

Extending the Read Range of UHF Mobile RFID Readers: Arbitration Methods Based on Interference Estimation

Si-Young Ahn*, Jun-Seok Park**, Yeong Rak Seong*** and Ha-Ryoung Oh†

Abstract – The read range of UHF mobile readers can be extended by a booster for mobile RFID readers (BoMR). But in an environment where multiple BoMRs are installed, the read success rate may be decreased due to signal interference. This paper proposes three arbitration methods based on interference estimation with the purpose of enhancing the read success rate. A central arbitration server manages global information in centralized arbitration method (CAM) without broadcast/multicast communication facility. In fully distributed arbitration method (FDAM), all the arbitration messages are broadcasted from a BoMR to every BoMR, and each BoMR decides with broadcasted global information. Events in FDAM are serialized naturally with broadcasted messages. Cluster Distributed Arbitration Method (CDAM) forms clusters with multicasted BoMRs and a selected BoMR acts as an arbiter in the cluster. Such effects as lengthened read range, improved the read success rates of readers can be obtained by the proposed methods without any hardware modification. In order to evaluate the arbitration methods, the RFID system is modeled by using the DEVS formalism and simulated by using the DEVSsim++.

Keywords: Arbitration method, BoMR, Booster, CAM, CDAM, FDAM, RFID

1. Introduction

The UHF Mobile RFID Reader (UMRR) is embedded to mobile phones. This device enables various services through a wireless network, but only short-distance services are available at present. This is because the read range of UMRR is only double-digit centimeter. Therefore, in order to expand service domain available with UMRR, the read range needs to be extended.

The main reasons for UMRR's limited read range are low sensitivity of passive tags and its limited output. A passive tag requires high-power signals (e.g. chip sensitivity nearly -10dBm) as it obtains operation power from the reader's signals [1]. However, UMRR has a very short read range because of its low transmission output due to the limited power supply and form factor problem. BoMR has been developed to overcome such problems [2].

BoMR is a kind of booster: it amplifies the reader's signals (①) and radiates them to the tags (②) as shown in Fig. 1. By using a BoMR, tag's backscattered response becomes stronger (③) because the reader's CW (Continuous Wave) signal inputted to the tags is amplified. As a result, the read range can be extended to

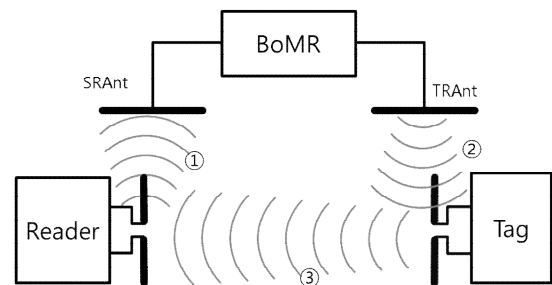


Fig. 1. Operation of BoMR [2]

more than 6m.

Previous studies have focused on a single BoMR environment [1, 2]. In order to apply BoMR for various services, however, we need to consider other environments where multiple BoMRs are installed. In such an environment, signal interference takes place and the read success rate may be thereby decreased. This signal interference is worsened due to the following three problems:

- P1) Expanded range of reader-to-reader interference
- P2) Expanded range of reader-to-tag interference
- P3) Occurrence of positive feedback

Problems such as P1 and P2 take place in the existing RFID systems. Since, however, a BoMR amplifies the signals from readers, the influence of P1 and P2 is more intensified compared to the case with only UMRR. These problems can lower the read success rate noticeably. As for P3, it is a problem that may not be found in traditional RFID systems. A BoMR amplifies RFID band signals to a

† Corresponding Author: Dept. of Electrical Engineering and Dept. of Secured Smart Electric Vehicle, Kookmin University, Korea. (hroh@kookmin.ac.kr)

* Dept. of Electrical Engineering, Kookmin University, Korea. (onsaiahn@gmail.com)

** Dept. of Electrical Engineering and Dept. of Secured Smart Electric Vehicle, Kookmin University, Korea. (jspark@kookmin.ac.kr)

*** Dept. of Electrical Electronic Engineering, Kookmin University, Korea. (yeong@kookmin.ac.kr)

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certain power without analysis. Therefore, as shown in Fig. 2(a), signals amplified by a BoMR (B1) can be amplified again by another adjacent BoMR (B2). In other words, positive feedback may take place, as shown in Fig. 2, it can paralyze the entire system.

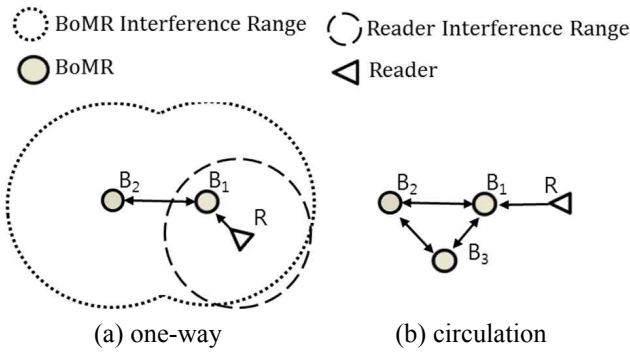


Fig. 2. Positive feedback

Therefore, the above three problems should be considered to ensure the performance of RFID system. P1 can be solved with operating time and channel. First, if the operating times of the readers and the BoMRs in the interference range are separated, this kind of interference does not take place. Also it is possible to reduce the interference by differentiating channels. Time efficiency can then be increased by controlling the operating times of readers in accordance with the state of channels.

A passive tag has no ability to select channels due to its simple hardware. Therefore, in order to solve P2, it is necessary to separate the operating times of BoMRs and readers that can interfere with the tag. Two solutions can be considered for P3: increasing the distance between BoMRs and controlling BoMRs. When the distance between BoMRs is long enough, signals become attenuated due to path loss and positive feedback does not occur. Since, however, BoMRs can be installed densely in accordance with intended services, controlling BoMRs is necessary to prevent positive feedback.

In addition, it is desirable that hardware revision of the existing readers such as additional communication interface is unnecessary. Requirements for RFID systems with multiple BoMRs can be summarized as follows:

- R1) Operation time of readers must be controlled to minimize interference and maximize parallelism (P1, P2)
- R2) Operating channel of readers must be controlled to minimize interference and maximize parallelism (P1)
- R3) Operation of BoMR must be controlled not to cause positive feedback and not to interfere readers (P1, P3)
- R4) Existing readers may be used without any hardware modification

In this paper, three arbitration methods that satisfy the above requirements are proposed. The three arbitration

methods were designed to meet the communication environment and computing power of BoMR. BoMRs with proposed arbitration can extend the read range of readers, reduce the existing signal interference and improve read success rates of readers without any hardware modification of existing readers. In order to measure the performances, the UHF RFID system was modeled by using DEVS formalism, and DEVSim++ was used for the simulation [3, 4].

2. Related Work

In order to solve the signal interference problem, various technologies have been studied. These technologies may be classified into FDMA (Frequency Division Multiple Access), TDMA (Time Division Multiple Access) and CSMA (Carrier Sense Multiple Access), etc. [5].

Among these, FDMA prevents collision by differentiating channels used by readers, and FHSS (Frequency Hopping Spread Spectrum) uses this method to reduce collision. FHSS is a technology stipulated in ISO/IEC 18000-6C (EPC class-1 generation-2), and readers read tags by allocating channels at random on a cycle. Since, however, FHSS allocates channels at random, the existing interference problems arise in such environments as those with dense readers. A dense-reader environment refers to a situation where the number of operating readers surpasses that of available channels [6].

TDMA is a technology that prevents interference by differentiating the operating time of readers in the interference range. It divides transmission time into frames and makes each reader operate for each frame to reduce collision. Technologies that use TDMA include Colorwave, Enhanced Colorwave, and DFSA (Dynamic Frame Size Adjustment) [7-9]. In the case of Colorwave and Enhanced Colorwave, collision arises and efficiency is lowered in such an environment as those with a fluid number of operating readers. DFSA determines the frame size dynamically by using the frequency of signal collisions to enhance efficiency. Since, however, this method determines the frame size based on the collision frequency of the previous round, it cannot ensure an overall read success rate. And this method is not appropriate where the number of tags varies significantly.

CSMA is the technology to prevent collisions before they happen. In many countries, use of the LBT (Listen Before Talk) method which is a kind of CSMA is recommended. In particular, it is compulsory to use LBT under the European regulations [10]. Operation by the LBT method proceeds in the following way. First, the reader checks the noise level of a channel for a certain listen time. Then, if the noise level is lower than the threshold, the reader transmits signals in listen-to-transmission turnaround time (L2T). In the case of using LBT, significant reduction of the signal interference is

possible.

As shown in Fig. 3, however, if the difference in LBT starting time between readers (T) is smaller than $L2T$, readers transmit signals simultaneously. With more readers, there are accordingly more collisions.

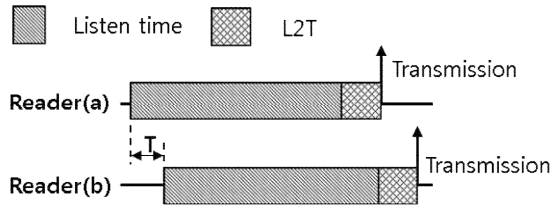


Fig. 3. Operation of LBT

Therefore, in order to reduce such collisions, a back-off scheme can be used. A back-off scheme is a technique to reduce collisions by making each reader wait for a certain time before transmitting signals. This time is divided into steps, and each reader is given randomly the number of steps for its own operation.

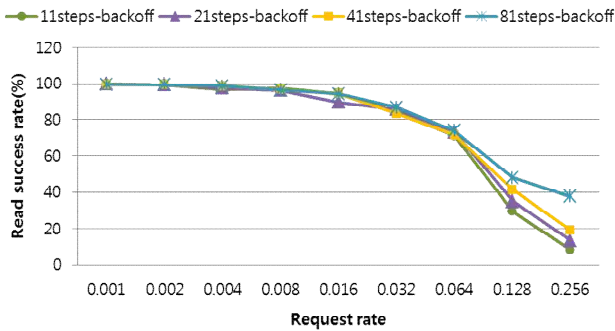


Fig. 4. Read success rate of LBT [11]

The LBT method with a back-off scheme was simulated in an environment that has BoMRs positioned in a 5×5 grid and 100 readers. Fig. 4 shows the results of the simulation. As the request rate in this graph increases, the number of readers operating simultaneously i.e., collisions can increase [11].

Under the European regulations, the maximum number of steps in a back-off was stipulated as 11. As shown in Fig. 4, however, in the case of a back-off with 11 steps, the read success rate is low, being approximately 10% at a request rate of 0.256. Therefore, in order to improve the read success rate, we increased the number of steps in a back-off to 21, 41 or 81. The simulation results showed that with an increase in the number of steps, the read success rate also increased. Even in the case of a back-off with 81 steps, however, the read success rate was below 40% with an increase in the number of readers. Accordingly, simple back-off scheme cannot guarantee a desired read success rate in an environment with many readers.

3. A Cell and Arbitration Communication

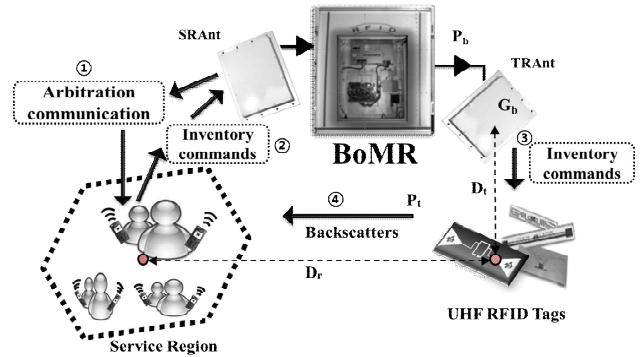


Fig. 5. The components in a cell

The region managed by one BoMR in a multi-BoMR environment is called a cell. A cell consists of tags, a BoMR, and (mobile) readers, as shown in Fig. 5. The BoMR has two antennas: SRAnt (Service Region Antenna) and TRAnt (Tag Region Antenna). SRAnt is installed to face the service region of UMRs. Through SRAnt, the BoMR is engaged in arbitration communication and receives signals of inventory commands from readers. The numbers (①~④) in Fig. 5 mean the operation sequence among readers, tags and a BoMR. At first, arbitration sequence takes place between readers and a BoMR (①). And then the permitted reader starts inventory sequence by sending commands to tags (②) and a BoMR amplifies the signal (③). Finally the tag backscatters its response with amplified CW to the reader (④). TRAnt is installed to face the tags and radiates signals of amplified reader inventory commands. Inventory commands consist of QUERY, QUERYADJUST, QUERYREPEAT, ACK, NAK, which refer to the signals of the reader to read the EPC (Electronic Product Code) of the tag. We only simulated the inventory commands in this paper. But readers can also transact the “select” and “access” commands with tags using BoMR.

Arbitration communication was designed for integrated control of readers and BoMRs to meet the requirement R1-R4. For R1 and R2, all the readers including UMRs should be arbitrated through some sort of communication. In addition, the BoMR should be controlled in accordance with operation of adjacent BoMRs to meet R3. If, however, operations of readers and BoMRs are controlled individually, a synchronization problem may arise due to a delay in communication. For example, even if the arbitration device approves the reader’s operation, inactivated BoMRs due to delayed communication can result in a failure of tag recognition. Therefore, it is necessary to control readers and BoMRs in an integrated manner through communication between them. To satisfy R4, arbitration communication was designed to be implemented with a simple addition of commands to the ISO/IEC 18000-6C standard. The BoMR transmits response signals while the reader is transmitting CW signals just like tags, as shown in Fig. 6. That means

any hardware revision of the reader such as addition of communication interface is not necessary.

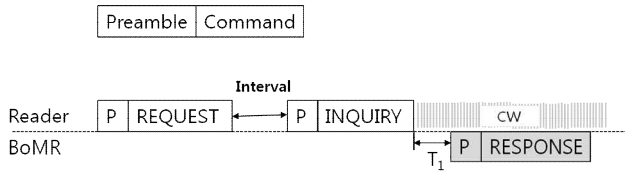


Fig. 6. Arbitration communication

Two commands i.e., REQUEST and INQUIRY are added to the command set of the standard. REQUEST is a preliminary command for the reader to request the use of the BoMR, and INQUIRY is a command to ask whether or not to use BoMR immediately.

Arbitration communication starts from the reader and the BoMR backscatters just like a UHF tag. The reader transmits REQUEST and waits for a given interval. During this interval, the BoMR or the arbitration server makes a judgment whether the transmission of the reader causes any collision. Then the reader transmits INQUIRY, and receives RESPONSE from the BoMR. It operates in accordance with the information of RESPONSE. The command was separated into INQUIRY and REQUEST so as to meet the regulations of ISO/IEC 18000-6C [6]. Under this regulation, the tag that has received a command from the reader should respond in T_1 in Fig. 6. While this T_1 takes hundreds of micros, the interval to make a judgment on the reader’s operation can take more time. Therefore, the command of REQUEST was designed as a no-response command similar to the SELECT command.

	Command	RID	GAIN	CRC-16
description	REQUEST	Reader ID	Reader antenna gain (dbj)	

(a) REQUEST

	Command	RID	CRC-16
description	INQUIRE	Reader ID	

(b) INQUIRE

	Command	RID	GRANT	CHAN	CRC-16
description	RESPONSE	Reader ID	Grant or Wait	Inventory round channel number	

(c) BoMR’s reply to INQUIRE command

Fig. 7. Arbitration command and reply

Composition of the command and reply set is shown in Fig. 7. The REQUEST command includes ID and antenna gain of the reader. The reader ID should be unique, and GAIN which refers to the peak power gain of reader antenna is used when the estimated SNR is calculated. The INQUIRE command only contains the command and reader ID, while RESPONSE reply includes the granted channel number for inventory round and ‘grant or wait’ for operation. Arbitration communication uses separated channel exclusively so as not to influence inventory round.

4. Interference Estimation

In this chapter, an interference estimation method is explained. The operations of readers and/or BoMRs are controlled based on estimated SNRs (Signal to Noise Ratio).

Assuming that the requesting reader transmits signal, SNRs of each operating readers are calculated. This implies that interferences from the requesting reader to other operating reader and vice versa are considered. The estimated SNR is compared to the threshold satisfied with the desired BER (Bit Error Rate). The request is granted if every estimated SNR exceeds this threshold. Calculation of estimated SNR is shown in (1).

$$Estimated\ SNR = \frac{Estimated\ Signal}{Estimated\ Noise} \quad (1)$$

Here, the estimated signal is the predicted power of the tag signal transmitted back to the reader. Since the readers are mobile and the tags are dissipated in the cell, the arbiter which estimates the SNR (i.e. signal and noise power) cannot decide the exact locations of the tags and readers in practice. Even though the locations of the tags are known in advance, the arbiter cannot know which tag may be identified. Therefore the arbiter inevitably should assume the locations of the readers and tags. The estimated signal is calculated by putting the tag’s transmission power (P_t) and the distance from the center of the service region to the center of the tag region (D_r), as shown in Fig. 5, in the Friis equation [1].

$$Estimated\ Signal = \left(\frac{\lambda}{4\pi D_r} \right)^2 \cdot P_t \cdot G_r \quad (2)$$

where G_r stands for the peak power gain of the reader antenna. The transmission power of the tag (P_t) is formulated as

$$P_t = \left(\frac{\lambda}{4\pi D_t} \right)^2 \cdot P_b \cdot G_b \cdot (G_t)^2 \cdot (\Delta\rho)^2 \quad (3)$$

where D_t denotes the distance between the center of tag region and the BoMR, P_b for BoMR’s output, i.e. EIRP (Equivalent Isotropically Radiated Power), G_b for TRAnt gain, G_t for tag antenna gain, and $\Delta\rho$ for the tag’s differential reflection coefficient, respectively [11].

Estimated noise refers to the predicted value of noise received by the reader. This noise takes place due to signals from other readers, the BoMRs, and the other tags, which use the same or adjacent channels. Among these, the signal from BoMR is the strongest, and has the dominant influence. Therefore, the estimated noise is calculated by simply summing signals transmitted by the adjacent operating BoMRs, i.e. EIRP (P_{bs}). If the channel is different with BoMR’s, the noise power of BoMR is calculated

based on transmit mask [6]. Estimated noise is formulated as

$$Estimated\ Noise = \sum_{i=1}^n \left\{ \left(\frac{\lambda}{4\pi D_{b(i)}} \right)^2 \cdot P_{bs(i)} \cdot G_r \right\}, \quad (4)$$

where n stands for the number of activated BoMRs, and P_{bs} is signal power transmitted by each adjacent operating BoMR, respectively.

D_b is the distance from the activated BoMRs to assumed location of the reader. This is because the arbiter does not know the reader's location or the antenna radiation pattern, the exact noise received by the reader cannot be calculated. The noise is hence estimated under the assumption that the reader is located at the same position as the BoMR itself.

Now we briefly evaluate the SNR estimation which may affect the performance of proposed arbitration methods. It is a bit pessimistic in a sense that estimated SNR may be probabilistically lower than real SNR. At first estimated signal strength is calculated under the assumption that the distance between the reader and the responding tag is maximum read range (i.e. 5m). For example, if the real distance between them is 1m, the error becomes -14dBm according to the Eq. (2). The maximum location error of the reader may be 5m. The minimum distance between activated BoMRs must exceed 80m to meet R3. From Eq. (4), we can conclude that the maximum absolute error of estimated noise power from any activated BoMR due to the location error is lower than 0.5dBm.

The information required for calculation of the estimated SNR — i.e., location of BoMRs, distance between the BoMR and the center of tag region, and distance between the service region and the tag which are dependent on installation of BoMRs — is assumed to be stored in the server or the BoMR in advance.

This estimated SNR enables judgment on the satisfaction of requirements. For R1, the criterions to make a judgment on satisfaction of R1 are different depending on arbitration methods. The estimated SNR is also used for R2, the reader receives the channel number with estimated SNR higher than the threshold and reads the tag by using the channel. R3 is satisfied when estimated noise is below the value (R3_value) that causes P1 and P3.

1) Interference Estimation

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1: for n := 1 to maximum channel number;
2: begin
3:   Calculates Estimated SNR of channel-n;
4:   if (Estimated SNR > threshold && Estimated Noise < R3_value) then
5:     begin
6:       GRANT is set as true;
7:       CHAN is set to n;
8:       Break;
9:     end;
10:  increase n ;
11: end;
```

5. Arbitration Method

This paper proposes three arbitration methods based on interference estimation with the purpose of enhancing the read success rate of UHF RFID readers. They are the Centralized Arbitration Method (CAM), Fully Distributed Arbitration Method (FDAM), and Cluster Distributed Arbitration Method (CDAM), respectively. These methods were designed to be applied in accordance with communication environment and computing power of BoMR.

A central arbitration server manages global information in CAM. It is desirable for CAM to be applied in the case where broadcast / multicast communication is not possible. It requires the smallest computing power and storage to BoMR. In FDAM, all the arbitration messages are broadcasted to every BoMR, and each BoMR decides with broadcasted global information. Events in FDAM are serialized naturally with broadcasting. CDAM forms clusters with multicasted BoMRs and a selected BoMR acts as an arbiter in the cluster. In this chapter, the operations of the three systems as well as the reader's operation in those systems are explained.

5.1 Centralized arbitration method

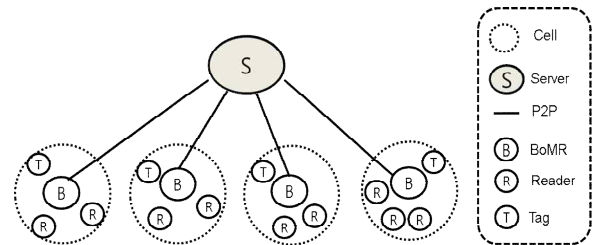


Fig. 8. The logical communication model of CAM

CAM was designed for non-broadcasting environments where the arbitration server and the BoMRs are connected logically in a star topology, as shown in Fig. 8. In this method, a BoMR has only local information on channel status, and arbitration is carried out between the readers and central arbitration server. When the request from the user is inputted, the reader transmits a REQUEST command, which is received by the BoMR and relayed to the server. The central server receives every REQUEST commands, calculates estimated SNR, makes a decision on whether grants the request or not, maintains global status of every channel according to the decision and transmits this decision to the BoMR. When an INQUIRY command is inputted from the reader, the BoMR transmits the server's decision to the reader. If the server's decision was 'Grant,' the BoMR transmits information to the server and amplifies the signal received from the reader. Since CAM processes the received REQUEST commands sequentially, simultaneous transmissions are prohibited naturally.

2) Centralized Arbitration Method

User request :

- 1: Reader sends a REQUEST command;
- 2: Reader waits for predefined duration;
- 3: BoMR relays the REQUEST to server;
- 4: **if** (Server received the REQUEST) **then**
- 5: **begin**
- 6: Server performs Interference Estimation;
- 7: Server sends the decision to the BoMR;
- 8: **end**;
- 9: Reader sends the INQUIRY command;
- 10: Reader waits RESPONSE command for T_1 ;
- 11: The BoMR sends RESPONSE to the reader;
- 12: **if** (decision is GRANT) **then**
- 13: **begin**
- 14: The BoMR is activated;
- 15: The BoMR sends its status to server;
- 16: Server updates global channel information;
- 17: Reader performs an inventory round on CHAN;
- 18: **end**;

3) Fully Distributed Arbitration Method

User request :

- 1: Reader sends a REQUEST command;
- 2: Reader waits for predefined duration;
- 3: **if** (BoMR received the REQUEST) **then**
- 4: **begin**
- 5: Broadcast REQUEST to other BoMRs;
- 6: Wait for other broadcasted REQUEST ;
- 7: Assume GRANT of other REQUEST as true;
- 8: Performs Interference Estimation;
- 9: **end**;
- 10: Reader sends the INQUIRY command;
- 11: Reader waits RESPONSE command for T_1 ;
- 12: BoMR sends RESPONSE to the reader;
- 13: **if** (decision is GRANT) **then**
- 14: **begin**
- 15: The BoMR is activated;
- 16: BoMR broadcast its status;
- 17: Every BoMR updates global information;
- 18: Reader performs an inventory round on CHAN;
- 19: **end**;

5.2 Fully distributed arbitration method

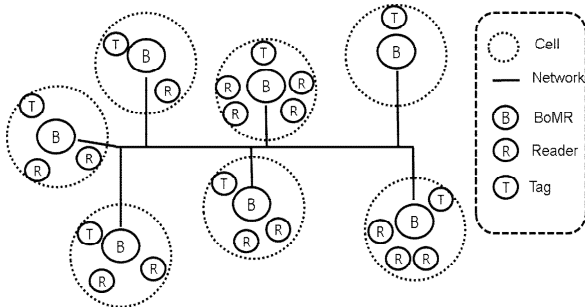


Fig. 9. The logical communication model of FDAM

FDAM was designed for broadcast communication environments. It requires largest storage and computing power to BoMR. The logical communication model of FDAM is shown in Fig. 9. In this method, each BoMR makes a decision on operations of readers in its cell with broadcasted global information. Upon receiving a REQUEST command from the reader, the BoMR calculates the estimated SNR. For this, every BoMR should have information on the state and the location of adjacent BoMRs. The information on the state of BoMRs is checked through the information broadcasted by each BoMR whenever a change arises in its state. This means that every BoMRs maintains global information on every channel status. All the information needed for the decision including the locations of BoMRs is stored in each BoMR in advance.

If each BoMR makes a local decision on operation of readers in FDAM, a couple of readers in adjacent cells can start transmission simultaneously, which means a failure to satisfy R1 and/or R2. Hence, when a REQUEST command is inputted to a BoMR, this REQUEST is also broadcasted to another BoMRs. And whether other REQUEST are received is checked for a certain interval. This means that all the REQUEST commands are serialized globally. Operation of BoMRs in FDAM is shown below.

5.3 Cluster distributed arbitration method

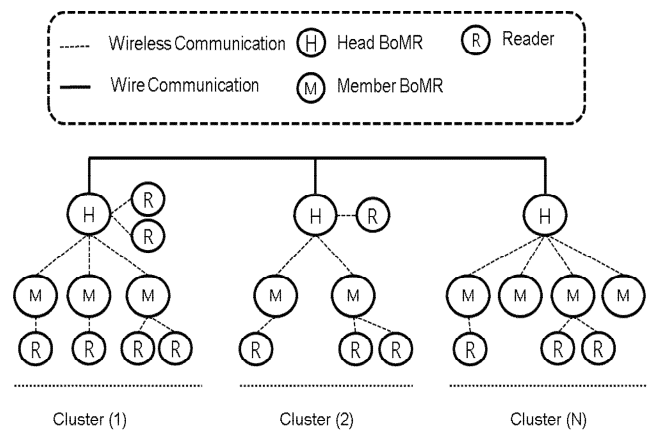


Fig. 10. The hierarchical communication architecture

CDAM was designed for multicast communication environments including Wi-Fi communication. In CDAM, a set of adjacent cells forms a cluster. One BoMR in a cluster is selected as the Head BoMR, which controls the BoMRs and the readers in the cluster.

The hierarchical communication architecture is shown in Fig. 10. BoMRs in a cluster are linked in a star topology as in CAM, and each Head BoMR is linked to broadcast, similar to FDAM.

Member BoMRs in CDAM play roles of linking readers to Head BoMR, as with the BoMRs in CAM. Like the server in CAM, upon receiving a REQUEST command from the reader in its cluster, the Head BoMR calculates the estimated SNR to make a decision. And when a change arises in the state of BoMRs in its cluster, the Head BoMR broadcasts this information to other Head BoMRs.

4) Cluster Distributed Arbitration Method

User request :

- 1: Reader sends a REQUEST command;
- 2: Reader waits for predefined duration;
- 3: **if** (Member BoMR received the REQUEST) **then**
- 4: **begin**
- 5: Relay REQUEST to Head BoMR;
- 6: Wait RESPONSE from Head BoMR;
- 7: **if** (Head BoMR received the REQUEST) **then**
- 8: **begin**
- 9: Broadcast REQUEST to other Head BoMRs;
- 10: Wait for other broadcasted REQUEST;
- 11: Assume GRANT of other REQUEST as true;
- 12: Performs Interference Estimation;
- 13: **end**
- 14: Reader sends the INQUIRY command;
- 15: Reader waits RESPONSE command for T_1 ;
- 16: BoMR sends RESPONSE to the reader;
- 17: **if** (decision is GRANT) **then**
- 18: **begin**
- 19: The BoMR is activated;
- 20: BoMR broadcasts its status to Head BoMRs;
- 21: Every Head BoMR updates global information;
- 22: Reader performs an inventory round on CHAN;
- 23: **end;**

6. Experimental Result

6.1 Simulation model

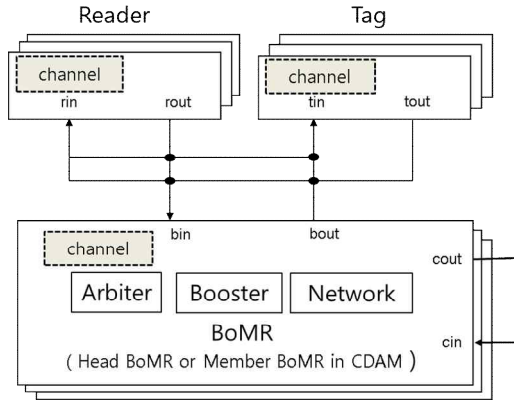
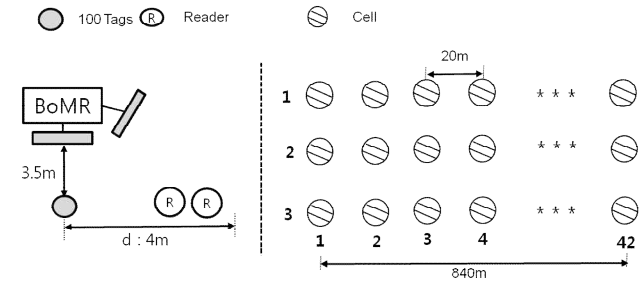


Fig. 11. Simulation model architecture

In order to compare the performance of the RFID system with BoMRs, a simulation model was constructed with the DEVS formalism described with hierarchical modules. And then it is implemented and simulated using DEVSIM++. The simulation architecture of this system is shown in Fig. 11. Readers and tags, which do not involve simultaneous operations, were implemented as an atomic model. In the case of BoMRs, however, operations for arbitration communication, signal amplification, and communication between BoMRs should be performed simultaneously. Therefore, BoMRs were designed as a coupled model, which includes three atomic models: the arbiter, booster, and network. Among these, the arbiter model performs arbitration while the booster model amplifies signals of

inventory commands and transmits them. The network model takes charge of communication with other BoMRs and the arbitration server.

RF features such as the antenna radiation pattern, the channel model, and the transmit mask of the reader, the tag, and the BoMR are the same as those in [11].



(a) Arrangement in a cell (b) Testbed

Fig. 12. Simulation model architecture

Table 1. Simulation parameters

	Parameter Name	Value
Reader	Signal Strength of Inventory round (EIRP)	15dBm
	Signal Strength of arbitration communication (EIRP)	-30dBm
	Sensitivity	-80dBm
	Link Frequency	40kHz
	The number of query rounds	2/request
	Round time	250msec
	The number of requests	250/reader
	Threshold of LBT	-70dBm
	Backoff slot time of LBT	500usec
	Listen time	5msec
	Back off time of LBT	5msec
	The maximum distance between reader and tag in a cell	4m
	Tag	Sensitivity
Backscatter-link frequency		40kHz
Differential reflection coefficient		0.5
The length of Electronic product code		96bits
BoMR	The maximum signal strength (EIRP)	33dBm
	Maximum gain	60db
	Sensitivity of arbitration communication	-80dBm
	Signal strength of arbitration communication	-30dBm
	Threshold of Estimated SNR	15db

In the simulation, BoMRs were positioned in a 3 x 42 grid, as shown in Fig. 12. To consider the effect of channel reuse, the horizontal length was set to 840m. The distance between BoMRs was set to 20m so as to enable consecutive amplification i.e., positive feedback. In each cell, 100 tags were positioned below a BoMR, with two readers, as shown in Fig. 12(a). The maximum distance between the reader and the tag (d) was set to 4m. This simulation model was constructed to meet the European regulations. The reader uses 10 channels that stipulated as maximum output of 2W in this regulation for the inventory round. As for the arbitration channel, only one channel with available output of 500mW in the regulation is used to

reduce interference with other readers. Since arbitration command is received by BoMRs, weak power does not make any problem. Table 1 shows the simulation parameter including the signal strength of each communication.

Two types of communication between BoMRs are assumed: broadcast and point-to-point communication. In the simulation, we use Ethernet communication for broadcasting. In the environment with an Ethernet switch, actual end-to-end latencies are within 20usec [13]. Therefore, 20usec was applied for the latencies due to communication in the simulation, and Wi-Fi of IEEE 802.11g was applied for point-to-point or multicast communication. Average throughput of TCP communication is set to 14.3 Mbps [14]. In the simulation, the time required for message transmission was assumed to be 500usec.

6.2 Simulation result

The performances of CAM, FDAM, and CDAM are studied in this section. For performance comparisons additional simulations are conducted. The first is the NoLBT scheme. This is a model in which no techniques to reduce signal interference between the reader and the BoMR are applied. The reader transmits inventory commands as soon as a request is inputted, and the BoMR amplifies all inputted signals.

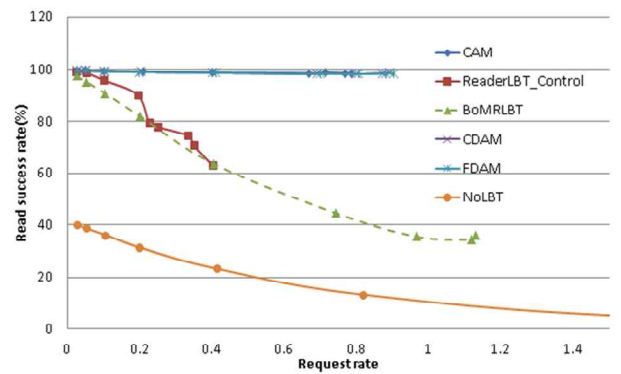
The second is ReaderLBT_Control scheme. The reader in this scheme reduces signal interference by using LBT. If, however, only LBT is used, consecutive amplification takes place. In order to prevent this phenomenon, the reader transmits a control signal to activate the BoMR before the inventory round. The third scheme is BoMRLBT. This is a model in which no communication takes place between BoMRs. The reader in this scheme also performs arbitration communication. The BoMR, however, checks the noise level of all channels through the LBT function and informs the reader whether or not to operate and available channels.

Fig. 13 shows the simulation results such as the read success rate, the throughput, and the average wait time [11] for requests. The request rate refers to the ratio of each reader's total simulation time to the total inventory round time. The inventory round time is calculated by multiplying the reader's transmission frequency by each inventory round's transmission time. The read success rate refers to the reader's read success rate. An inventory is assumed to be success only when all the tags are identified successfully. Therefore, even if just one tag was not read, such a case was regarded as a failure. The throughput refers to the average number of tags read by all readers per second. And the wait time refers to the time the reader waits for a success message after requesting tag-reading.

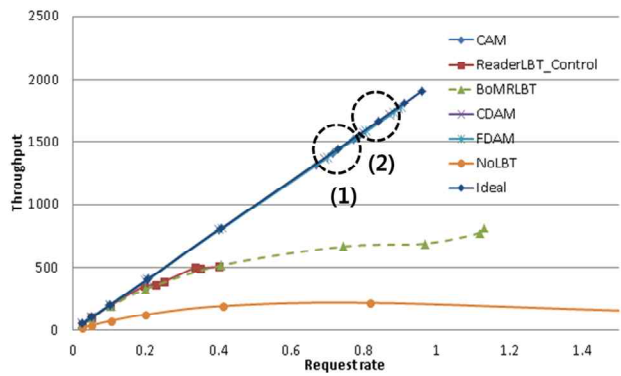
NoLBT is the most basic method and satisfies none of the requirements. Therefore, it shows the lowest read success rate and the lowest throughput, as shown in Figs. 13(a) and (b).

In the case of ReaderLBT_Control, it satisfies R1 and R2 through LBT, and R3 through control signals. Since, however, there is no communication between readers, simultaneous start of transmission can occur and results in reader collision. Hence, as the request rate rises, the number of readers simultaneously requesting increases, reducing the read success rate, as shown in Fig. 13(a). As the request rate rises, the average wait time also increases sharply due to the decreased read success rate, as shown in Fig. 13(c). Throughput is also under 500. Therefore, in the case of multiple operating readers, this scheme also cannot guarantee performance.

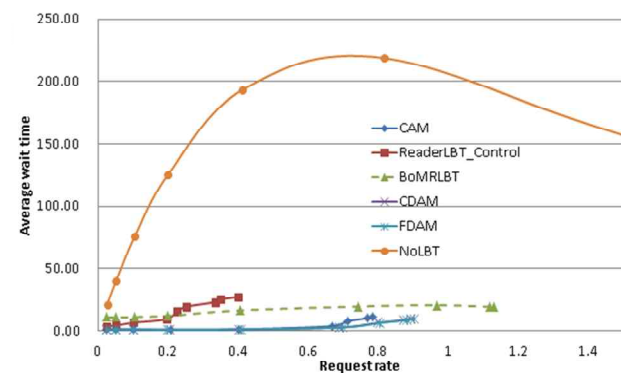
BoMRLBT has a read success rate lower than that of ReaderLBT_Control, because the BoMR instead of reader



(a) Read success rate versus request rate



(b) Throughput versus request rate



(c) Average wait time versus request rate

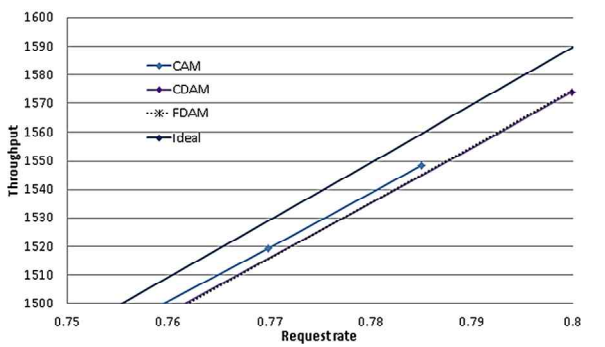
Fig. 13. Simulation results

monitors the channel by using SRAnt. The BoMR's SRAnt has directivity to enhance the reception rate of reader signals, and therefore it cannot accurately monitor the channel situation at the rear or the side. Because it cannot satisfy R1 and R2 sufficiently, it has a much lower read success rate than that of ReaderLBT_Control, as shown in Fig. 13(a). Nonetheless, the read success rate of this scheme is too low to be applied in real application.

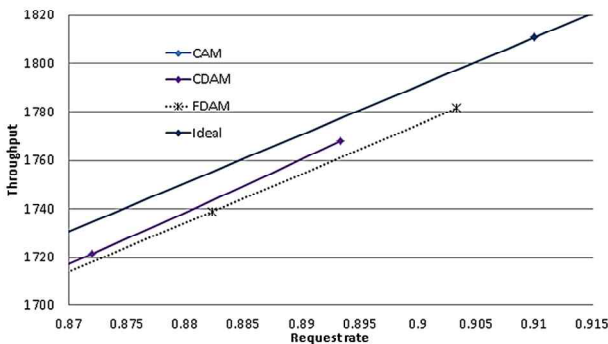
The CAM, the FDAM, and the CDAM suggested in this paper were designed to satisfy all requirements. Therefore their read success rates stand at 99% or over. As shown in graphs Figs. 13(a), (b), and (c), these three schemes present better performance in terms of average wait time, throughput, and read success rate as compared to other schemes.

Ideal scheme denotes a system that controls readers and BoMRs without any communication delay by using global information in the figures. This was simulated to measure the ideal performance in each environment. The throughputs of the three schemes show nearly those of ideal scheme.

These three schemes, however, show performance differences, as presented in Fig. 14. Figs. 14(a) and (b) show enlarged parts of the (1) and (2) in Fig. 13(b), respectively. The differences arise due to the overhead required for communication. In the case of CAM, where broadcast communication is not possible, the total simulation time is longer because of longer communication time relative to other schemes. Therefore, the maximum throughput in this



(a) Enlarged part of the (1) in Fig. 14

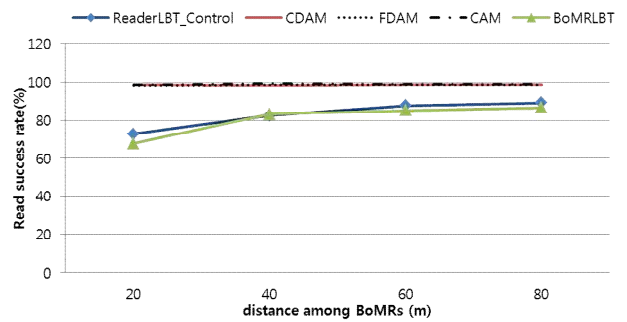


(b) Enlarged part of the (2) in Fig. 14

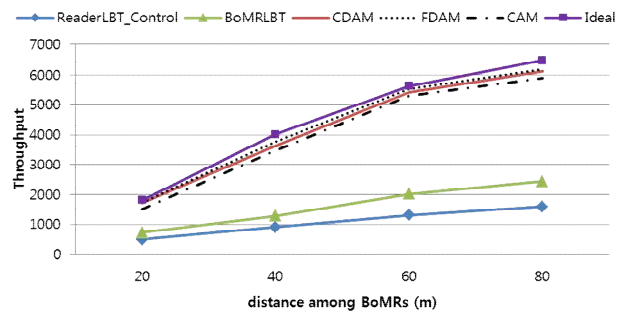
Fig. 14. Throughput

scheme is lower than those of FDAM and CDAM as shown in Fig. 14(a). In CDAM, multicast communication takes place in a cluster, and because of this overhead, CDAM has a maximum throughput lower than FDAM.

Figs. 15(a) and (b) show the throughput and the read success rate according to the distance between BoMRs. The distance between BoMRs can vary depending on the requirement of service. Performance comparisons were made at distances of 20m, 40m, 60m, and 80m, respectively. As the distance between BoMRs increases, the read success rates of CAM, CDAM, and FDAM schemes slightly increase. In addition, the performance ranking of all schemes is the same regardless of the distance between BoMRs. The throughput in graph (b) increases as the distance increases, because the number of channels simultaneously operating, i.e. parallelism increases due to channel reuse. The throughput at a distance of 40m is doubled compared with that at 20m, and the throughput at 60m and at 80m shows a three-fold and a four-fold increase, respectively.



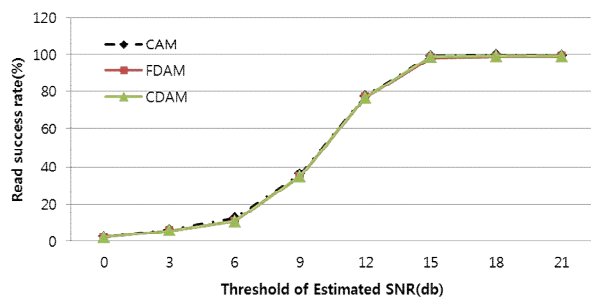
(a) Read success rate versus distance among BoMRs



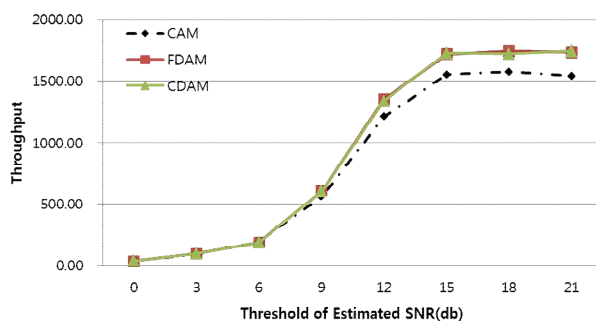
(b) Throughput versus distance among BoMRs

Fig. 15. Simulation result versus distance among BoMRs

Fig. 16 shows the performance versus threshold of Estimated SNR. It shows some tradeoff between BER and parallelism. As the threshold rises, read success rate increase due to the lowered BER. If the threshold is over 15db, read success rate stand at 99% or over. Throughput also increases as the threshold rises and if the threshold approaches 15db, it shows highest performances. However, when the threshold is over 15db, throughputs are decreased since some parallelism, i.e. the effect of channel reuse may be lost.



(a) Read success rate versus threshold



(b) Throughput versus threshold

Fig. 16. The performance versus threshold

7. Conclusion

The UMRR enables various services through a wireless network, but reveals some limitation due to its low power emission. In order to expand the range of UMRR, BoMR has been developed. But installation of multiple BoMRs may bring some problems such as positive feedback. In this paper, the problems are analyzed and some requirements are derived for effective operation of multiple BoMRs. And three arbitration methods, i.e. CAM, FDAM, and CDAM, to meet the requirements are presented. They can be applied in accordance with communication environment and computing power of BoMR.

Central arbitration server manages global information in CAM without a broadcast/multicast communication facility. In FDAM, all the arbitration messages are broadcasted to every BoMR, and each BoMR decides with broadcasted global information. Events in FDAM are serialized naturally with broadcasted messages. CDAM forms clusters with multicasted BoMRs and a selected BoMR acts as a local arbiter in the cluster.

In order to measure the performance of the RFID system with BoMRs and proposed arbitration schemes, a simulation model was constructed with DEVS formalism. And then it is implemented and simulated using DEVSIM++. The simulation results shows that their read success rates stand at 99% or over even in relatively high request rate.

Acknowledgements

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Si-Young Ahn He received B.S, M.S. and Ph.D. degrees in 2003, 2007 and 2012, respectively, from Kookmin University, Korea, all in electrical engineering. He was a Postdoctoral researcher with Department of Electrical Engineering at Illinois Institute of Technology at Chicago, in 2013. His research interests are sensor network, computer science and embedded system.



Ha-Ryoung Oh He received B.S degree in electrical engineering from Seoul National University, Seoul, Korea, in 1983 and M.S. and Ph.D. degrees in electrical engineering from Korea Advanced Institute of Science and Technology, Daejeon, Korea, in 1988 and 1992, respectively. Since 1992, he has been a professor with Kookmin University, Seoul. His current research interests include RFID system, wireless sensor networks, Internet of Things and embedded system.



Jun-Seok Park He received his B.S. and M.S. degrees in electronic engineering and his Ph.D. degree in radio frequency and monolithic microwave and integrated circuits from Kookmin University, Seoul, South Korea, in 1991, 1993 and 1996, respectively. In 1997, he joined the department of electrical engineering at the University of California at Los Angeles, where he was a postdoctoral researcher. From 1998 to 2003, he was a professor in the division of information technology engineering at Soonchunhyang University, Asan, South Korea. He is currently an assistant professor at Kookmin University's school of electrical engineering. His current research involves RF and microwave hybrid module design using low temperature co-fired ceramic (LTCC) techniques and surface acoustic wave devices.



Yeong Rak Seong He received B.S degree in electronic engineering from Hanyang University, Seoul, Korea, in 1989 and the M.S. and Ph.D. degree in electrical engineering from Korea Advanced Institute of Science and Technology, Daejeon, Korea, in 1991 and 1995, respectively. Since 1996, he has been with Kookmin University, Seoul, where he is currently a professor. His current research interests include real-time systems, wireless sensor networks, and discrete event system modeling and simulation.