

Wireless Fieldbus for Networked Control Systems using LR-WPAN

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Abstract: This paper examines the use of a wireless Fieldbus based on IEEE 802.15.4 MAC protocol. The superframe of IEEE 802.15.4 is applied to a transmission scheme of real-time mixed data. The transmission and bandwidth allocation scheme are proposed for real-time communication using a superframe. The proposed wireless Fieldbus protocol is able to transmit three types of data (periodic data, sporadic data, and non real-time messages), and guarantee real-time transmission simultaneously within a limited timeframe.

Keywords: IEEE 802.15.4, networked control systems, real-time transmission scheme, wireless fieldbus.

1. INTRODUCTION

In an industrial network, the field level network connecting sensors and actuators plays a significant role in the networked control system (NCS). At the field level network of factory automation, I/Os, PLCs, sensors, and actuators are connected with a real-time control network. These networks are referred to as the Fieldbus.

The industrial environment is composed of a number of sensors, actuators and I/Os. Most transmitted I/O data other than network maintenance data are less than 1 byte [1]. The Fieldbus should be able to transmit real-time periodic data, sporadic data for alarm and non real-time message data for network maintenance [2]. Because of these limitations, existing Fieldbuses are based on wired technology.

With advancements in wireless technology, a wireless network can be integrated into an existing Fieldbus system [3]. The wireless Fieldbus has strengths based on mobility, ease of installation and maintenance due to the lack of cabling. In general, the industrial environment is error prone and the reliability of wireless technology is lower than wired one. Therefore, it is difficult to support a real-time transmission and multiple I/O nodes in the industrial

environment.

For these reasons, it is necessary to design a wireless Fieldbus which can support multiple nodes and guarantee real-time transmission of mixed traffic in an industrial environment. In general, commercial wireless technologies (IEEE 802.11(WLAN), IEEE 802.15.1(Bluetooth), and IEEE 802.15.4(LR-WPAN)) can be applied to the wireless Fieldbus or hybrid industrial network.

There have been some studies on the hybrid Fieldbus technology using IEEE 802.11 [4-7]. The hybrid Fieldbus technology based on Profibus was presented for wireless extension [4,5]. In [6,7], the wireless Fieldbus, called R-fieldbus, based on IEEE 802.11 was described. However, IEEE 802.11 nodes are expensive and have reliability limitations. In general, multiple nodes are required in an industrial environment. Therefore, the wireless Fieldbus based on IEEE 802.11 is limited by high installation and maintenance costs.

A wireless Fieldbus based on Bluetooth technology has been proposed [8] because of its low cost and fast transmission rate, however it is composed of few nodes and has a small coverage area. Hence, it is difficult to apply in large factory area where multiple nodes are required.

A low rate wireless personal area network (LR-WPAN, IEEE 802.15.4) have been suggested [9]. The LR-WPAN was proposed for data gathering and control through wireless sensors. The coordinator node of the LR-WPAN can manage multiple nodes and support wide range by mesh network [10]. Each node of the LR-WPAN is inexpensive and a coordinator node can support multiple I/O nodes. However, it cannot handle mixed real-time traffic efficiently. Therefore, an efficient transmission of mixed real-time traffic is required for industrial applications.

In this paper, an efficient transmission scheme is

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proposed for the use of a wireless Fieldbus using a superframe of IEEE 802.15.4. To the best knowledge of the authors, the wireless fieldbus based on IEEE802.15.4 has not been reported on in technical literature.

This paper is organized as follows. Section 1, describes existing Fieldbus technologies. Then, the proposed wireless Fieldbus is compared to existing Fieldbuses. In Section 3, a design scheme for the wireless Fieldbus based on IEEE 802.15.4 is presented. In Section 4, simulation results are provided to show that the proposed wireless fieldbus is useful. The conclusions are presented in Section 5.

2. WIRED/WIRELESS FIELDBUS TECHNOLOGY

The maximum transmission range according to data rate and the number of allocable nodes of existing wired & wireless Fieldbuses are shown in Table 1. Profibus and DeviceNet can support 500 kbps within 200m and 100m, respectively. However, as the transmission range increases more, the data transmit more slowly. The transmission range of a wired Fieldbus depends on the length of trunk line. Therefore, the length of trunk line and the location of nodes should be considered in order to ensure desired transmission rates. A wireless Fieldbus, is connected peer to peer. Hence, nodes can be assigned more freely than wired technologies.

This paper aims to design a wireless Fieldbus which can guarantee response times around 100ms and consist of multiple nodes. The R-fieldbus, which is one of existing wireless Fieldbuses, supports high rates transmission up to 2Mbps. However, an R-fieldbus network may only be composed of up to 30 nodes which is considered low. The Elpro is a commercial wireless Fieldbus. The transmission rate of the Elpro is 4.8kbps and the transmission time is 80ms [11]. Hence, this wireless Fieldbus can't support short response times of 100ms.

Table 1. Comparison table between wired & wireless Fieldbuses.

	Name	Segment length(m)	Data rate (kbps)	Nodes
Wired	Profibus	1200	93.75	32
		600	182.5	
		200	500	
	DeviceNet	500	125	64
		250	250	
		100	500	
Wireless	R-Fieldbus	100	2000	30
	Elpro [11]	2000	4.8	95

The proposed wireless Fieldbus can manage up to 255 multiple nodes. Although IEEE 802.15.4 technology supports low rate transmission, the response time of the proposed wireless Fieldbus can be guaranteed within 100ms by using proper bandwidth allocation and traffic control. The proposed wireless Fieldbus based on IEEE 802.15.4 can be applied to multiple I/O nodes in large automated factory area.

3. WIRELESS FIELDBUS BASED ON IEEE 802.15.4

3.1. Superframe of IEEE 802.15.4

In general, the superframe structure of IEEE 802.15.4 can be described as shown in Fig. 1 [9]. For low power consumption, the superframe of IEEE 802.15.4 can be divided into two periods: active and inactive. The active period is from the start of the beacon frame to the end of contention free period (CFP). In this period, every node can transmit data. From the end of the CFP to the start of next beacon frame, the inactive period, all nodes turn off their radio, and set a timer to wake itself.

The active period is composed of beacon broadcast, contention access period (CAP), and the CFP. The active period is divided into 16 equal sized slots. A maximum of 7 slots can be allocated to the CFP. These slots are used in the guaranteed time slot (GTS). The remaining slots are used during the beacon and the CAP periods.

At the start of the superframe, the beacon frame is broadcasted by the coordinator for synchronization and configuration of nodes. The beacon frame contains the superframe specification field which adjusts the superframe structure including the length of the superframe, active period, inactive period, and CAP. The beacon frame structure is shown in Fig. 2.

After the beacon frame period, the CAP is started, IEEE 802.15.4 protocol can use two types of MAC protocol, un-slotted or slotted carrier sense multiple access (CSMA). In a beacon enabled mode, the slotted CSMA is used. In the CAP, every node tries to access a slotted CSMA channel. The length of the CAP is

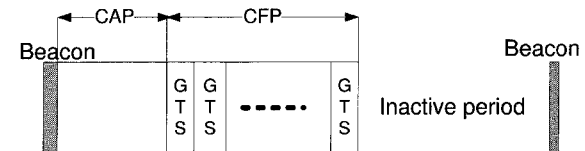


Fig. 1. Superframe structure of IEEE 802.15.4.

6 Byte	2 Byte	1 Byte	4 / 10 byte	2 byte	variable	variable	2Byte		
Sync. header	PHY header	Frame Control	Seq. number	Addr. Info.	Superframe spec.	GTS field	Pending addr. field	Beacon payload	FCS

Fig. 2. Beacon frame structure of IEEE 802.15.4.

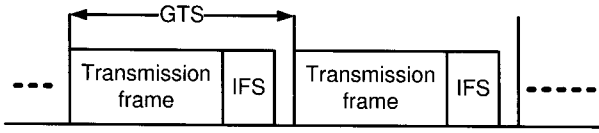


Fig. 3. Interframe space in the GTS.

determined by final CAP slot bits in the superframe specification field of the beacon frame. The CAP has length of at least 7ms.

The CFP appears at a slot boundary immediately following the CAP. Allocated slots are assigned GTSs by the coordinator. The coordinator determines the GTS allocation for nodes, and broadcasts beacon frames containing this information into the GTS list fields. In the CFP, all nodes are accessed to channel by time division multiple access (TDMA) protocol using their appointed slot. The nodes can transmit their data from its slot without contention. After data transmission, the interframe space (IFS) occurs before the boundary of the allocated GTS as shown in Fig. 3.

3.2. Transmission scheme of three types of data

In order to transmit three types of data effectively, the real-time periodic data is transmitted in the CFP while real-time sporadic data and non real-time message are transmitted in the CAP. The inactive period is defined to zero to reduce delay. Fig. 4 shows the modified superframe structure.

The length of a superframe can be determined by (1),

$$\begin{aligned} T_{SF} &= T_{BD} \times 2^{SO}, \\ T_{BD} &= 480\text{Byte}, \quad 0 \leq SO \leq 15, \end{aligned} \quad (1)$$

where the T_{SF} is the length of a superframe. The T_{BD} represents the base superframe duration that is a constant of a mac sublayer. The SO stands for the superframe order and can be set at MAC PIB. The transmission rate of IEEE 802.15.4 is 250kbps. Hence, if SO is defined to zero, the duration of the superframe is 15.36ms. If some data needs a transmission period less than 15.36ms, it cannot be transmitted.

Because most of the data in an industrial environment is periodic, the maximum number seven

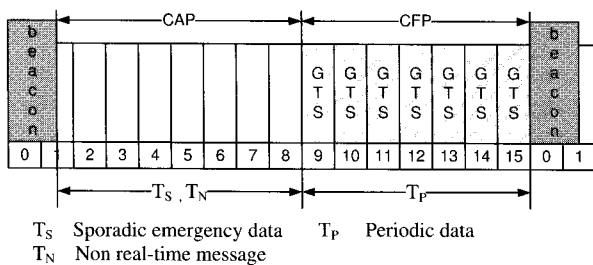


Fig. 4. Frame structure of modified superframe.

slots are allocated the CFP. The coordinator should determine the number of allocated GTSs of nodes in consideration of both the length of data and the IFS. If the data frame format of IEEE 802.15.4 is transmitted in a no-acknowledge mode, the number of allocated GTS can be calculated by (2).

$$\begin{aligned} T_{NGT} &= \left\lceil \frac{T_O + T_d + IFS}{T_{slot}} \right\rceil, \\ (T_{slot} &= T_{Bslot} \times 2^{SO}, T_{Bslot} = 30\text{Byte}), \end{aligned} \quad (2)$$

where $IFS = \begin{cases} T_d \leq 5\text{Byte}, IFS = SIFS = 6\text{Byte} \\ T_d > 5\text{Byte}, IFS = LIFS = 20\text{Byte} \end{cases}$, $\lceil Z \rceil$

is the smallest integer larger than or equal to the value Z . T_{NGT} represents the number of allocated GTSs. T_O is the length of the remainder of the frame except for the payload in data frame format of IEEE 802.15.4. T_d is the length of transmitting data. The T_{slot} and T_{Bslot} represent the none slot duration and the base slot duration, respectively. By (2), in the case of a 2 byte address mode where the data size is less than 5 Byte, T_{NGT} is 1 regardless of T_{slot} .

The CAP occupies more than half the size of the superframe. Therefore, it is necessary to manage the bandwidth of the CAP to improve real-time performance. In the CAP, real-time sporadic data and non real-time message data can be transmitted. The priority between sporadic and non real-time messages can be assigned by upper layer protocol. In Fig. 5, the flow chart of bandwidth allocation in the CAP is

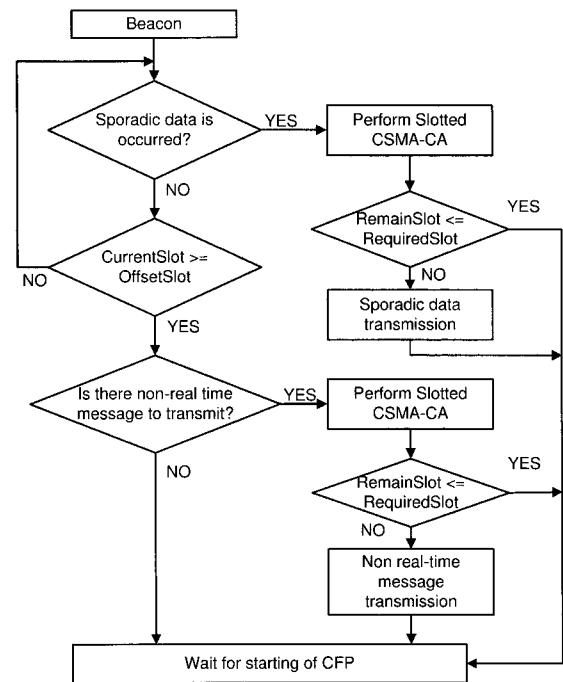


Fig. 5. Flow chart of procedure on CAP.

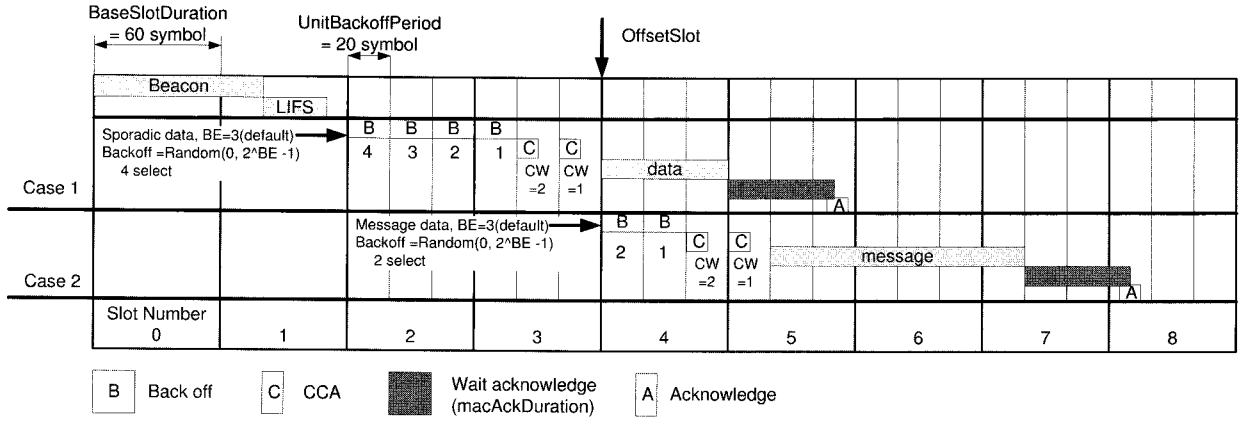


Fig. 6. Timing chart of the CAP.

described.

The CAP is started when beacon frame ends, then the sporadic nodes try to access channels immediately. The sporadic node succeeding in channel access compares the number of slots required to transmit with the remaining slots in the CAP. If the number of remaining slots is larger than required, the node starts transmission. This case is described in the case 1 of Fig. 6.

The non real-time message node can access to a channel after the *offsetSlot* as shown in the case 2 of Fig. 6. The *offsetSlot* can be used to give priority channel access to the sporadic node.

3.3. GTS allocation

The modified GTS request frame is used for maintenance of periodic nodes. In the modified GTS request frame, the 1 byte deadline field is added to the existing GTS request frame. The deadline field contains deadline information for periodic data. The coordinator has the GTS allocation table which includes the addresses and deadlines of periodic nodes. Using this table, the coordinator allocates the GTSs to the periodic nodes.

The real-time performance depends on the length of the basic period. The basic period is used to schedule periodic nodes and determine the transmission period for periodic data [2]. In this paper, the superframe duration is used as the basic period. For the GTS allocation, the multiple of the superframe duration is determined for the task period of each node. By the deadline of each node, the task period of the i th real-time periodic data is calculated by (3)

$$T_{TP}^i = \left\lfloor \frac{T_D^i}{T_{SF}} \right\rfloor \times 16, \quad (3)$$

where $\lfloor Z \rfloor$ is the largest integer smaller than or equal to the value Z . T_{TP}^i represents i th task period. T_D^i indicates the deadline of i th node. The

number of usable GTSs which the i th real-time periodic node can use within its task period, can be written as

$$T_{UGT}^i = \frac{T_{TP}^i}{16} \times 7, \quad (4)$$

where T_{UGT}^i represents the usable GTSs of i th node. Knowing the number of the usable GTSs of each node, the GTS allocability can be checked using the following equation (5)

$$U_{GTS} = \sum_{i=1}^n \frac{1}{T_{UGT}^i} \leq 1, \quad (5)$$

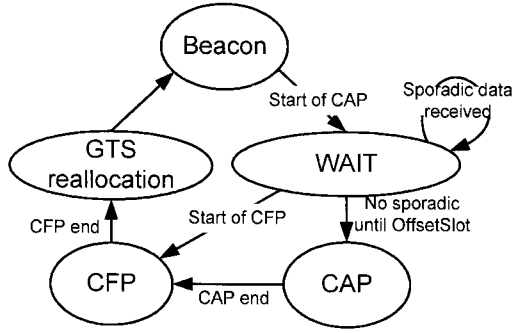
where U_{GTS} represents the GTS utilization. If (5) is not satisfied, the GTS cannot be allocated.

When a new periodic node is added to the existing network, the GTS allocation procedure is as follows:

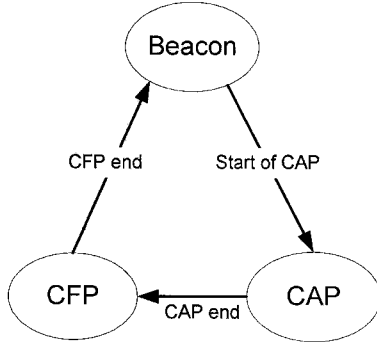
1. An inserted periodic node transmits the modified GTS request frame to the coordinator after the beacon period.
2. The coordinator determines the task period by (3) and checks the GTS allocability by (5).
3. $U_{GTS} \leq 1$, the coordinator reschedules and reallocates.
4. $U_{GTS} > 1$, the coordinator rejects the GTS request of the periodic node.

The periodic nodes can be scheduled using the earliest deadline first(EDF) algorithm. Before the beacon frame broadcasts, the coordinator reschedules the periodic nodes using the EDF algorithm and allocates the GTSs to the periodic nodes. After the periodic nodes transmit data at the allocated GTS, the information is removed in order to allow new GTS information to be obtained for the next superframe.

Fig. 7 shows the state transition diagrams of both the coordinator and the device. The coordinator has a WAIT and GTS reallocation state unlike the device. During the WAIT state, the coordinator checks the



(a) Coordinator.



(b) Device.

Fig. 7. State transition diagrams.

sporadic data occurrence. In the GTS reallocation state the coordinator updates the GTS list for periodic data.

4. SIMULATION RESULTS

By the proposed transmission algorithm, the real-time periodic data and the sporadic and message data are transmitted independently in CFP and CAP. Therefore, they cannot have an effect on each other.

Firstly, the transmission of real-time periodic data is simulated. For a simulation, the following assumptions are used:

- The multi-hop communication is not considered.
- It operates in 2.4Ghz/250kbps.
- In a CFP, the real-time periodic data is transmitted by the data frame format and the no-acknowledge mode is used.
- The length of real-time periodic data is lower than 5byte.

The first and second assumptions are considered for the reduction of a transmission delay. The third and fourth assumptions are used to allocate one GTS to a periodic node. For the simulation, the network is configured with ten nodes for real-time periodic data on Table 2.

In Table 2, the T_D , T_{TP} , and T_{UGT} of each node is described. The T_{TP} and T_{UGT} can be obtained by (3) and (4), respectively. By (5), the U_{GTS} can be

Table 2. Deadline, task period, and usable GTS of each periodic node.

Node No.	T_D (ms)	T_{TP} (slot)	T_{UGT} (slot)
1~3	20	16	7
4~8	50	48	21
9~10	100	96	42

Table 3. Result of GTS allocation.

Beacon No.	Allocated Node No.						
	1	1	2	3	4	5	6
2	1	2	3	8	9	10	C
3	1	2	3	C	C	C	C
4	1	2	3	4	5	6	7
5	1	2	3	8	C	C	C
6	1	2	3	C	C	C	C

obtained as $U_{GTS} = \frac{1}{7} \times 3 + \frac{1}{21} \times 5 + \frac{1}{42} \times 2 = 0.71$. Hence, the GTSs can be allocated to periodic nodes.

In Table 3, the GTS allocation results are shown. Table 3 shows the consecutive six superframes. The node numbers at a CFP are shown at Table 2. The empty GTSs are allocated to the network maintenance by the coordinator.

For performance evaluation in CAP, following network and configuration are tested. Three real-time sporadic nodes are tested. Each node generates 30, 20, and 10 packets per second, respectively. A non real-time message node, which generates packets continuously, is implemented. The coordinator node receives real-time sporadic and non real-time message data simultaneously.

The simulation results are shown in Figs. 8 and 9. The X axis represents the size of *OffsetSlot*. The Y axis in Fig. 8 represents mean value for time interval of received non real-time message data. The Y axis in Fig. 9 represents mean delay of received real-time sporadic data. It can be expressed as follows:

$$M_{Rcv} = \frac{\sum_{i=1}^n \{T_g^i - T_R^i\}}{n},$$

where T_g^i and T_R^i are the generation and reception time of i -th data. n is number of transmitted data.

In Fig. 8, if the size of *OffsetSlot* is increased or the number of packet generation of the real-time sporadic data is decreased, the mean time interval of received non real-time message data is increased. In other words, the probability of non real-time message data

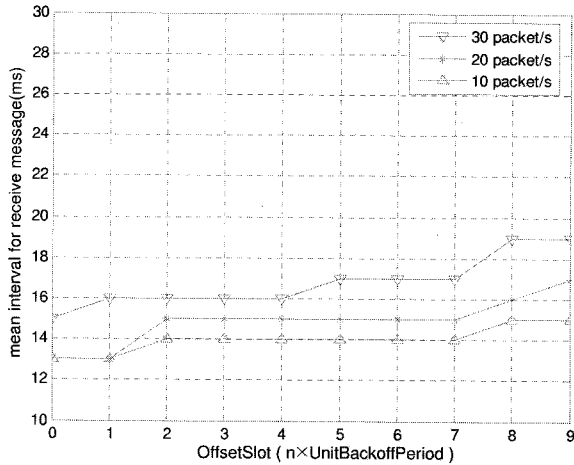


Fig. 8. Mean of reception period of message data.

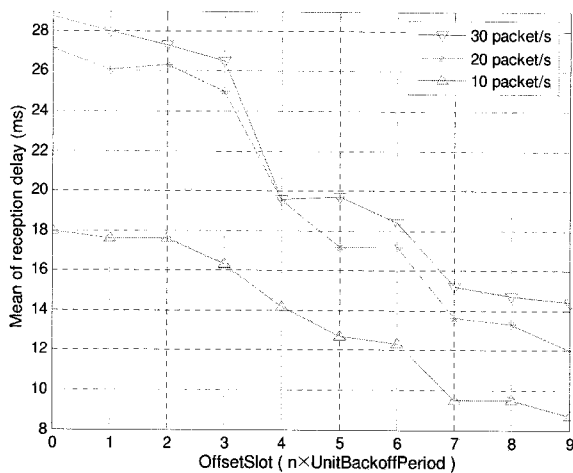


Fig. 9. Mean of reception delay.

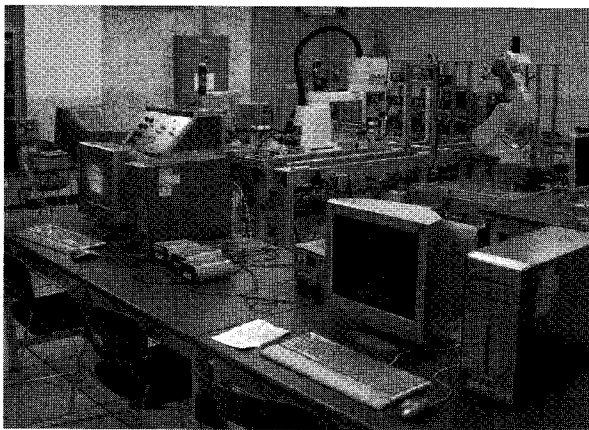


Fig. 10. CIM system used for testbed.

transmission decreases. In Fig. 9, the size of *OffsetSlot* is increased, the M_{Rcv} is decreased. Therefore, the real-time performance of sporadic data is improved by increasing *OffsetSlot* size, which gives priority to sporadic data.

The proposed wireless Fieldbus was implemented using CC2430 Zigbee development kit (ZDK) [12].

The proposed methods were tested at computer integrated manufacturing (CIM) plant on Fig. 10.

5. CONCLUSION

In this paper, a wireless Fieldbus based on the IEEE 802.15.4 is proposed. The proposed wireless Fieldbus provides reliable data transmission using a superframe based on IEEE 802.15.4 MAC protocol. The transmission and bandwidth allocation schemes are proposed to guarantee the transmission of the real-time mixed data.

Periodic data is transmitted using the GTS in the CFP. By distributing the CAP properly, the sporadic and non real-time messages are transmitted effectively. The designed wireless Fieldbus can guarantee transmission of real-time periodic and sporadic data within desired time limits.

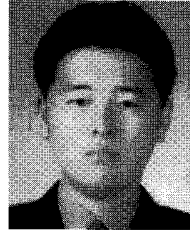
As a future direction of this work, one may consider beacon scheduling for multi-coordinators and dynamic GTS scheduling as well as allocation algorithms.

REFERENCES

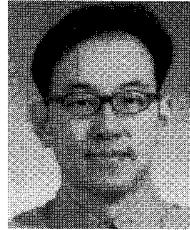
- [1] R. Patzke, "Fieldbus basics," *Computer Standards & Interfaces*, Elsevier Science, vol. 19, no. 5/6, pp. 275-293, 1998.
- [2] D. S. Kim, Y. S. Lee, W. H. Kwon, and H. S. Park, "Maximum allowable delay bounds of networked control system," *Control Engineering Practice*, vol. 11, no. 11, pp. 1301-1313, November 2003.
- [3] A. Willig, K. Matheus, and A. Wolisz, "Wireless technology in industrial networks," *Proc. of the IEEE*, vol. 93, no. 6, June 2005.
- [4] A. Willig, "An architecture for wireless extension of PROFIBUS," *Proc. of the 29th Annual Conference on Industrial Electronics Society*, vol. 3, pp. 2369-2375, 2003.
- [5] S. Lee, K. C. Lee, M. H. Lee, and F. Harashima, "Integration of mobile vehicles for automated material handling using Profibus and IEEE 802.11 networks," *IEEE Trans. on Industrial Electronics*, vol. 49, no. 3, pp. 693-701, June 2002.
- [6] L. Rauchhaupt, "System and device architecture of a radio based fieldbus-the RFieldbus system," *Proc. of the 4th IEEE International Workshop on Factory Communication Systems*, pp. 185-192, 2002.
- [7] J. Haehnliche and L. Rauchhaupt, "Radio communication in automation systems: The R-fieldbus approach," *Proc. of IEEE International Workshop on Factory Communication Systems*, pp. 319-326, September 2000.
- [8] D. Dzung, J. Endresen, C. Apneseth, and J. Frey, "Design and implementation of a real-time

wireless sensor/actuator communication system,” *Proc. of the 10th IEEE Conference on Emerging Technologies and Factory Automation*, vol. 2, pp. 433-442, September 2005.

- [9] IEEE Computer Society, *IEEE 802.15.4 standard : Wireless Medium Access Control and Physical Layer Specifications for Low-Rate Wireless Personal Area Networks*, IEEE, New York, 2003.
- [10] N. Baker, “ZigBee and bluetooth strengths and weaknesses for industrial application,” *Computing & Control Engineering*, vol. 16, no. 2, pp. 20-25, 2005.
- [11] Elpro Technology, *User manual-105U Radio Telemetry module*, Elpro Technology, Australia, 2004.
- [12] Chipcon web site, <http://www.chipcon.com/>



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