A Multi-hop Based Media Access Control Protocol Using Magnetic Fields in Wireless Sensor Networks

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Abstract. Recently wireless communication technology using magnetic fields has been proposed as an alternative communication technology for wireless sensor network in unfavorable underwater or underground environment. However, the previous works have limit on communication distance between nodes since they only consider direct communication between nodes. In this paper, we propose a multi-hop based media access control protocol for magnetic field communication to extend communication distance between nodes. The proposed scheme provides a relay node that can relay packets from source nodes to multi-hop distance destination node. We analyze the performance of the proposed scheme by simulation study with qualnet simulator.

Keywords: MAC protocol, magnetic field communication, wireless sensor network.

1 Introduction

Wireless sensor networks are one of the active areas of research. There are a variety of existing and potential applications such as environmental monitoring, infrastructure monitoring, location determination, and border patrol and security monitoring [1]. A lot of applications require underground sensors for monitoring soil conditions, such as water and mineral content, and soil properties. However, there are some limits in applying typical electromagnetic waves to the wireless communication in underground environment [2]. The electromagnetic waves encounter much higher attenuation in soil environment comparing to air environment, which results in poor communication quality. The path loss is determined by both the frequency of the electromagnetic wave and the properties of the soil or rock through which it propagates [1]. Low frequencies show less attenuation than high frequencies over a given distance and soil condition for the electromagnetic waves. The path loss is also dependent on soil type and water contents. As the sizes of soil particles are reduced and the water contents in soil increase, signal power attenuation increases.

Magnetic field communication may be an attractive alternative to the typical electromagnetic waves in the underground environment [3]. Unlike the electromagnetic signals, magnetic field signals are affected mainly by the permeability of medium. Since

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the permeability of dense medium in the underground, such as soil and water, is similar to air, the channel conditions in the underground environment for the magnetic field signals remain constant. Additionally, since a magnetic dipole loop antenna is used for the magnetic field communication, the antenna can be maintained significantly smaller than that of the electromagnetic waves even with the low frequencies.

Recently, a communication system using magnetic fields has been proposed for the underground environment [3][4][5]. There is also an international standard activity for the magnetic field communication in the name of Magnetic Field Area Network(MFAN) in ISO/IEC JTC1 SC6 WG1 [6][7]. The critical technologies for the wireless communications system using magnetic fields include a physical layer and a media access control layer. Here, we focus on the media access control protocol. The previous media access control protocol using magnetic fields only considers single-hop direct communication. Therefore, the range of communication is bounded to the distance that the signal from a transmitter reaches. Considering that the underground environment enforces comparatively high path loss, it is reasonable to extend the communication distance in a manner of relaying packets with many short-distance hops.

In this paper, we enhance the media access control protocol for the magnetic field communication system to extend the communication distance by adopting a relay node. The relay node can relay packets to communicate with a node in multi-hop distance. The relay node utilizes a relay table to forward packets to the next node and filter unnecessary packet propagation. The remainder of the paper is organized as follows. In Section 2, we provide an overview of the original media access control protocol for the magnetic field communication. Section 3 describes the proposed media access control protocol. In section 4, we analyze the performance of the proposed protocol by a simulation study. We conclude the paper in Section 5.

2 Media Access Control Protocol for Magnetic Field Communication

In this section, we briefly describe the previous media access control protocol proposed for the magnetic field communication [5][6].

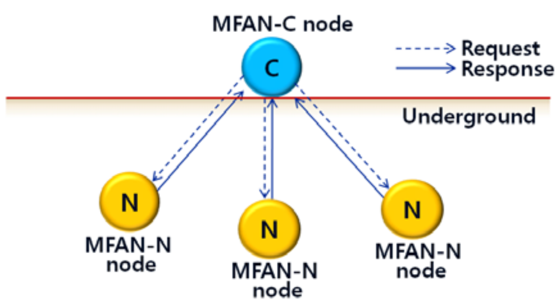


Fig. 1. Magnetic field area network structure

2.1 Magnetic Field Area Network Structure

As shown in figure 1, Magnetic Field Area Network (MFAN) is composed of MFAN-C(Magnetic Field Area Network Coordinator) node and MFAN-N(Magnetic Field Area Network Node) nodes. MFAN-C node is on duty of constructing a super-frame and configuring a MFAN. The super-frame provides synchronization information, network control, and management information such as network join/disjoin request, data request, join status request and group address setup. Any node can be MFAN-C node. However, there must be only one MFAN-C node in a MFAN. All nodes in the MFAN except the MFAN-C node correspond to MFAN-N nodes. A MFAN can have 65,519 MFAN-N nodes maximally.

2.2 Super-Frame Structure

Figure 2 shows the super-frame structure for communication between MFAN-C node and MFAN-N nodes. The super-frame consists of a request period, a response period, and an inactive period. The response period is subdivided into several time slots. The sizes of the three periods in a super-frame are all variable according to the sizes of the packets that are carried on the request period and the response period. MFAN-C node determines both the contents of a super-frame and transmission timing. The request period starts as MFAN-C node transmits a request packet. A request packet includes the command code field that represents request types, such as join request, disjoin request, join state request, data request, and group address setup request.

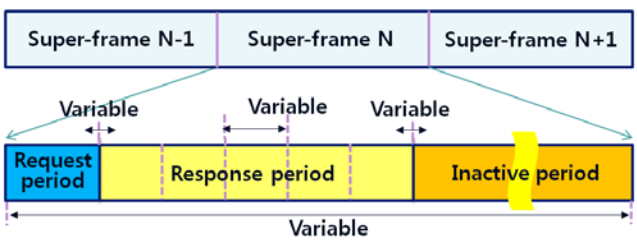


Fig. 2. Super-frame structure

In response to a request packet from MFAN-C node, MFAN-N nodes transmit response packets during the response period of current super-frame. When a MFAN-N node receive a join request packet that asks MFAN-N nodes to join MFAN, the MFAN-N node tries to transmit a join response packet containing it's own unique address in a contention manner. In this paper, we assume that a join response packet is transmitted by a probability based packet transmission scheme. The inactive period starts when there are no MFAN-N nodes that try to transmit packets. The inactive period continues until a new request period starts. During the inactive period, MFAN-N nodes may transmit data packets without the data request from MFAN-C node.

2.3 Protocol Operation

2.3.1 Node Operation

MFAN-C node starts a new request period by transmitting a request packet. MFAN-C node determines the command code in a request packet according to the scheduling strategy that is implementation dependant. After MFAN-C node transmits a request packet, MFAN-C node starts a response period and waits response packets from MFAN-N nodes in MFAN. When MFAN-C node receives a response packet successfully, MFAN-C node interprets the response packet and can transmit an acknowledgement packet to the MFAN-N node according to the acknowledgement option in the response packet. MFAN-C node can start an inactive period if there is no response packet from MFAN-N nodes during the predefined time duration. During the inactive period, MFAN-C node can be in an energy saving mode.

MFAN-N nodes wait a request packet from MFAN-C node. When a MFAN-N node receives a request packet, it interprets the command code in the request packet. The MFAN-N node does the corresponding action according to the command code in the request packet. If the command code is join request and the MFAN-N node has not been joined to MFAN, the MFAN-N node tries to transmit a join response packet in the response period of current super-frame. Here, we assume that each MFAN-N node tries to transmit a join response packet at the start point of each time slot with the transmission probability P_r. At the beginning of each time slot, a MFAN-N node generates a random value between 0 to 1 and compares the random value with P_r. If the random value is less than P_r, the MFAN-N node transmits a join response packet in the current time slot. Otherwise, the MFAN-N node tries to transmit the join response packet in the following time slot by doing the same transmission procedure. After a MFAN-N node transmits any response packet, the MFAN-N node waits an acknowledgement packet for the response packet if the MFAN-N node set the acknowledgement option to receive an acknowledgement packet. Subsequently, the MFAN-N node goes to inactive state until it receives a new request packet from MFAN-C node.

2.3.2 MFAN Join Procedure

MFAN-N nodes are required to be joined to MFAN before they transmit data packets to MFAN-C node. MFAN-C node gives chances of joining MFAN to MFAN-N nodes by a join procedure. MFAN-C node starts the join procedure by transmitting a join request packet during a request period. When a MFAN-N node receives a join request packet, the MFAN-N node tries to send a join response packet at the start point of each time slot of the response period with the transmission probability P_r.

Figure 3 shows an example of MFAN join procedure. In the figure 3, coincidentally, MFAN-N node 1 and MFAN-N node 2 have chances to transmit join response packets in the first time slot of the response period. There is a collision between the two join response packets and MFAN-C node cannot decode any join response packet. In the next time slot, only MFAN-N node 2 has chance to transmit a join response packet and the join response packet is delivered to MFAN-C node successfully. The MFAN-N node that succeeds in transmitting a join response packet is assigned an exclusive time slot in the response period to transmit data packets without contention with other MFAN-N nodes. Subsequently, MFAN-C node transmits the acknowledgement packet containing the assigned time slot information to the MFAN-N node.

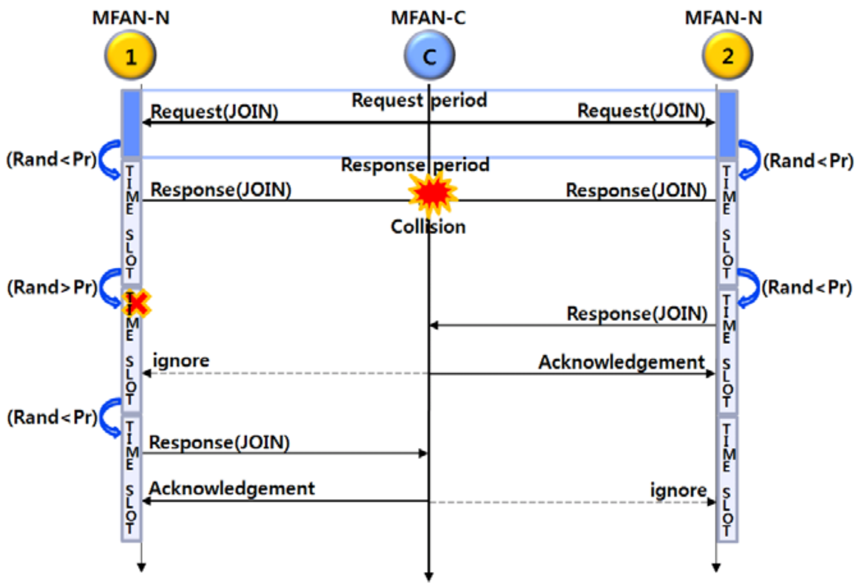


Fig. 3. An example of MFAN join procedure

2.3.3 Data Transmission Procedure

MFAN-C node can transmit a data request packet to ask MFAN-N nodes, already joined to MFAN, to transmit data response packets. The data request packet carries a set of request blocks in the packet payload. Each request block consists of a MFAN-N node address field and a time slot number field. The MFAN-N node address field represents the node address of the MFAN-N node that will be asked to transmit a data response packet. The time slot field represents the time slot number reserved for the MFAN-N node addressed by the MFAN-N node address field. When a MFAN-N node receives a data request packet during a request period, the MFAN-N node parses the data request packet and then checks whether the request packet includes the node's own address. If the MFAN-N node finds it's own address in the data request packet, the MFAN-N node transmits a data response packet in the assigned time slot of the response period. On the other hand, if the MFAN-N node doesn't find it's own address in the request packet, the MFAN-N node waits the next data request packet. Figure 4 shows an example of data transmission procedure. As shown in figure 4, MFAN-N node 1 and 2 have been respectively assigned the second and the first time slot in the response period and respectively transmit data response packets in the second and the first time slot.

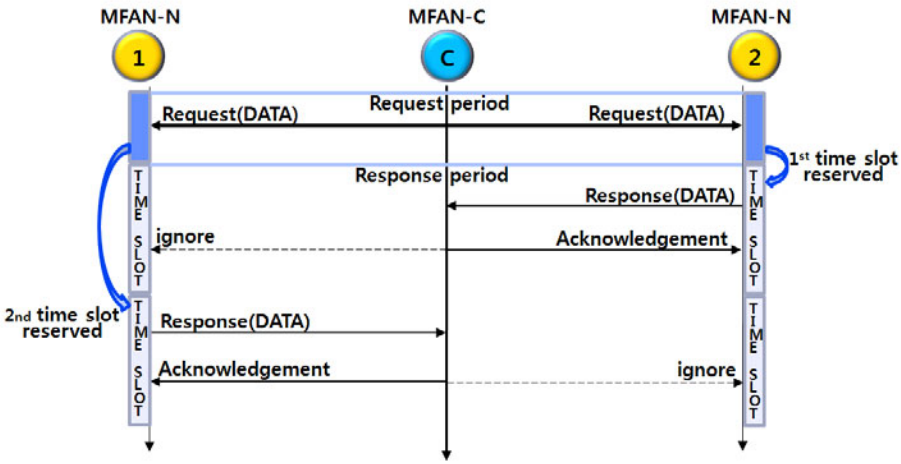


Fig. 4. An example of data transmission procedure

3 Multi-hop Based Media Access Control for Magnetic Field Communication

In this section, we describe the proposed media access control protocol supporting packet relaying through multi-hop MFAN. The packet relaying function is implemented in a new MFAN relay node (MFAN-R).

3.1 Multi-hop MFAN Structure with Relay Nodes

We assume that MFAN is multi-hop network if there is at least one MFAN-N node that should communicate with MFAN-C node via one or more additional node. Here, we propose a relay node (MFAN-R) to extend communication distance. The MFAN-R node has a function of relaying packets to the nodes in the next hop.

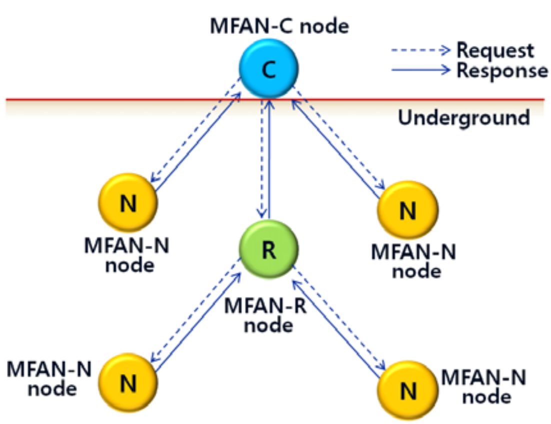


Fig. 5. MFAN structure with relay nodes

Figure 5 shows the structure of multi-hop MFAN. The MFAN in figure 5 is exactly 2 hop network. There is a MFAN-C node in the multi-hop MFAN and the MFAN-C node is responsible for constructing a super-frame and configuring MFAN. MFAN-N nodes just process the request packets received from MFAN-C node and transmit response packets. On the other hand, MFAN-R node relays request packets from MFAN-C node and relays response packets from MFAN-N nodes.

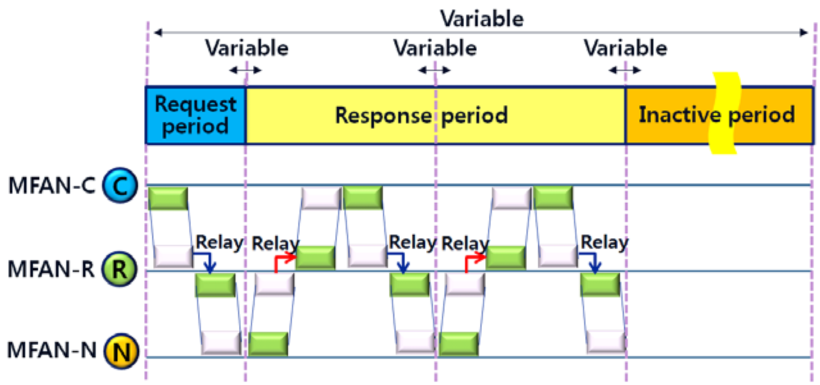


Fig. 6. Super-frame structure for multi-hop communication

3.2 Super-Frame Structure for Multi-hop Communication

Figure 6 shows the super-frame structure for the proposed media access control protocol. The basic structure of the super-frame is similar to that of the previous media access control protocol except the sizes of the request period and the response period. The sizes of the request period and a time slot of the response period in a super-frame expand in proportion to the maximum hop count of MFAN. In case of two-hop MFAN, the sizes of the request period and the response period are two times longer than those of a single-hop MFAN as shown in figure 6.

The durations of the request period (P_{req_join} or P_{req_data}) and the response period (P_{resp_join} or P_{resp_data}) can be calculated from the following equations. Here, we just consider two request types, i.e. join request and data request.

$$P_{req\_join} = D_{req\_join} \times H_{max} . \quad (1)$$

$$P_{req\_data} = D_{req\_data} \times H_{max} . \quad (2)$$

$$P_{resp\_join} = \left((D_{resp\_join} + D_{ack}) \times H_{max}\right) \times N_{total} . \quad (3)$$

$$P_{resp\_data} = \left((D_{resp\_data} + D_{ack}) \times H_{max}\right) \times N_{total} . \quad (4)$$

where, D_{req_join}, D_{req_data}, D_{resp_join}, D_{resp_data}, and D_{ack} represents the sizes of a join request packet, a data request packet, a join response packet, a data response packet, and an acknowledgement packet respectively. The H_{max} represents the maximum hop count in MFAN. The N_{total} means the total number of MFAN-N nodes that have been joined to MFAN.

3.3 Relay Table Management

MFAN-R node performs packet relaying by using a relay table. Each MFAN-R node keeps a relay table and the entries of the relay table are assumed to be set up in a static manner by a network operator. An entry of the relay table consists of two fields, i.e. <MFAN-N node address> and <previous node address>. The <MFAN-N node address> field represents the node address of the MFAN-N node that MFAN-C node wants to communicate with. The <previous node address> field represents the node address of any node to which the current MFAN-R node should relay the response packets originated from the MFAN-N node addressed by the <MFAN-N node address> field.

3.4 Packet Relay Procedure in Multi-hop Environment

3.4.1 Packet Relay Procedure from MFAN-C Node to MFAN-N Nodes

MFAN-C node broadcasts request packets and acknowledgement packets to all nodes in MFAN. MFAN-R nodes should relay request packets and acknowledgement packets to support multi-hop communication. When packets are broadcasted in a wireless network, nodes can receive the same packet several times. Therefore, we need a proper packet filtering strategy to avoid the duplicate packet reception. In this point of view, MFAN-R node relays only the request packets or the acknowledgement packets received from the nodes listed in the <previous node address> fields of the relay table.

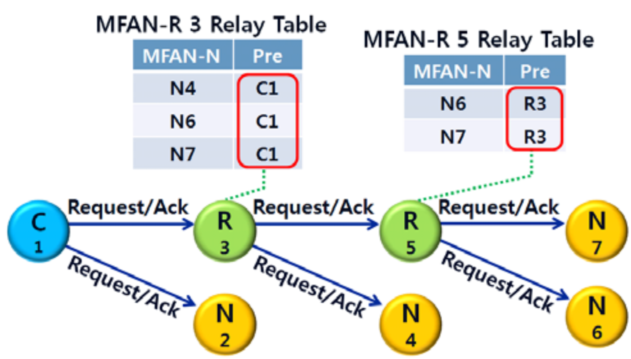


Fig. 7. An example of packet relay from MFAN-C node to MFAN-N nodes

Figure 7 shows an example of packet relay operation in a sample MFAN topology. As shown in figure 7, when MFAN-R node 3 receives a request(ack) packet from MFAN-C node, addressed as C1, the MFAN-R node 3 searches it's own relay table for an entry including C1 address in the <previous node address> field. If the MFAN-R node 3 finds an entry including C1 address, the MFAN-R node 3 relays the request (ack) packet. Otherwise, the MFAN-R node 3 stops relaying the received packet. The request (ack) packet arrived at the MFAN-R node 5 will be processed in a similar manner.

3.4.2 Packet Relay Procedure from MFAN-N Nodes to MFAN-C Node

MFAN-N nodes transmit response packets in response to a request packet from MFAN-C node. The response packets head to MFAN-C node in an uncast manner.

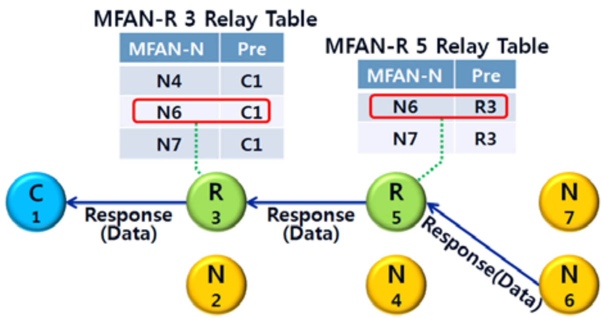


Fig. 8. An example of packet relay from MFAN-N node 6 to MFAN-C node

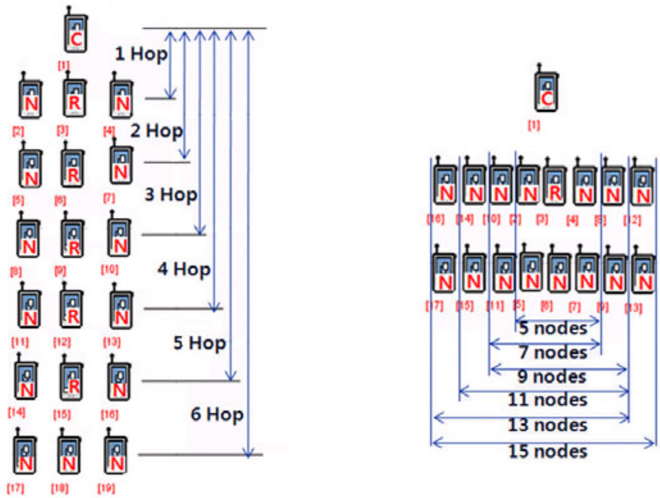
Figure 8 shows that a response packet from MFAN-N node 6 traverses to the MFAN-C node via MFAN-R node 5 and MFAN-R node 3. When MFAN-R 5 node receives a response packet, MFAN-R 5 node retrieves the address of the MFAN-N node originating the response packet from the relay table. If MFAN-R node 5 finds the matching entry in the relay table, MFAN-R node 5 relays the response packet to the next node addressed by <previous node address> field of the found entry. The response packet arrived at MFAN-R node 3 will be processed in a similar manner. Finally, the response packet will arrive at MFAN-C node.

4 Performance Evaluation

In this section, we analyze the performance of the proposed media access control protocol through the simulation study using qualnet simulator.

4.1 Simulation Environment

Figure 9 shows two types of MFAN topologies assumed for this simulation study. We consider the two types of MFAN topologies to see the influences of both the maximum hop count and the number of MFAN-N nodes in a MFAN on the protocol performances. Figure 9 (a) shows the MFAN topology with varying hop counts. With this topology, we examine the performances of the proposed protocol by varying the hop count from 1 to 6. In this topology, we assume only three nodes in each hop to reduce the effect of the number of MFAN-N nodes. Each hop consists of a MFAN-R node and two MFAN-N nodes except the last hop. The last hop includes three MFAN-N nodes because the nodes in the last hop are not required to relay packets. The MFAN-R node in each hop is responsible to relay packets between the previous hop and the next hop. In addition, we consider another MFAN topology with varying number of MFAN-N nodes as shown in figure 9 (b). We examine the performance of the proposed protocol by varying the number of MFAN-N nodes from 5 to 15. In this case, we consider a MFAN with just 2 hops to reduce the effect of the hop counts. For each MFAN topology, there is only one MFAN-C node addressed as 1.



(a) Topology with various hop counts (b) Topology with various node numbers

Fig. 9. Two MFAN topologies

System parameters for the simulation study are summarized in Table 1. It is assumed that all MFAN-N nodes generate CBR traffic. The CBR traffic generates a packet every 20 seconds and the size of a packet is 32 bytes. The CBR traffic generation starts at 20 second simulation time and ends at 500 second simulation time. We also assume that MFAN-C node is scheduled to transmit a data request packets to MFAN-N nodes after all MFAN-N nodes in the MFAN have been joined.

Table 1. System parameters

Items	Values	
	Topology (a)	Topology (b)
Super-frame size (sec)	0.7 ~ 16	2.2 ~ 6.2
Data request packet size (D_{req_data}) (msec)	90 ~ 160 / 3 ~ 15 MFAN nodes	
Join request packet size (D_{req_join}) (msec)	80	
Acknowledgment packet size (D_{ack}) (msec)	70	
Join response packet size (D_{resp_join}) (msec)	80	
Data response packet size (D_{resp_data}) (msec)	125	
CBR Traffic parameters	32Bytes, Start:20sec, End:500sec, Interval: 20sec	
Channel	Bandwidth: 5Kbps, Frequency: 300KHz	

We assume that a super-frame consists of a request period and a response period without an explicit inactive period. Therefore, the size of the super-frame can be calculated as ($P_{req\_join} + P_{resp\_join}$) for the join request procedure and ($P_{req\_data} + P_{resp\_data}$) for the data request procedure from the equations (1)~(4). Given the packet sizes of D_{req_join}, D_{req_data}, D_{resp_join}, D_{resp_data}, and D_{ack}, the size of the super-frame can be determined by both the maximum hop count and the number of MFAN-N nodes. As the maximum hop count increases, both the request period and the response period increases in proportion to the maximum hop count. As the number of MFAN-N nodes increase, the size of the data request packet (D_{req_data}) and the number of time slots in the response period increase to accommodate the MFAN-N nodes. The channel frequency and data bandwidth are assumed as 300KHz and 5Kbps respectively according to the specification for MFAN communication system [6].

As mentioned previously, MFAN-N nodes are required to be joined to a MFAN before they start transmitting data packets. Therefore, we examine the join procedure and the data transmission procedure separately to find characteristics of the two procedures. We use join completion time and average packet transmission delay as performance measures. The join completion time means the total time elapsed until all MFAN-N nodes succeed in joining to a MFAN. The average packet transmission delay is defined as the average elapsed time between the generation of a packet at a MFAN-N node and the arrival of the packet at MFAN-C node.

4.2 Join Completion Time

We examine join completion time performance for two MFAN topologies. We also examine the effects of various transmission probability P_r on the join completion time since the join completion time is directly influenced by the transmission strategy for join response packets. We are expected to find an optimal P_r, showing the best join completion time performance, for each MFAN topology.

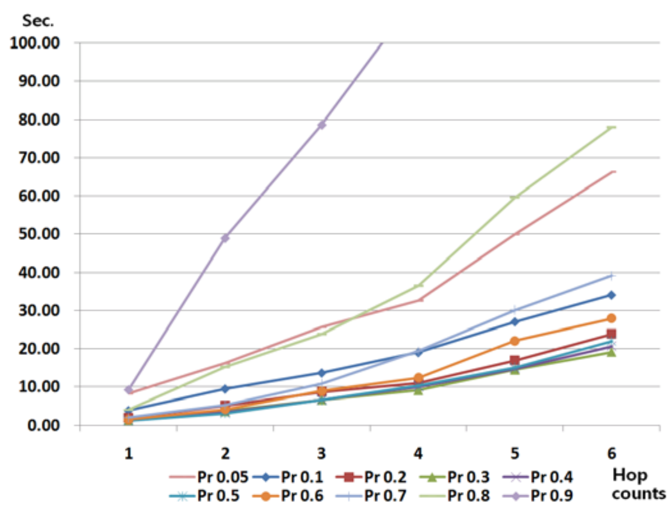


Fig. 10. Join completion time versus the maximum hop count for various $\mathbf{P_r}$

Figure 10 shows the simulation results with the MFAN topology of varying the maximum hop count. Simulation has been performed as the maximum hop count increases from 1 to 6. According to the results, the join completion time increases gradually within the P_r range of (0.1, 0.7) as the maximum hop count increases. The gradual performance degradation is mainly due to the growth of super-frame size rather than the collisions among the join response packets from contending MFAN-N nodes. The sizes of the request and response periods in a super-frame increase in proportion to the maximum hop count as shown in equations (1)~(4). On the other hand, with the P_r of 0.8 and 0.9, the join completion time performance degrades rapidly as the maximum hop count increases. For this case, the rapid performance degradation is mainly due to severe collisions among the join request packets from contending MFAN-N nodes. In addition, the result with P_r = 0.05 also shows comparatively rapid performance degradation. This is because MFAN-N nodes are allowed little chances to transmit join request packets when P_r goes below 0.05.

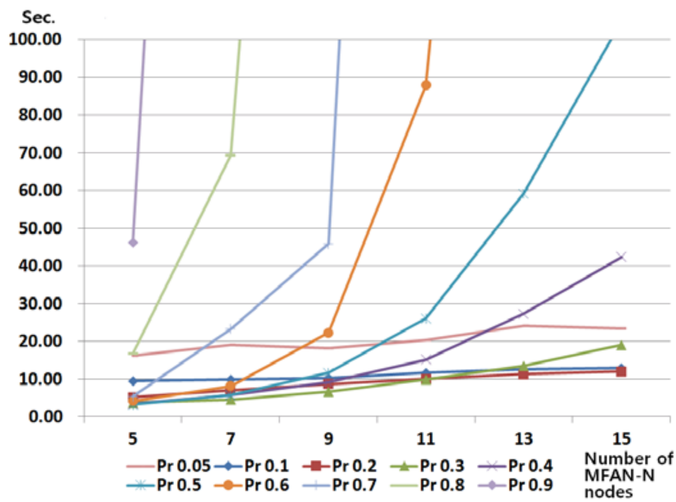


Fig. 11. Join completion time versus the number of MFAN-N nodes for various P_r

Figure 11 shows the simulation results with the MFAN topology of varying number of MFAN-N nodes. Simulation has been performed as the number of MFAN-N nodes varies from 5 to 15 with various P_r. Since we assume that the maximum hop count is fixed as 2, the join completion time performance mainly influenced by the collisions among the join response packets from contending MFAN-N nodes. According to the results, the join completion time maintains very stable state within P_r range of (0.1, 0.3). On the other hand, the join completion time performance deteriorates rapidly due to the severe collisions among the join response packets from contending MFAN-N nodes as P_r approaches 0.4. In case of P_r = 0.05, the join completion time maintains a little high over the whole range of the number of MFAN-N nodes due to the rare chance of transmitting join response packets by MFAN-N nodes. From the above simulation results, we respectively select 0.3 and 0.2 as optimal P_r values for the MFAN topologies with various maximum hop counts and with various numbers of MFAN-N nodes. The optimal P_r values will be used in evaluating the average packet transmission delay performance.

4.3 Average Packet Transmission Delay

We analyze the impacts of both the maximum hop count and the number of MFAN-N nodes on the average packet transmission delay. We also examine the effect of packet generation interval on the average packet transmission delay. The packet generation interval means the time interval between two CBR packet generations.

Figure 12 shows the simulation results of average packet transmission delay for different maximum hop counts. According to the results, the average packet transmission delay increases as the maximum hop count increases. In general, when a new CBR packet is generated during a super-frame, the packet can be delivered during the response period of the next super-frame. Therefore, the average packet transmission delay increases as the duration of a super-frame increases. The duration of a super-frame is enlarged in proportion to the maximum hop count (H_{max}) as mentioned before. In addition, the number of MFAN-N nodes joined to MFAN (N_{total}) also increases as the maximum hop count increases as shown in figure 9 (a). The increased number of MFAN-N nodes also contributes to enlarge the super-frame duration and degrade the average packet transmission delay performance.

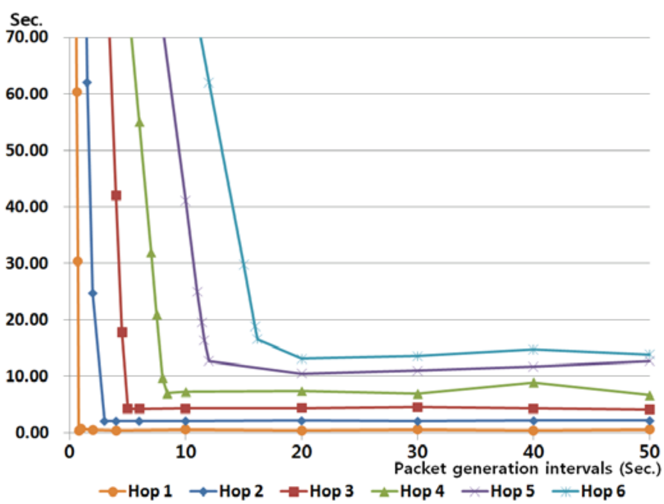


Fig. 12. Average packet transmission delay versus packet generation interval for various hop counts

Considering the impact of the packet generation interval on the average packet transmission delay, we can also find that when packet generation interval is less than the duration of a super-frame, the average packet transmission delay performance deteriorates dramatically. As the packet generation interval becomes less than the super-frame duration, the rate of packet generation becomes greater than the rate of packet transmission and packets start to be stored in a transmission queue. The increased length of the transmission queue results in drastic performance degradation in terms of the average packet transmission delay.

Figure 13 shows the simulation results of average packet transmission delay for different numbers of MFAN-N nodes. According to the results, the average packet transmission delay increases as the number of MFAN-N nodes increases mainly due to the increase of super-frame duration. According to the simulation results of figure 12 and 13, we can find that the average packet transmission delay is more sensitive to the maximum hop count rather than the MFAN-N node numbers. We can also find that the average packet transmission delay performance degrades rapidly as packet generation interval becomes less than the duration of a super-frame.

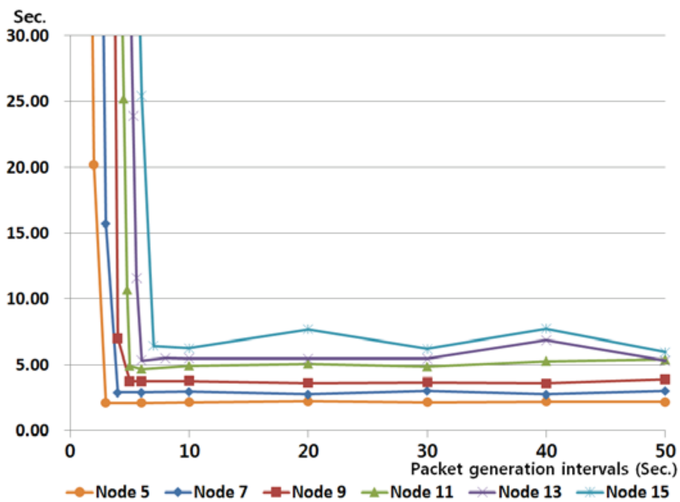


Fig. 13. Average packet transmission delay versus packet generation interval for various MFAN-N node numbers

4.4 Node-by-Node Pattern of Average Packet Transmission Delay

We also examine the node-by-node pattern of the average packet transmission delay performance. Here, we assume the MFAN topology of figure 9 (b). It is also assumed that the number of MFAN-N nodes is 12 and the maximum hop count is 2 and the other system parameters are based on those of Table 1.

Figure 14 shows that the patterns of average packet transmission delay performance are not uniform. This non-uniform performance patterns are caused by the positions of the time slots, assigned for MFAN-N nodes, in the response period. As the position of the assigned time slot is closer to the start point of the response period, the average packet transmission delay performance is better. From this fact, MFAN-C node can schedule the positions of time slots considering the traffic characteristics of each MFAN-N node.

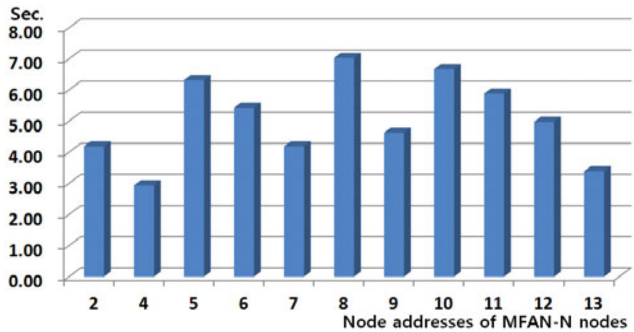


Fig. 14. MFAN-N node specific average packet transmission delay performance

5 Conclusion

In this paper, we enhanced the media access control protocol for magnetic field communication to extend communication distance by introducing packet relay functions. The proposed protocol allows MFAN-C node to communicate with MFAN-N nodes residing in multi-hop distances. We analyzed the proposed protocol in terms of join completion time and average packet transmission delay through simulation study. According to the results, the join completion time increases as the maximum hop count and the number of MFAN-N nodes increase. In steady state, the join completion time is more sensitive to the maximum hop count than the number of MFAN-N nodes. In addition, the join completion time performance degrades rapidly mainly due to the severe collisions among the join response packets from contending MFAN-N nodes as the number of MFAN-N nodes increases. Therefore, it is important to find an optimal transmission probability when a probability based transmission scheme is used for transmitting join response packets. The average packet transmission delay also increases as the maximum hop count and the number of MFAN-N nodes increase. The performance degradation mainly caused by the increase of super-frame duration. The maximum hop count has more effects on the increase of super-frame duration rather than the number of MFAN-N nodes. It is also memorable that packet generation interval should be less than the super-frame duration. Since the node-by-node pattern of the average packet transmission delay is non-uniform according to the positions of the time slots assigned for MFAN-N nodes, a scheduling mechanism considering traffic characteristics can be explorable.

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