploits either circular transmissions of RTS/CTS, additional control channels, or clock synchronization to handle deafness by notifying the state of the node to neighbors, which may incurs control overhead and complexity. RI-DMAC uses neither one of these approaches. Instead, RI-DMAC uses the RTR frame to poll a potential deafness node after the completion of every dialog. The details of RI-DMAC are presented next.

A. Assumptions

While the idea behind RI-DMAC is not bounded to any directional MAC protocols, for simplicity of discussion, this paper assumes DMAC [4] as the baseline MAC protocol. Because this paper focuses on handling deafness, we assume that each node knows the location of neighboring nodes a priori to point the beam in the appropriate direction as assumed in DMAC. Mechanisms to determine the neighbors' location are proposed in [12–14].

B. Omni-directional Physical Carrier Sensing

DMAC [4] performs physical carrier sensing in the Directional mode during backoff periods. It leads to "persistent deafness" and "deadlock" [18] as illustrated in Fig. 1. Unlike DMAC, each node switches back to the Omni mode during backoff periods in RI-DMAC as similar to ToneDMAC [18]. When the node senses a signal in backoff periods, it performs the beam scan to determine the direction of the arriving signal. If the estimated direction is in a different direction from that of the intended receiver, then the transmitter continues backing off; otherwise the transmitter considers that channel is busy. If the transmitter receives RTS addressed to it during backoff periods, the transmitter freezes the backoff timer and replies with CTS. It can mitigate "persistent deafness" and "deadlock", and also improve spatial reuse of the wireless channel by allowing simultaneous communications. However, the wastage of the channel due to deafness is not solved.

C. Polling Table

Each node maintains a polling table (Table I) to poll a potential deafness node in RI-DMAC. The polling table presents the nodes which have a packet addressed to the node and may experience deafness. To construct the polling table, if there is a packet addressed to the same receiver in the head of its queue (i.e., a next packet), the transmitter appends a size of the next packet to the Data frame header (a 16-bit additional field) for each transmitted packet; otherwise the field is set to zero. When the node receives the Data frame, it checks the frame header and updates its own polling table with its reception time. Because each node can acquire the next packet information of neighbor nodes exactly using the polling table, it does not require a traffic estimator at each node. If the elapsed time of the entry exceeds a certain threshold value, it is removed from the table for handling mobility. The optimal value of the threshold depends on the mobility and the traffic, and it is our future work.

TABLE I
POLLING TABLE

ID	Packet Size	Reception Time
B	L_B	T_B
E	L_E	T_E

D. Polling Scheme

In RI-DMAC, all frames are transmitted and received directionally to exploit range extension. The channel reservation and data communication phases are similar to DMAC. Initially, all nodes operate in sender-initiated mode using a four-way handshake. After exchanging the Data/ACK frames, the transmitter and the receiver check its own polling table whether potential deafness nodes exist or not. If more than two nodes are registered in the polling table, it also checks its reception time and the longest delayed node (i.e., the least recently transmitted node) is selected as a candidate polled node among potential deafness nodes. Furthermore, the receiver compares the wait time of its own pending packet with that of the candidate polled node. If the wait time of its own pending packet is longer than that of the candidate polled node, the receiver node cancels its polling. Note that the previous transmitter is not selected as a polled node even when the polling table is empty except for it. This scheme can improve fairness among the neighbor nodes.

After selecting a polled node, the nodes move to RI-mode. In RI-mode, the directional RTR frame addressed to the selected polled node is transmitted when the medium remains idle for DIFS and backoff periods. The duration field of RTR is set according to the packet size registered in its own polling table. When the polled node receives RTR, it immediately transmits the Data frame. This reduces the channel wastage due to unnecessary backoff as illustrated in Fig. 2. In RI-DMAC, the RTR frame is not retransmitted like RTS even if the receiver does not receive the Data frame. However, the polling table is not updated and the polled node may be selected again as the polled node at the next opportunity. Neighboring nodes that overheard RTR update its DNAV

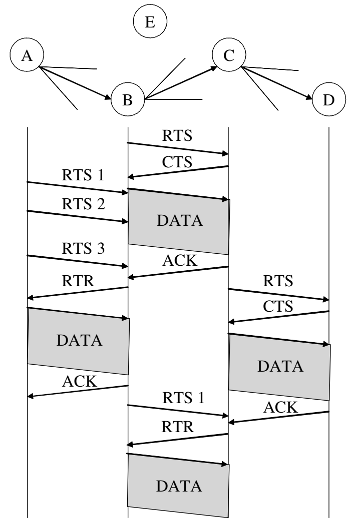

Fig. 2. RI-DMAC.

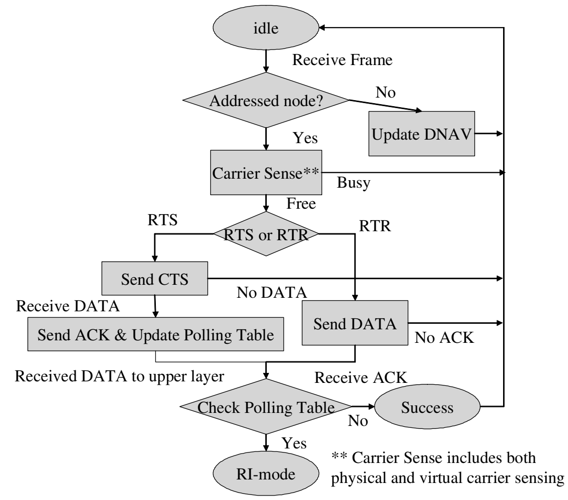

Fig. 4. Flowchart of RI-DMAC (Receiver side).

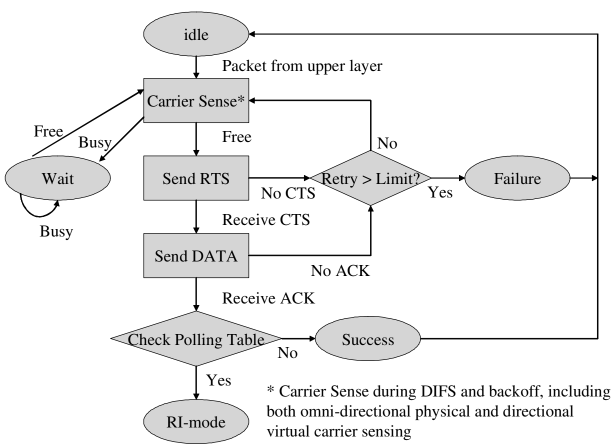

Fig. 3. Flowchart of RI-DMAC (Sender side).

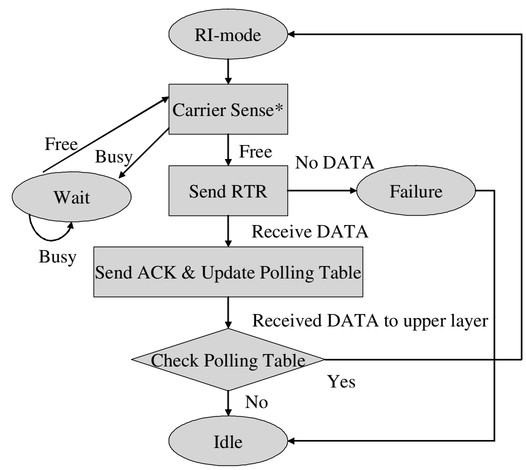

Fig. 5. Flowchart of RI-DMAC (RI-mode).

(Directional NAV) [4] with the duration field contained in RTR, in similar with RTS.

Unlike other receiver-initiated MAC protocols, in RI-DMAC, the sender transmits RTS even when the receiver is in the RI-mode and it may receive RTR as illustrated in Fig. 2. This is because when RTR is not received successfully due to collision or deafness, the transmitter should wait for the next RTR from the receiver, and it may result in the wastage of the wireless channel and increase the delay as in other receiver-initiated MAC protocols.

Figs 3, 4 and 5 show the flowchart of RI-DMAC at the sender side, receiver side and RI-mode respectively, as the summary of our proposed scheme.

V. Performance Evaluation

To evaluate the performance of RI-DMAC we developed an event driven simulator. In addition to RI-DMAC, we evaluate IEEE 802.11 [2] using omni-directional antennas with transmission range of 250 meters, DMAC with DPCS (Directional Physical Carrier Sensing) [4], DMAC with OPCS (Omni-directional Physical Carrier Sensing) [18], Circular RTS MAC [14] and ToneDMAC [18] for eight antenna beams with transmission range of 500 meters. We make the following assumptions. A packet size is 512 bytes and the data rate is 11 Mbps. We do not consider mobility. We first consider three deafness scenarios (Fig. 6) same as in [18].

A. Scenario (i)

In scenario (i), node 1 intends to communicate to node 3, using the route through node 2. As described in Section I, node 1 is a deafness node when node 2 is communicating with node 3. This scenario measures only the effect of deafness in directional MAC protocols because spatial reuse is not possible. The throughput versus the offered load in scenario (i) is shown in Fig. 7. IEEE 802.11 performs better than existing directional MAC protocols because the omni-directional RTS/CTS solves deafness. RI-DMAC outperforms IEEE 802.11 because it solves deafness properly and reduces control frames compared with a four-way handshake. Although ToneDMAC also solves deafness using omni-directional out-of-band tones, throughput

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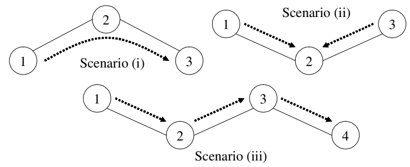

Fig. 6. Scenarios used for evaluating deafness.

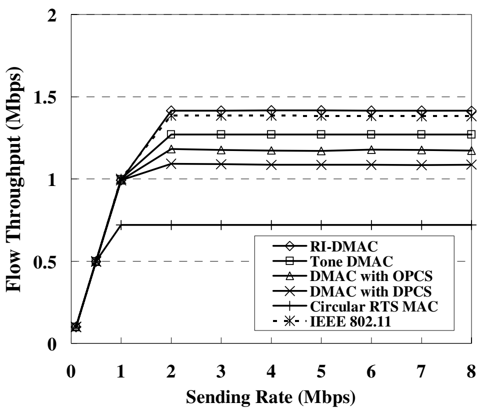

Fig. 7. Throughput for scenario (i).

of ToneDMAC is lower than IEEE 802.11 because the available data rate for data communication is 10.5 Mbps due to allocating the bandwidth to the control channel. Circular RTS MAC achieves the least throughput because of the multiple RTS transmissions.

B. Scenario (ii)

Fig. 8 shows the throughput of three protocols in scenario (ii). In scenario (ii), two nodes intend to communicate to the same node and spatial reuse is also impossible. RI-DMAC outperforms others because it reduces the channel wastage due to unnecessary backoff. Omni-directional carrier sensing does not solve deafness in scenario (ii), and it is only useful when the transmitter is also the receiver of other links. Therefore, the benefit of polling scheme is evident from the performance improvement of RI-DMAC over DMAC.

C. Scenario (iii)

In scenario (iii), “deadlock” [18] problem occurs; all nodes on a chain may fail to communicate except for the last communicating pair on the chain. Fig. 9 shows the throughput of four protocols in scenario (iii). Although RI-DMAC performs better than DMAC with OPCS under 1.5 Mbps sending rate, DMAC with OPCS outperforms RI-DMAC when the sending rate is high. To analyze and explain this situation, throughput per link of DMAC with DPCS, DMAC with OPCS, RI-DMAC and IEEE 802.11 are shown in Fig. 10, Fig. 11, Fig. 12 and Fig. 13, respectively. DMAC with DPCS suffers from “deadlock” as shown in Fig. 10. Although DMAC with OPCS mitigates “deadlock”, link throughput of 2-3 is dramatically low. This is because it is hard for node 2 to acquire the channel to initiate a transmission. Node 2 can acquire the channel only

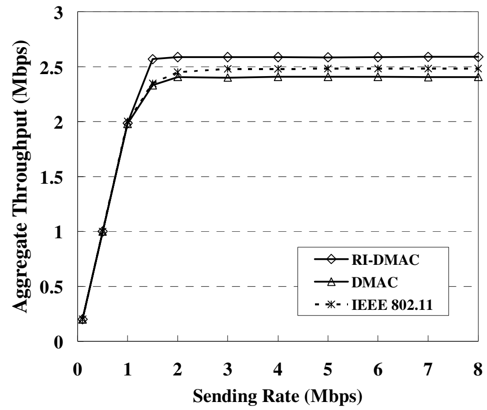

Fig. 8. Throughput for scenario (ii).

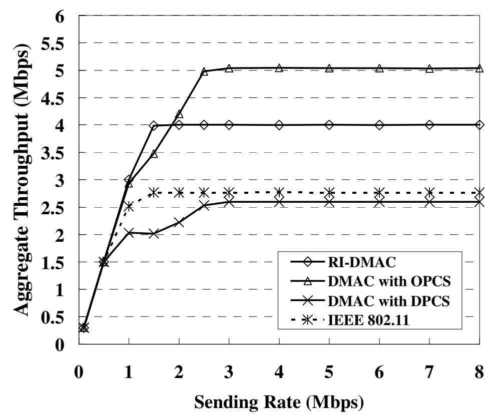

Fig. 9. Throughput for scenario (iii).

if node 1 and node 3 are idle. Unlike node 2, nodes 1 and 3 can acquire the channel when an addressed node is idle. This is a serious fairness problem. As shown in Fig. 12, throughput of each link is comparatively same in RI-DMAC. This is because our proposed polling scheme can select a “least recently transmitted node” as a polled node and solve the fairness problem. In IEEE 802.11, it also appears the fairness problem. This is because node 1 cannot overhear the signal between 3 and 4. When node 3 initiates a transmission, it transmits RTS omni-directionally and node 2 sets NAV. Under these situations, if node 1 transmits RTS to 2, node 2 cannot reply because of NAV. It reduces the possibility for node 1 to acquire the channel. Fig. 14 shows the fairness index of four protocols in scenario (iii). Assuming the throughput of flow i is x_i, fairness index is calculated as

$$f(x_1, x_2, \ldots, x_n) = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n \sum_{i=1}^{n} x_i^2}. \quad (1)$$

Results show that RI-DMAC outperforms others in terms of fairness.

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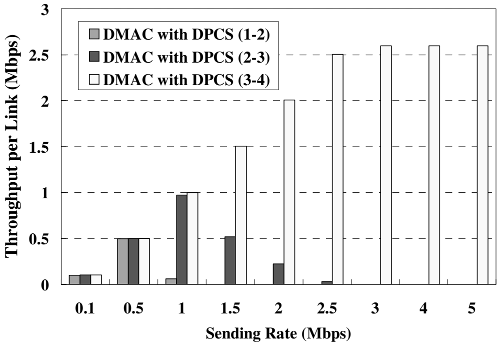

Fig. 10. Link throughput of DMAC with DPCS for scenario (iii).

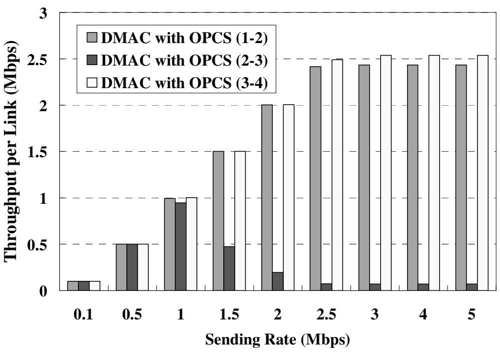

Fig. 11. Link throughput of DMAC with OPCS for scenario (iii).

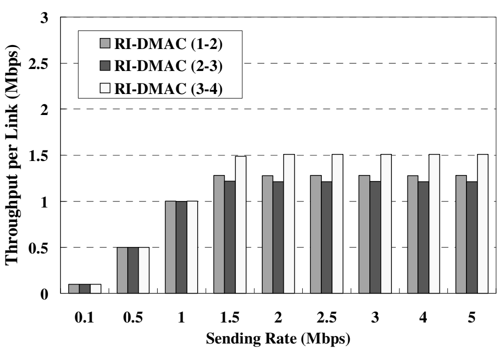

Fig. 12. Link throughput of RI-DMAC for scenario (iii).

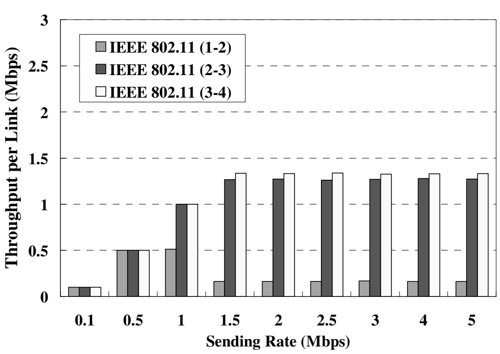

Fig. 13. Link throughput of IEEE 802.11 for scenario (iii).

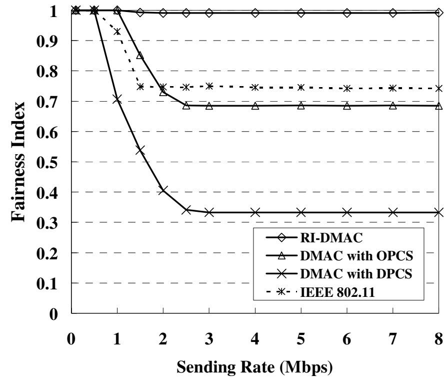

Fig. 14. Fairness index for scenario (iii).

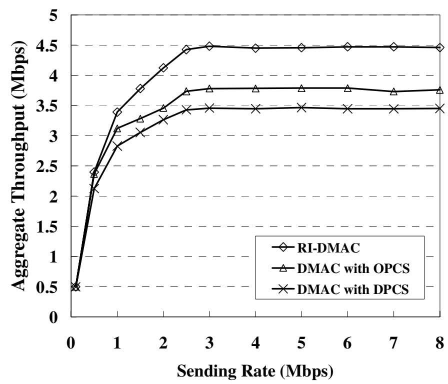

Fig. 15. Aggregate throughput in random topology.

D. Multi-hop Random Topology

We consider a network of 50 nodes placed randomly in a region of 1500 m 1500 m. Five random source-destination pairs are chosen and the routes are statically assigned. Figs 15 and 16 show throughput and fairness index, respectively. RI-DMAC also outperforms others in the random topology in terms of throughput and fairness performance because it mitigates deafness using a sophisticated polling scheme.

Fig. 17 shows the average end-to-end delay in the random topology. It can be observed that RI-DMAC has less delay than DMAC with OPCS. This is because RI-DMAC reduces idle time due to unnecessary backoff caused by deafness. In Fig. 17, results show that DMAC with DPCS outperforms others when the sending rate is high. Note that the results do not include the latency of packets that are dropped due to exceeding the maximum retry limit, which is set to 7 in our simulations, and the routing overhead is not included. DMAC with DPCS suffers from excessive packet drops caused by deafness and "deadlock", and therefore route discovery procedures may be initiated throughout the network, which increase the end-to-end delay. Evaluating the impacts of deafness on the network layer is a part of our future work.

VI. Conclusion

This paper addressed issue of deafness in directional MAC protocols. This paper proposed RI-DMAC, a novel receiver-

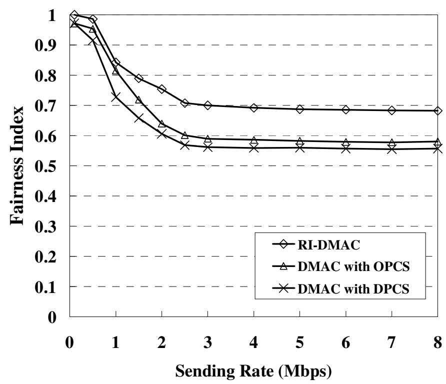

Fig. 16. Fairness index in random topology.

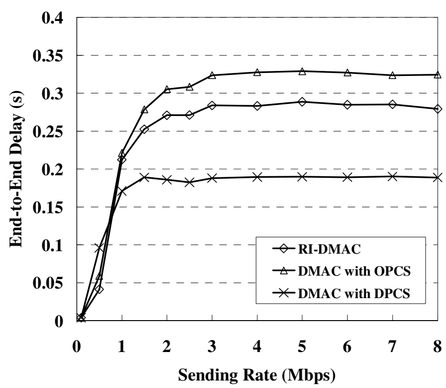

Fig. 17. End-to-End delay in random topology.

initiated mechanism to handle deafness problem. RI-DMAC handles deafness problem reactively using a polling scheme and uses neither circular RTS/CTS nor additional control channel. In RI-DMAC, each node maintains a polling table and polls a potential deafness node using the RTR frame after the completion of every dialog. The potential deafness node can recognize that the intended receiver becomes idle, and deliver a packet immediately after receiving RTR. Among potential deafness nodes in the polling table, the least recently transmitted node is selected as a polled node to improve fairness. The experimental results show that RI-DMAC performs better than existing directional MAC protocols in terms of throughput and fairness. In our future work, we plan to enhance RI-DMAC to incorporate QoS requirements.

REFERENCES

[1] R. Jurdak, C. V. Lopes and P. Baldi, "A Survey, Classification and Comparative Analysis of Medium Access Control Protocols for Ad hoc Wireless Networks," *IEEE Communications Surveys and Tutorials*, Vol.6, No.1, First Quarter 2004.

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

[3] 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.

[4] R. R. Choudhury, X. Yang, R. Ramanathan and N. H. Vaidya, "Using Directional Antennas for Medium Access Control in Ad Hoc Networks," Proc. *ACM International Conference on Mobile Computing and Networking (MobiCom)*, pp.59-17, Sep. 2002.

[5] 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.

[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] T. Ueda, S. Tanaka, D. Saha, S. Roy and S. Bandyopodhyay, "Location-Aware Power-Efficient Directional MAC Protocol in Ad Hoc Networks Using Directional Antenna," *IEICE Trans. Commun.*, Vol.E88-B, No.3, pp.1169-1181, March 2005.

[8] 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.

[9] M. Takai, J. Martin, A. Ren, and R. Bagrodia, "Directional Virtual Carrier Sensing for Directional Antennas in Mobile Ad Hoc Networks," Proc. *ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc)*, pp.183-193, June 2002.

[10] R. Ramanathan, "On the Performance of Ad Hoc Networks with Beamforming Antennas," Proc. *ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc)*, pp.95-105, Oct. 2001.

[11] 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.

[12] R. Ramanathan, J. Redi, C. Santivanez, D. Wiggins and S. Polit, "Ad Hoc Networking With Directional Antennas: A Complete System Solution," *IEEE Journal on Selected Areas in Communications*, Vol.23, No.3, pp.496-506, March 2005.

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

[15] G. Jakllari, I. Broustis, T. Korakis, S. V. Krishnamurthy and L. Tassiulas, "Handling Asymmetry in Gain in Directional Antenna Equipped Ad Hoc Networks," Proc. *IEEE International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, Sep. 2005.

[16] H. Gossain, C. Cordeiro and D. P. Agrawal, "MDA: An Efficient Directional MAC scheme for Wireless Ad Hoc Networks," Proc. *IEEE Global Communications Conference (GLOBECOM)*, Nov. 2005.

[17] H. Gossain, C. Cordeiro, D. Cavalcanti and D. P. Agrawal, "The Deafness Problems and Solutions in Wireless Ad Hoc Networks using Directional Antennas," Proc. *IEEE Global Communications Conference (GLOBECOM)*, Nov. 2004.

[18] R. R. Choudhury and N. H. Vaidya, "Deafness: A MAC Problem in Ad Hoc Networks when using Directional Antennas," Proc. *IEEE International Conference on Network Protocols (ICNP)*, pp.283-292, Oct. 2004.

[19] J. Wang, Y. Fang and D. Wu, "SYN-DMAC: A Directional MAC Protocol for Ad Hoc Networks with Synchronization," Proc. *IEEE Military Communications Conference (MILCOM)*, Oct. 2005.

[20] M. Takata, M. Bandai and T. Watanabe, "Performance Analysis of a Directional MAC Protocol for Location Information Staleness in MANETs," *IPSJ Journal*, Vol.46, No.11, pp.2623-2632, Nov. 2005.

[21] M. Sekido, M. Takata, M. Bandai and T. Watanabe, "A Directional Hidden Terminal Problem in Ad hoc Network MAC Protocols with Smart Antennas and its Solutions," Proc. *IEEE Global Communications Conference (GLOBECOM 2005)*, Nov. 2005.

[22] F. Talucci and M. Gerla, "MACA-BI(MACA By Invitation) A Wireless MAC Protocol for High Speed ad hoc Networking, Proc. *IEEE International Conference on Universal Personal Communications (ICUPC)*, pp.913-917, Oct. 1997.

[23] D. Lal, R. Toshniwal, R. Radhakrishnan, D. P. Agrawal and J. Caffery, "A Novel MAC Layer Protocol for Space Division Multiple Access in Wireless Ad Hoc Networks, Proc. *IEEE International Conference on Computer Communications and Networks (ICCCN)*, pp.614-619, Oct. 2002.