An RSSI-Based Cross Layer Protocol for Directional Ad Hoc Networks and its Implementation

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ABSTRACT

Smart antenna (or directional antenna) technology has been developed recently, which can control its antenna beam pattern to a specified direction by software. Medium access control (MAC) protocols using smart antennas, called directional MAC protocols, have the following potentials: higher spatial reuse, larger extension of communication range, less interference and higher total throughput compared to that with omni-directional antennas. Despite the great potential, there is rare implementation of directional MAC protocols for ad hoc networks. In this paper, we propose and implement a RSSI (Receive Signal Strength Indicator)-based cross-layer protocol for directional ad hoc networks. In the proposed protocol, the RSSI is used for computing the direction and randomizing backoff time. Moreover, backoff time is weighted according to number of hops from a source node. Additionally, simple incorporated routing functions are implemented. We implement the proposed protocol on a testbed with the electronically steerable parasitic array radiator (ESPAR) antenna and IEEE 802.15.4. The results of fundamental evaluation show that the proposed protocol can achieve about 2.4 times higher data arrival ratio than the conventional random backoff method with directional antennas.

Keywords: ad hoc networks, MAC, routing, directional antenna

1 INTRODUCTION

Wireless ad hoc networks have been intensively studied in recent years because the networks can be built only with mobile nodes without any fixed infrastructure. Directional media access control (directional MAC) protocols are studied in [1]-[7], using the antenna beam forms adaptively and effectively. Directional MAC protocols control the antenna beam forms depending on the situation of data communication, which improve throughput and reduce delay etc. due to high spatial reuse. Most directional MAC protocols are evaluated by computer simulations where antenna beam forms and radio propagations are ideal. However, if we use them in a real environment, we have to consider the effects of actual antenna beam forms, the feature of wireless devices and actual radio propagations. Some work implement directional MAC protocol [8]-[11]. These systems have full protocol stack including physical, MAC, routing and transport etc. Although use of directional antenna for ad hoc networks has a great potential, there is no promising implementation of directional MAC protocols. In [9], the authors implement a system for vehicular-to-vehicular link. They use omni-directional beam to broadcast for neighbor discovery. In addition, they define line-of-sight (LOS) beam whose main lobe is closest to the straight line direction to the other node in terms of angles, and compute LOS beam using GPS coordinates. In [12], the authors show that the observations are clearly different from the general belief that LQI (link quality indicator) is a good indicator of link quality and that RSSI is inappropriate. In [13], the authors proposed a routing protocol based on RSSI and evaluated it not by an implementation but a simulation.

In this paper, we propose and implement a RSSI-based cross layer protocol for ad hoc networks using directional antenna with a small number of nodes. In the proposed protocol, the RSSI is used for computing the direction and randomizing backoff time. Moreover, backoff time is weighted according to number of hops from a source node. Additionally, simple incorporated routing functions are implemented. We implement the proposed protocol on a testbed with ESPAR antenna [14] and IEEE 802.15.4 [15]. The results of fundamental evaluation show that the proposed protocol can achieve about 2.4 times higher data arrival ratio than the conventional random backoff method with directional antennas.

In Section 2, the design concept of the proposed protocol is described in four parts. A brief description of the implementation is in Section 3. The experimental results in single-hop and multi-hop communications are provided in Section 4. We show the concluding remarks and future work in Section 5.

2 DESIGN CONCEPT

We propose a RSSI-based cross layer protocol between MAC layer and network layer using directional antenna for ad hoc networks.

The proposed protocol is described in the following 4 parts:

2.1 RSSI-based backoff control,

2.2 Routing function embedded in MAC layer,

2.3 Making Angle-SINR table (AST),

2.4 Other Detailed Features.

In this Section, we show some detailed implementation matters in addition to the above four parts.

2.1 RSSI-based backoff control

For ad hoc networks, simple random value generation is one of the important issues. The proposed protocol uses RSSI value for random value generation. The observed value of RSSI is randomized naturally because of the signal strength fluctuations. Therefore, the absolute value of RSSI is used for randomizing backoff time. In the proposed protocol, RSSI is also used for prioritization of links. Each node has AST table (See Figure 6), which is including RSSI value from neighbor nodes (See Section 2.3). According to the AST, the backoff time for a node with strong RSSI can be shortened. So they have a high priority and can complete communication earlier, which can prevent the interference to the other nodes. On contrast, a long distance node with weak RSSI has a long backoff time, so the priorities become lower.

Furthermore, to make the data stream of multihop communication smoothly, the backoff time of the node is set according to the distance from the source node. In other words, the backoff time of the node uses the number of hops in routing table. The backoff time for a link near destination is set shorter, and the backoff time near the source is set longer.

For example, the network topology is shown in Figure 1. In the proposed protocol, the backoff time is set to $\mathrm{BO} + n \times \alpha$. The BO is set to $8\mu\mathrm{sec} \times \mathrm{RSSI}$, and the n is the number of hops to the destination node. If we set α to 60, and the RSSI value between node 1 and node 2 is -40, then the backoff time will be set to $560\mu\mathrm{sec}(= 8\mu\mathrm{sec} \times 40 + 4 \times 60)$.

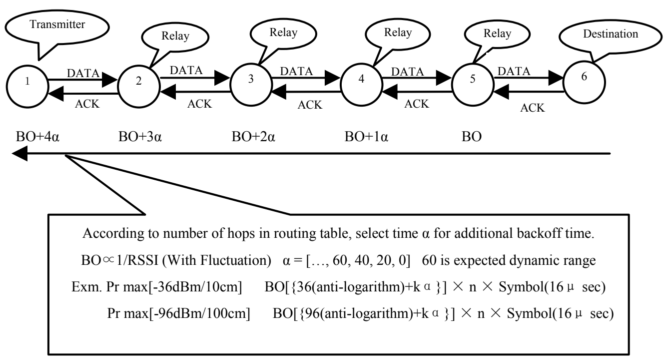

Figure 1: Topology of Experiment.

In general, directional antenna can mitigate interference to other communications because antenna gain for un-specified direction is quite small. Therefore, data contention occurs less frequently than omni-directional protocol. The total backoff time can be reduced due to less interference. Furthermore, if the backoff time of nodes with strong RSSI can be shortened, they can complete communication earlier, and mitigate the interference to the other nodes. Based on the observation, the backoff time should be used for prioritization of links rather than avoiding contention in directional MAC protocol.

2.2 Routing function embedded in MAC layer

We implement a simple routing function in MAC layer based on RSSI. We consider at most a few hops between the source and the destination. For that environment, the conventional routing protocols such as DSR, AODV and OLSR are over spec. The proposed protocol uses AST (See Section 2.3).

Firstly, we set a RSSI threshold whose arrival ratio is almost 100% according to the experimental result. If the RSSI is stronger than the threshold, the arrival ratio is almost 100%. Then, according to the newest received packets, the RSSI information measured from each node while sensing carrier is recorded into the tables. Finally, after determining the route, the newest RSSI table is referenced. If the RSSI to the destination is stronger than the threshold, the packet of any node can be transmitted almost 100% arrival rate, so we select the route of small number of hops. While the number of hops is the same at the nodes whose RSSI are stronger than the threshold, the RSSI table will be referenced to select the node of weak RSSI with long distance. Therefore, the route with short distance between nodes can be avoided as much as possible. On the other hand, if the RSSI is weaker than the threshold, we select a route to the node with strong RSSI whose packet arrival rate is higher. In addition, the number of hops is the same at the nodes whose RSSI are weaker than the threshold, the node with strong RSSI will be selected referencing the RSSI tables. The proposed routing function does not use IP address, but MAC address. The routing function is embedded at MAC layer.

For example, we set the threshold to 60. As shown in Figure 2, the RSSI value between node S and node A is 40, and the RSSI value between node S and node C is the same. Because both of them are stronger than 60, the packets will be transmitted to node A with a few hops from the source node S to destination node D. As shown in Figure 3, both of node A and node B have the same number of hops from source node S to destination node D. If we use the RSSI which are weaker than the threshold shown in brackets, the packets will be transmitted to node A. On the contrary, the packets will be transmitted to node B.

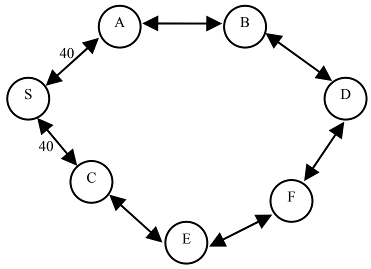

Figure 2: Topology with Strong RSSI.

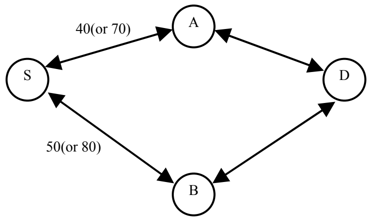

Figure 3: Topology with the Same Hops.

2.3 Making AST Tables

Firstly, each node exchanges AstBroadCast packet which is a kind of Hello packet periodically, and observes the RSSI value of the AstBroadCast packet. The direction and RSSI values are recorded in the AST tables (See Figure 6). Node n rotates its directional antenna sequentially in all directions at 30° interval to send AstBroadCast packet, which is including node number, PAN ID, beam angle, time synchronization information, routing information, and AST result as shown in Figure 4.

The receiver receives the information, performs the synchronization procedure, makes AST tables, and makes routing tables in the omni-mode. Then they share the information over the network.

The frame structure of AstBroadCast packet is shown in Figure 5. The AST table structure is shown in Figure 6. The routing table structure is shown in Figure 7. The broadcast procedure of AstBroadCast packet is shown in Figure 8.

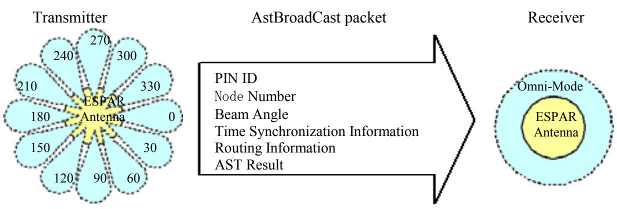

Figure 4: Making AST.

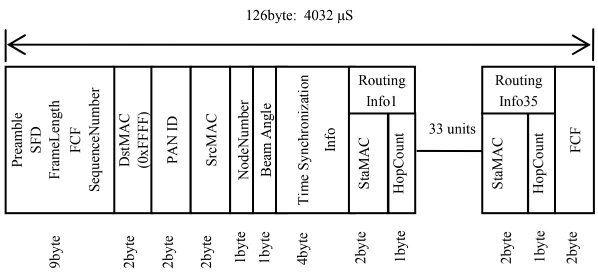

Figure 5: Frame Structure of AstBroadCast Packet.

AST MAC	AglRssi												Direction
	0	30	60	90	120	150	180	210	240	270	300	330	
2byte	1byte	1byte	1byte	1byte	1byte	1byte	1byte	1byte	1byte	1byte	1byte	1byte	1byte

Figure 6: AST Table Structure.

Sta MAC	Gw MAC	Hop Count	Agl Rssi
2byte	2byte	1byte	1byte

Figure 7: Routing Table.

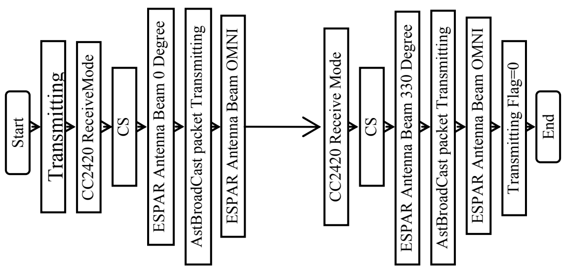

Figure 8: Broadcast Procedure.

The detailed procedure of sender for making AST is the following:

- Broadcast Timing: If the remainder of (AST Timer × 50)/(AST Time Slot × 50 × MaxNumNodes) is equal to (NodeNumber × AST Time Slot × 50), then the node with the NodeNumber starts broadcasting. So each node transmits the AST Broadcast Packet orderly by the sequence of node number in AST time slot interval.
- Calculate AST Direction: After having transmitted the AST Broadcast Packet, the sender will calculate the value of AST direction according to the value of RSSI. That the direction has the maximum of RSSI value is the direction and will be recorded into the direction field in the AST table.
- Update AglRssi Value: When exchanging the AST packets between nodes firstly, the AglRssi value was set to -1 in the routing table. This time, the RSSI value of the calculated direction will be recorded into the AglRssi field in the routing table.

The detailed procedure of receiver for making AST is the following:

- Synchronization Procedure: The time synchronization info is included in the AstBroadCast packet. The AST timer is set according to the first AstBroadCast packet. (All packets except the first one will be ignored.)
- Update Routing Table: For example, node B broadcasts AST, and node A has received the AstBroadCast packet. Node A will check whether one entry whose StaMAC is B is in the routing table. If no such entry is recorded, one entry will be added as the following: The StaMAC is set to B, the GwMAC is set to 0, the HopCount is set to 0, and the AglRssi is set to -1. Moreover, if the routing info in the AstBroadCast packet shows that StaMAC is C and the HopCount is 0. Node A will add one entry into the routing table like as the following: The StaMAC is C, the GwMAC is B, the HopCount is 1, and the AglRssi is set according to the other entry. (If some entry whose StaMAC is B and GwMAC is 0, the AglRssi value will be copied to the new entry. If no such entry, the AglRssi will be set to -1.)

As shown in Figure 5, only 35 Routing Infos can be carried by the AST Broadcast Packet, so the proposed protocols can be used for a small network.

2.4 Other Detailed Features

The other detailed features such as the data frame structure and the carrier sense procedure are described as the following.

2.4.1 Data Frame Structure

We use DATA/ACK of IEEE802.15.4/Zigbee to perform handshaking for data communication. Therefore, the ACK response relay time is only the transmitting preparation time (192µ sec). The data frame structure is shown in Figure 9.

The fields of the DATA are the following:

- DstMAC: The receiver MAC address of data packet
- SrcMAC: The transmitter MAC address of data packet
- StaMAC: The destination MAC address of data packet (The final recipient MAC address in multihop)
- BsrcMAC: The source MAC address of the transmission
- TimeExceed:
  - ・The lifetime of this packet
  - ・The initial value is the number of nodes -1
  - ・The value minus 1 while being transferred one hop
  - ・When the value becomes 0, the packet will be dropped, and no delivered notification will be send
- Packet Type
  - 0 …….. Data Packet
  - 1 …….. Time Exceed Error
  - 2 …….. Routing Error
  - 3 …….. Retry Error
  - 4 …….. Queue Overflow

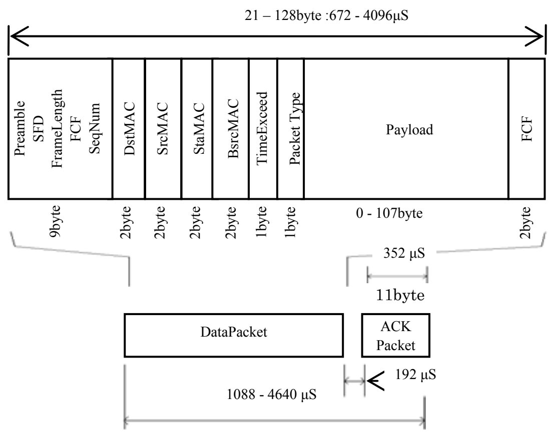

Figure 9: DATA Frame Structure.

2.4.2 Carrier Sense Procedure

Carrier sense is performed before transmitting data or broadcast packets. The procedure is shown in Figure 10.

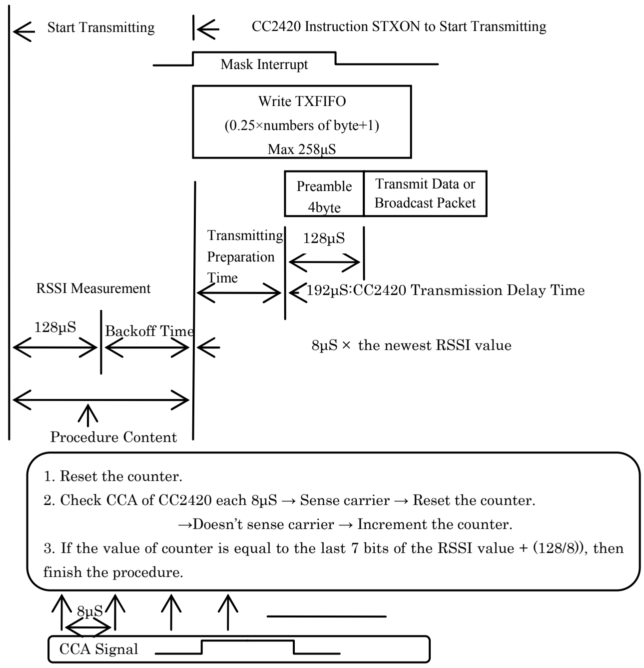

Figure 10: Event Handling Procedure.

For instance, the value of slot time in backoff is $\frac{1}{2}$ symbol (8µsec). The RSSI value of just received packet is used to calculate the backoff time. Therefore, the backoff time is random. Hence, the maximum backoff time is $8\mu\text{sec} \times 2^7 = 1{,}016\mu\text{sec}$ which is the value of CW (Contention Window). The value of slot time is changeable too. Using ZigBee chip, TI/Chipcon-CC2420 [14], RSSI measurement time needs 128µ sec to perform carrier sense, and transmitting preparation time needs 192µsec.

3 IMPLEMENTATION

According to the design concept shown in Section 2, we implement the proposed protocol on a testbed called

UNAGI/ESPAR (UNAGI is a Japanese word meaning "eels"/Electronically Steerable Parasitic Array Radiator). The testbed uses the physical layer of IEEE 802.15.4 and ESPAR antenna.

The overview of testbed and the device list are shown in Figure 11 and Table 1, respectively.

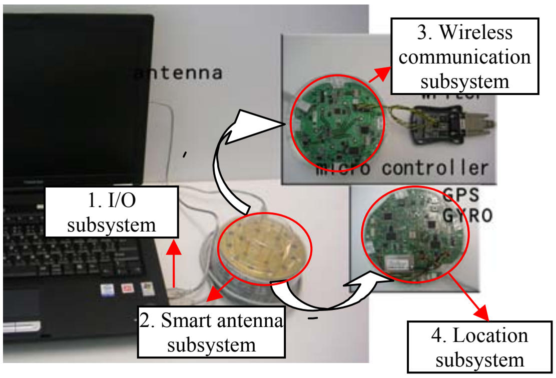

Figure 11: Overview of Testbed.

RF Module	ChipconCC2420 802.15.4 2.4 GHz
Micro controller	ATMEL ATmega128L CPU 8 MHz Flash memory 128 kbyte
GPS	FURUNO GN-80B1M
GYRO	Analog Device ADXRS401
Writer	ATMEL AVR ISP

Table 1: Device List.

As shown in Figure 11, this testbed consists of 4 subsystems:

(1) I/O subsystem,

(2) Smart antenna subsystems,

(3) Wireless communication subsystem,

(4) Location subsystem.

We use a laptop PC as an I/O subsystem to issue commands to control the experiments, and to scrutinize logs and statistics. In the smart antenna subsystem, ESPAR antenna developed by ATR is used to form not only an omni-directional beam, but also a directional beam. In wireless communication subsystem, we use IEEE 802.15.4 and adopt all the frames of MAC protocol without 802.15.4 control frames. The frame structure is shown in Section 2. In Location subsystem, the micro controller of the wireless communication subsystem can refer to the location and angle information with GPS and gyro.

Above all are the brief descriptions. More details are available in [11].

4 FUNDAMENTAL EVALUATION

In this section, we evaluate the proposed protocol implemented on the testbed with ESPAR antenna and IEEE 802.15.4 in single-hop communication and multi-hop communication.

Some of the initial parameters are set as the following:

(1) MaxNumNodes is 8, but it can be adding up to 35, because the number of Routing Info in the AST Broadcast Packet is 35,

(2) RSSI threshold is -40 dbm,

(3) AST timer is 1000 mS,

(4) Transmitting Power is 0 dbm.

In the following, we provide the experimental results in single-hop communication and multi-hop communication.

4.1 Single-hop Communication

First, we evaluate the proposed RSSI-based backoff control in the case where two nodes exist in a small room (single-hop communication). Among the comparatively near nodes, as an implementation of the proposed protocol, the backoff time is set according to the absolute value of RSSI (dBm) multiplied by 0.5 (also 1 or 2). Before showing the result, we show the simply calculated throughput in Figure 12. As shown in Figure 12, small value of the multiplication makes better throughput.

From some experiments, we obtain throughput of 155 Kbps at -67 dBm in the case of no data retransmission. The measured throughput is 92.8 percent (=155Kbps/167Kbps) of the calculated throughput. Since throughput decreases quickly while the absolute value of RSSI is 1 or 2 symbols, we set to 0.5 time symbol hereinafter.

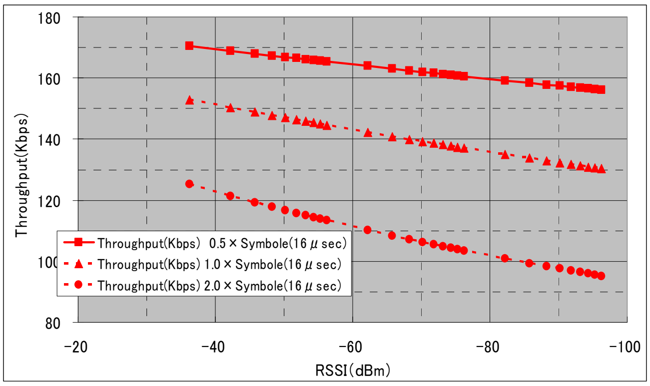

Figure 12: Calculated Throughput.

In the proposed method, the backoff time is integrally with RSSI. There occurs a fluctuation though the distance is the same, so the backoff time randomly changes and the collision can be avoided. We measure the RSSI fluctuation in an outdoor environment where two nodes are located with relatively long distance (50cm to 20 meter). The experimental data of RSSI fluctuation are shown in Figure 13 and 14. Figure 13 and 14 show time line fluctuation and deviation, respectively. In the case of long distance, with a small RSSI, it is easy to be affected by surrounding environment, and the fluctuation becomes greater.

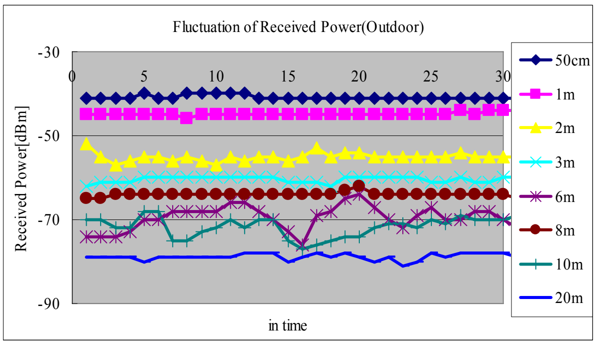

Figure 13: RSSI Fluctuation in Time.

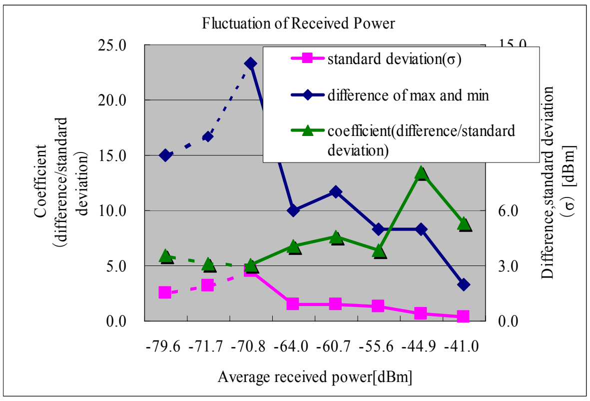

Figure 14: RSSI deviation.

4.2 Multi-hop Communication

In multihop communication, we use 2way (DATA/ACK) of IEEE802.15.4/Zigbee to perform handshaking, the packet arrival rate to select the relay node is shown in Figure 15. According to the figure, in the case of fading on, we observe that packet arrival ratio between two nodes degrades excessively when RSSI < -60dBm in our testbed. Therefore, we select the relay node whose RSSI is in the center of -60dBm.

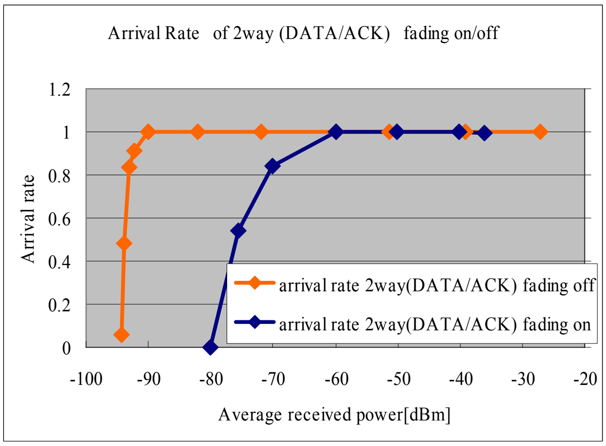

Figure 15: Packet Arrival Rate (Fading on/off).

We evaluate the multi-hop performance of the proposed protocol under the topology in Figure 1. To make the data stream of multihop communication smoothly, the backoff time is set according to the distance from the source node. The backoff time is set to $BO + n \times \alpha$. The BO is set to $8\mu sec \times RSSI$, and the n is set according to the number of hops between source node and destination node. So the backoff time for a link near destination is set smaller, and the backoff time for the source is set greater. The experimental results are shown as the following.

Figure 16 shows the observed backoff time of each link, which is normalized by data transmission time. The additional backoff time α is a variable and is 20, 40 and 60. 8-bit random means the conventional backoff time of IEEE 802.15.4. RSSI-fix always uses a constant backoff time. As shown in Figure 16, the proposed method sets longer backoff time for nodes near the source node, and the nodes near the destination have a short backoff time.

Figure 17 shows data throughput of each link. As shown in the Figure, the proposed protocol has a high throughput than the 8 Bit Random and RSSI Fix methods near the destination.

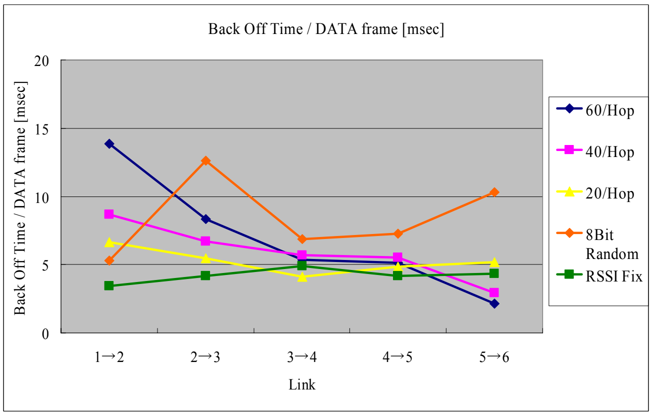

Figure 16: Observed Backoff Time (Duration).

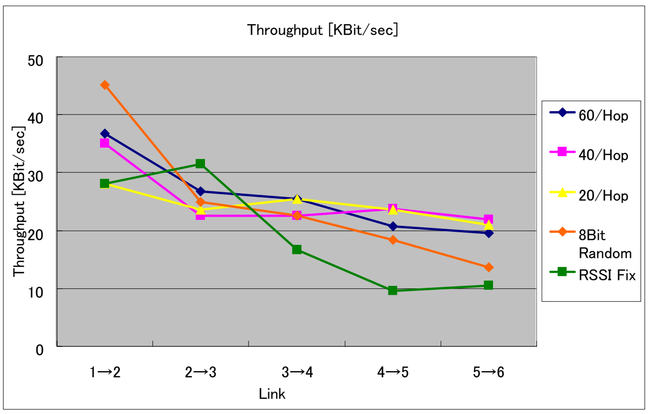

Figure 17: Observed Throughput (Duration).

Figure 18 shows data arrival ratio, which is defined as the ratio of data received at the receiver and total transmitted data. In this figure, we show the data arrival ratio of each link. We find that RSSI-fix and 8-bit random degrade in the link far from the source (link 5 to 6 is an exception) because links far from the source is interfered by the links near from the source. In contrast, three proposed method can achieve better data arrival rate in these links, which is obtained by the prioritized backoff time weighted near the source of the proposed method.

Figure 19 shows data arrival ratio. This figure shows the data arrival ratio of each route, which means multi-hop communication between source and destination. We find that the proposed method with $\alpha = 60$ achieves the superior performance. Especially, when number of hops of route is small such as one and two hops, the proposed method with $\alpha = 60$ is almost 2.4 (=41.8%/17.6%) times higher data arrival ratio than the conventional 8-bit random backoff method. Comparing the proposed three methods, we can see that performance is better for larger α.

These fundamental experiments show the effectiveness of the proposed backoff method in both single-hop and multi-hop environments. The proposed backoff method is easily implemented in resource-restricted systems because it can handle MAC and routing functions without using much memory and CPU processing. We believe this work can contribute the use of directional antennas in ad hoc networks.

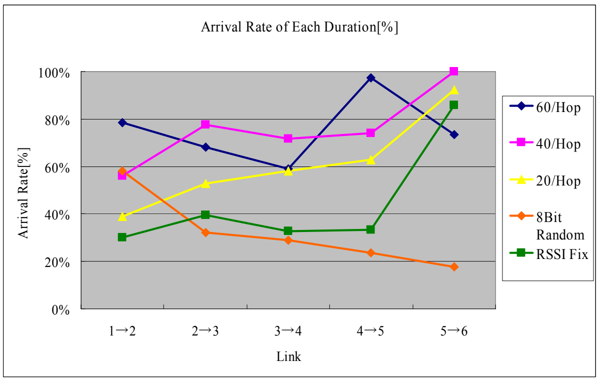

Figure 18: Packet Arrival Rate (Each link).

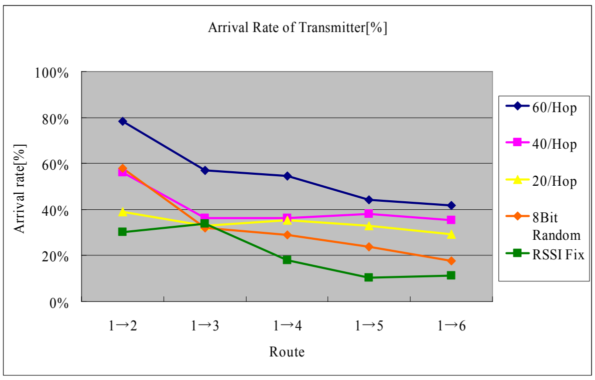

Figure 19: Packet Arrival Rate (Route).

5 CONCLUSION

In this paper, we have proposed and implemented a cross layer protocol for directional ad hoc networks. In the proposed protocol, the RSSI is used for computing the direction and randomizing backoff time. Moreover, backoff time is weighted according to number of hops from a source node. Additionally, simple incorporated routing functions are implemented. We have implemented the proposed protocol on a testbed with ESPAR antenna and IEEE 802.15.4. The result of fundamental evaluation has shown that the proposed protocol can achieve about 2.4 times higher data arrival ratio than the conventional random backoff method with directional antennas. As our future work, we evaluate more detailed performance of the proposed protocol more complicated network topologies where collisions occur frequently by means of testbed implementation. In addition, we set backoff time adaptively according to situation such as network congestion.

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