Delay and Reliability Evaluation of Industrial Wireless LAN System

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***Abstract*—In this paper, an industrial wireless LAN including a Media Access Control (MAC) layer and a Physical (PHY) layer based on the industrial communication standard is described. The hardware implementation is processed on Software Defined Radio (SDR) platform which provides fast processing for the hardware and software co-design. The experimental results show that the proposed wireless system can control up to four motors with 500 *us* to 750 *us* per motor which has a lower transmission time compared to PROFINET wireless standard. On the other hand, the high reliability of this system is also considered in this paper. It is important to formulate the communication error rate because it takes a long time to verify by the simulation. We need to investigate a quantitative evaluation method from the formulation of the communication error rate and evaluate the reliability of the system. This paper shows the evaluation results that reliability can be guaranteed even after three years of operation by performing at least one re-transmission time of the system which is suitable to the industry wireless communication standard.**

I. Introduction

In recent years, wireless technology has been attracting attention as an effective means of industrial communication because of its flexibility in adapting to mobile terminal settings (e. g. , robots, actuators, sensors, etc.). Some studies related to industrial wireless communication systems were discussed, such as industrial positioning [1], industrial Bluetooth [2], industrial ZigBee [3], industrial communication standard WirelessHART [4] and PROFINET [5]. However, WirelessHART lacks compatibility with IEEE 802.11 wireless LAN devices which made it difficult to work with standard office devices such as PCs, laptops, and mobile phones in factory environments where wireless LAN connections are legacy wireless communications. To address these requirements, PROFINET has offered an industrial WLAN system using the industrial point coordination function (iPCF) protocol. However, unfortunately, this protocol only achieves low throughput because it uses a time-division multiple access (TDMA) scheme and supports a single-user (SU) transmission. Therefore, this protocol's performance can not meet the real-time requirements of FA systems in dense networks with a large number of robots (terminals), such as in FA environments.

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The novel iWLAN protocol is proposed to address the limitation of iPCF protocol, as presented in [6]. This protocol introduces a low overhead multiple-access Downlink (DL) and Uplink (UL) transmission scheme for the fast communication system. Packet Division Multiple Access (PDMA) transmission scheme with multi-user access is employed for DL communication, while Frequency Division Multiple Access (FDMA) is employed in UL transmission. Co-operating with the multi-user technique, this transmission protocol can significantly eliminate the overhead and able to achieve high throughput. On the other hand, the industrial network used in the actual FA environment requires that the data transmission be performed normally between the terminals even if the system is operated for several years [7]. Therefore, it is necessary to evaluate the transmission performance of long-term communication in addition to the evaluation of single data transmission in the verification of the actual machine. However, in verification using actual equipment, conditions such as how long the execution period should be secured in order to evaluate sufficient reliability. Since the number of samples of data that can be obtained is limited, it is considered difficult because the reliability of the data cannot be guaranteed. Therefore, in this research, by formulating the communication error rate of the proposed industrial wireless LAN system, we propose a method to quantitatively evaluate the reliability of the system.

In this paper, we implement and verify the design of a MAC-PHY system supporting PDMA and FDMA transmission schemes on an FPGA board and evaluate the delay of transmission time between AP and STA. In addition, we also evaluate the reliability of the system by simulation. The rest of this paper is organized as follows. Section II introduces a system overview of FA-WLAN PHY and MAC design. Section III explains the communication error rate of the entire system when using the proposed system in industrial wireless communication. Section IV describes the verification methods, and results, and evaluates the proposed system. Finally, the conclusions of this paper are provided in section V.

II. Design of Proposed System

In this section, we describe a proposed industrial wireless LAN system (iWLAN) as in Fig. 1. An AP is connected to the Programmable Logic Controller (PLC) side in the conventional high-speed control communication system for industrial robots. An STA is connected to several industrial Robots (iRBs) sides to make the system wireless. The FA-WLAN system consists of MAC and PHY layer transmission technology to communicate between the PLC and iRB.

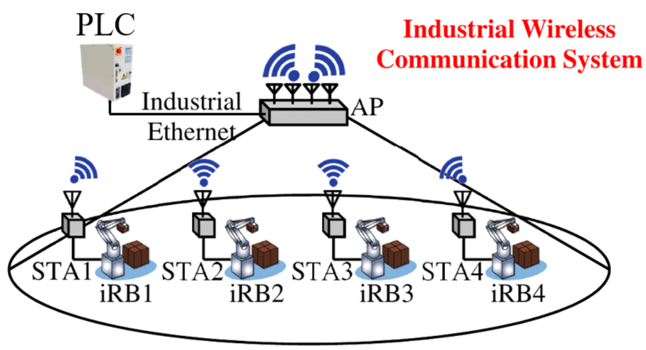

Fig. 1. System Model for 4 iRBs

A. Physical Layer (PHY)

This section describes the specification of the physical layer of the proposed industrial wireless LAN system. The system communicates between APs and STAs in the 5[GHz] band used in IEEE802.11. In the control communication of industrial robots, control data must be sent and received reliably at a fixed and predetermined time. Therefore, it is assumed that the communication channel acquired in advance before the communication starts in this system is always secured until the end of the system communication.

In downlink (DL) communication, Packet Division Multiple Access (PDMA) is used in which the AP combines data addressed to multiple STAs into a single frame and adds MAC and PHY headers for multicast transmission. PDMA is a communication method originally developed for the proposed system, which can be used when data confidentiality is not required between STAs and is effective in cases where managers share common control information, such as control communication for industrial robots in the FA field. In the UL communication, each STA can communicate simultaneously by assigning 20 *MHz*, which is the minimum bandwidth unit in IEEE802.11, to each STA using FDMA. In the proposed system, the communication is performed in one of the bandwidths supported by IEEE802.11ac, namely 20/40/80 *MHz*. Fig. 2 shows the communication methods for communication using the communication bandwidth of 80 *MHz*.

The specification of the PHY transceiver is compliant with the IEEE 802.11ac standard as well as supporting PDMA and FDMA technology. Table I shows the important parameters for PHY design.

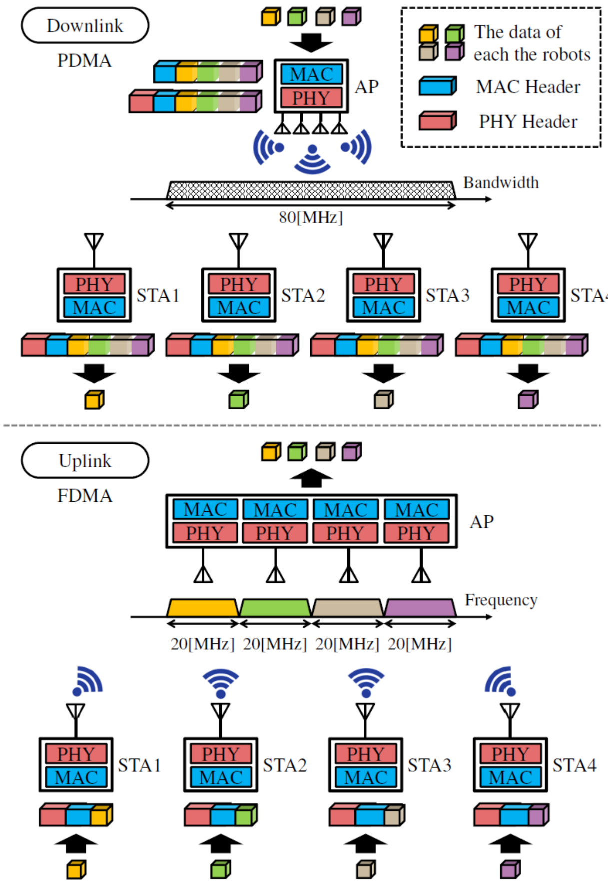

Fig. 2. Proposed Multiple Access Transmission Scheme (80 *MHz*)

TABLE I
PHY Transceiver System Specification

Parameters	Supported Values
Number of Antennas	1-4
Packet Mode	Legacy, Mixed HT, Mixed VHT
Channel Bandwidth	20 *MHz* / 40 *MHz* / 80 *MHz*
FFT Point	64/128 Points
Guard Interval (GI) Duration	0.4 and 0.8 μs
Forward Error Correction (FEC) Code	Convolutional Code

B. Media Access Control (MAC)

In this section, we describe the MAC layer specification of the proposed industrial wireless LAN system. In the MAC layer, we describe a method to enable real-time communication and a frame format that supports PDMA and FDMA. The method of frame generation on hardware is described in detail in our previous work [8]. The protocol diagram of the proposed FA-WLAN is shown in Fig. 3.

The protocol sequence behavior consists of three stages.

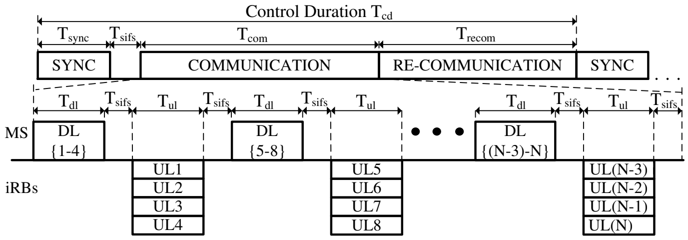

Fig. 3. Proposed FA-WLAN Protocol.

- Stage 1 (SYNC): PLC starts a new control duration (Tcd) by broadcasting a synchronization (SYNC) frame to all iRBs on the bandwidth of 20/40/80 *MHz*. SYNC frame carries the information of the Precision Time Protocol (PTP). The duration of SYNC frame transmission is denoted by Tsync.
- Stage 2 (COMMUNICATION): PLC communicates with all *N* iRBs. This communication duration is denoted by T_{com}. This interval includes the following operations:
  - DL transmission: After the wait of SIFS duration (T_{sifs}), PLC transmits the Multi-User Downlink (MU-DL) frame to iRBs on the bandwidth of 20 or 40 or 80 *MHz*. We support MU-DL frames of up to 4 users using the PDMA technique. The values of *u* can be 1, 2, 3 or 4. The duration of DL transmission is denoted by T_{dl}.
  - UL transmission: If iRB successfully receives its own data from the DL frame, it will respond to PLC after T_{sifs} by sending the UL frame using a bandwidth of 20 *MHz*. Up to 4 iRBs are supported to send their UL frames simultaneously using the FDMA technique. The duration of UL transmission is denoted by T_{ul}.
  - The DL and UL transmissions are performed until PLC finishes sending data to all of *N* iRBs. An iRB error occurs if the iRB fails to either receive the DL packet from PLC or transmit the UL packet to PLC.
- Stage 3 (RE-COMMUNICATION): If there are any iRB errors during stage 2, the PLC will re-communicate with them again. This re-communication duration is denoted by T_{recom}. The operations during this stage are the same as in stage 2. Stage 3 is repeated until PLC successfully communicates with all *N* iRBs or the T_{cd} elapses. When the T_{cd} elapses and there is not any iRB error in this stage, a new T_{cd} is performed.

III. Error Probability Simulation

This section explains the communication error rate of the entire system when using the proposed system in the industrial system. By formulating the communication error rate, we can quantitatively evaluate the communication performance and reduce the time cost for verification. Since the proposed system is formulated from the viewpoint of iRB control by PLC, the communication error rate in each route is different.

A. System Error Probability

We consider the topology shown in Fig.1 which consists of one AP and N STAs to formulate the error rate. A communication error is defined if even a single bit of the transmitted data is incorrect. In the system's communication, control data is sent from the PLC to each iRB via APs and STAs. If the control data is received correctly, response information is sent from the iRB to the PLC, and the communication is considered successful. Assuming that the error rate of each flow is P_{P2R} and P_{R2P}, and the number of retransmissions in case of a system error is m_{system}, the probability of an error in the entire system, P_{system}, can be expressed as follows.

$$P_{\text{system}} = \{P_{\text{P2R}} + (1 - P_{\text{P2R}}) \times P_{\text{R2P}}\}^{m_{\text{system}}+1} \qquad (1)$$

Next, we will discuss the error rate of each flow in P_{P2R} and P_{R2P}. In each flow, there are three communication paths: a wired transmission path of industrial Ethernet between PLC and AP, a wireless transmission path of the proposed system between AP and STA, and a wired transmission path of industrial Ethernet between STA and iRB. In the flow from the PLC, we define the error rate of each path is $P_e^{\text{Ether}}.P_e^{\text{WLAN}}$ and $P_e^{\text{Ether'}}$. At this time, the error rate of the Ethernet standard depends on the physical cable and is derived by the BER error rate of the control data, P_{P2R} and P_{R2P}, is

$$\begin{aligned} P_{\text{P2R}} \;&=\; P_e^{\text{Ether}} + (1 - P_e^{\text{Ether}}) \times P_e^{\text{WLAN}} \\ &\quad + (1 - P_e^{\text{Ether}}) \times (1 - \{1 - P_e^{\text{Ether'}}\}^N) \end{aligned} \qquad (2)$$

$$\begin{aligned} P_{\text{R2P}} \;&=\; (1 - \{1 - P_e^{\text{Ether'}}\}^N) + (1 - P_e^{\text{Ether}})^N \times P_e^{\text{WLAN}} \\ &\quad + (1 - P_e^{\text{Ether}})^N \times (1 - P_e^{\text{WLAN}}) \times P_e^{\text{Ether}} \end{aligned} \qquad (3)$$

B. Proposed System Error Probability

In this case, the error rate of the Ethernet standard depends on the physical cable and is derived by BER, while the communication error of the wireless part can be derived from the original communication procedure of the proposed system. In the proposed system, a communication error occurs when at least one STA needs to be retransmitted when the communication retransmission is completed. When the total number of STAs is N and the number of retransmissions is m, the error rate P_e^{WLAN} is given in Eq. (4).

$$\begin{aligned} P_e^{\text{WLAN}} = \sum_{n_1=1}^{N} \sum_{n_2=1}^{n_1} \cdots \sum_{n_{m+1}=1}^{n_m} P(N, n_1) \times \\ P(n_1, n_2) \times \cdots \times P(n_{m-1}, n_m) \times P(n_m, n_{m+1}) \end{aligned} \qquad (4)$$

$P(n_t, n_e)$ represents the error that occurred at the n_e STA after sending a frame to the n_t STA. The probabilities $P(N, n_1)$ for DL and UL are then calculated. In the DL case, when the AP sends control data to the STA, the error rate depends only on the DL error rate because the control data needs only to be sure that is sent to the STA and received by the STA. Therefore, the error rate at DL can be expressed as a binomial distribution following PER,

$$P^{\mathrm{DL}}(n_t, n_e) = {}_{n_t}C_{n_e} \times (\mathrm{PER})^{n_e} \times (1 - \mathrm{PER})^{n_t - n_e} \tag{5}$$

On the other hand, in UL, when the STA sends a response to the AP, it must first receive a DL from the AP. This is because the AP controls communication as a protocol, and the DL from the AP is the trigger for the STA to send UL. Therefore, the probability of success of the DL must also be considered during UL. Thus, the error rate for UL can be presented as below:

$$P^{\mathrm{UL}}(n_{\mathrm{ul}}, n_{\mathrm{ul}}) = {}_{\mathrm{ul}}C_{n_{\mathrm{ue}}} \times (\mathrm{PER})^{n_{\mathrm{ue}}} \times (1 - \mathrm{PER})^{n_{\mathrm{ul}} - n_{\mathrm{ue}}}$$
$$n_{\mathrm{ue}} = n_e - n_{\mathrm{de}}, \quad n_{\mathrm{ul}} = n_t - n_{\mathrm{de}} \tag{6}$$

n_{ue} is the number of STAs that fail in UL, and n_{ul} is the number of STAs that succeed in DL and transmit UL.

C. Evaluation Method

We describe the evaluation method of the system based on the formulated error rate. The system is designed to have a probability of less than 1% of at least one communication error during a period of three years, which is enough time for the system to stop once a year for periodic inspection. In other words, the probability that a system with an error probability, P will never make an error when it communicates N times in succession by a set number of years must satisfy the following Eq. 7.

$$1 - (1 - P_{\mathrm{system}})^N \ll 0.01 \tag{7}$$

Eq. 7 can be approximated by the following Eq. 8 from the binomial theorem

$$1 - (1 - P_{\mathrm{system}})^N \simeq P_{\mathrm{system}} \times N \tag{8}$$

IV. Implementation and Result

A. FPGA Evaluation Platform

In the proposed system, the implementation platform called Software Defined Radio (SDR) includes a ZC706 FPGA board for SoC design and an SDR daughter-board for RF. The real iWLAN design is developed on ZC706. In this SDR platform, the CPU and the iWLAN design are on the same FPGA board, ZC706. Therefore, this platform provides faster processing for the hardware and software co-design. Moreover, by configuring the system using SDR, various frequencies and bandwidths can be freely selected. We also use the RZ / T1 motion control solution kit with motors as the robots to be tested.

B. Motor Control Results

We verify the proposed system's implementation using the SDR board and control for 4 motors as in Fig. 4.

In the motor control verification, four motors that represent iRBs are connected to two controllers, as shown in Fig. 4. Based on one AP one STA implementation, we connect the STA to one controller by using an RS-232C interface; another controller is also connected to AP to provide the connection of two other motors. The system is controlled by asynchronous communication. These four motors are synchronized rotating, we confirm that the iRBs can be controlled by using the proposed system.

Next, in the same environment as the verification of 4-motor control, an oscilloscope was connected and the transmission time measurement of the proposed system was performed as shown in Fig. 5. In this measurement, the minimum value was 2 *ms* and the maximum value was 3 *ms* to control 4 motors. Fig. 6 and Fig. 7 show the waveforms observed by the oscilloscope when the minimum value and the maximum value are taken, respectively. Based on this result, we can calculate the maximum transmission time per motor is 750 *us* and the minimum transmission time per motor is 500 *us*. It is confirmed that the control communication on the order of *us* is possible.

C. Error Probability

In this section, we use the formula (1) explained in Section 3 to obtain the error rate of the system and investigate the conditions that satisfy the reliability evaluation criteria. Table II shows the parameters used in this verification. As a condition, BER is set to 10^{-15} considering the fact that cables used in industrial Ethernet are noise-resistant and that high reliability is emphasized.

First, the communication error rate in the proposed wireless LAN system is obtained, and the condition satisfying the equation (7) is investigated. Fig. 8 shows the calculation results obtained from the formulation, with the PER in wireless communication set to 10^{-3} and the number of retransmissions set to 4. From the calculation results, when the number of retransmissions is 4, the condition of formula (7) is not satisfied when the number of STAs is 6 or more, so the number of retransmissions in the LAN system must be 5 or more. Therefore, Fig. 9 shows the result of recalculating the communication period by increasing the number of retransmissions to 5 times. When the number of retransmissions is 5, the value is much lower than the reliability condition of 0.01. From the calculation results, it can be seen that the wireless system part is capable of communication that satisfies the reliability criteria even when multiple terminals communicate.

Next, we evaluate the value of the communication time when changing the STA by comparing it with the previously proposed method. The communication duration when the bandwidth used is 80 *MHz*, the number of retransmissions is 5, and transmission is performed to all terminals in the retransmission period (Control Duration). The communication duration using the method proposed is shown in Fig. 3. From the calculation results, it can be seen that the industrial wireless system part is capable of communication that satisfies the reliability criteria even when multiple terminals communicate with each other compared with the previous communication time.

In addition, we compare whether the formulated error rate follows the error generation behavior of the system using simulations. The simulation simulates the case where an error occurs in data transmission/reception between each route of the actual proposed system and assumes that no error occurs in processing other than data transmission/reception.

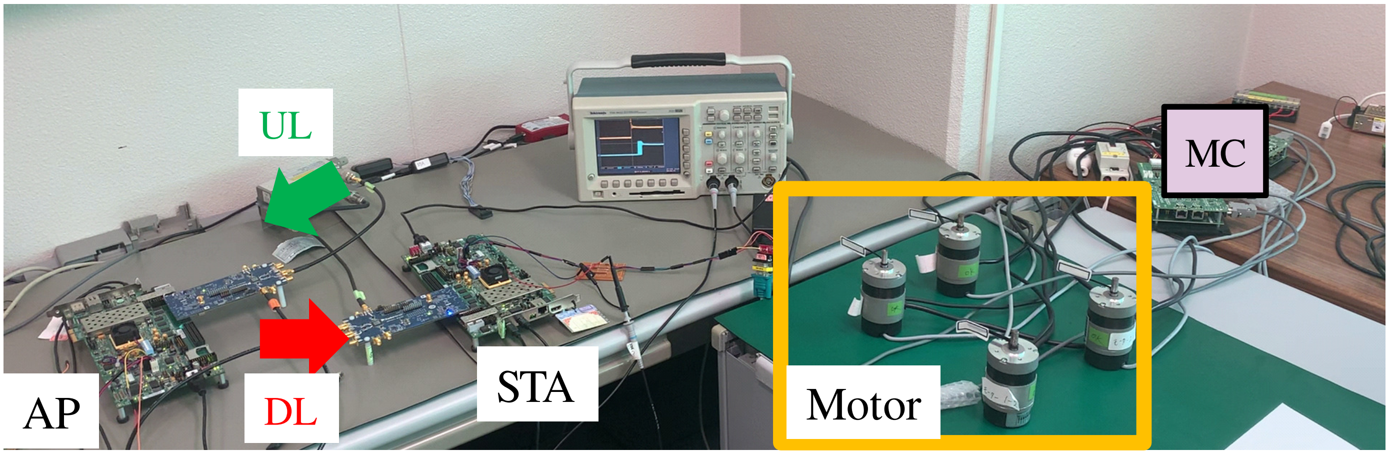

Fig. 4. Environment of 4 Motors Control Verification

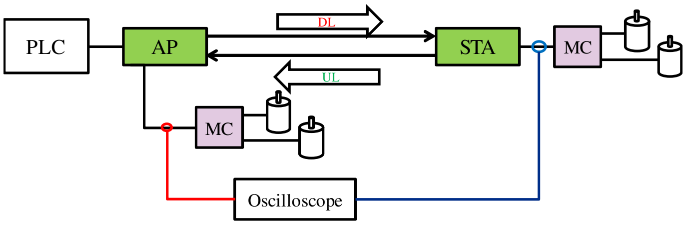

Fig. 5. Control delay measurement environment

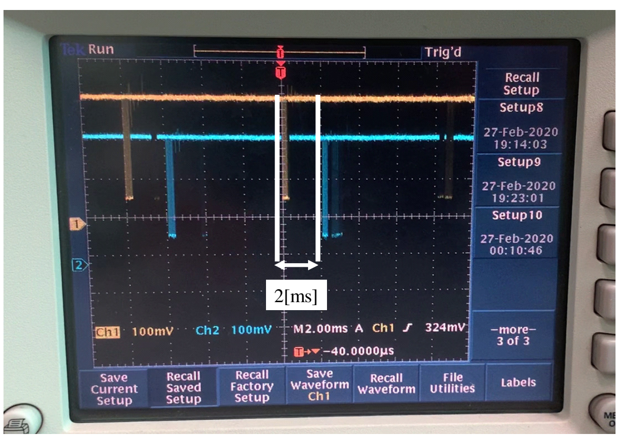

Fig. 6. Control delay measurement result (best case)

Fig. 7. Control delay measurement result (worse case)

TABLE II
ENVIRONMENT PARAMETERS.

Parameters	Supported Values
System Retransmission m_{system}	0
WLAN Retransmission m	5
BER	10^{-15}
PER	10^{-3}
PacketSize	32 *Byte*
Bandwidth	80 *MHz*
STA number$N$	32

Next, we compare the communication error rate when changing each bandwidth. Consider the case where multiple STAs and multiple iRBs exist. The proposed system can change the STAs that can communicate simultaneously by changing the bandwidth. The condition that the product of the number of communications L and the value of P_{system} when communicating without rest for 3 years when the communication band is set to 80 *MHz* satisfies the formula (7) to examine. As a result, if there is no retransmission mechanism in the system, the error rate in the wired communication section becomes a bottleneck, and the condition is not satisfied. Therefore, when communicating with multiple STAs, it is necessary to resend data when an error occurs in the application layer or network layer. If the system retransmits once without changing other conditions in 80 *MHz* communication, the result is shown in Fig. 10, and communication that satisfies the equation (7) is possible. In this verification, we confirmed that 4 retransmissions are required for less than 5 terminals, and 5 retransmissions are required

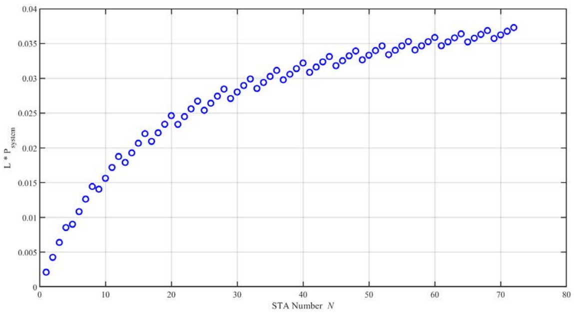

Fig. 8. Reliability evaluation result of wireless LAN system with 4 retransmissions

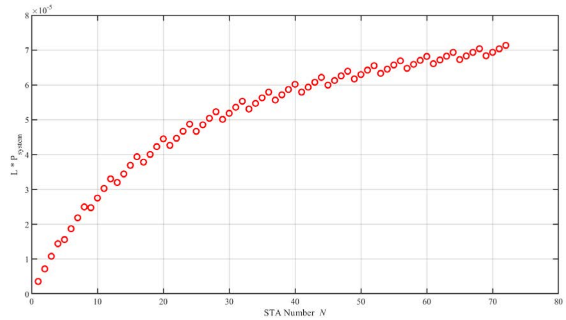

Fig. 9. Reliability evaluation result of wireless LAN system with 5 retransmissions

for 5 or more terminals. On the other hand, Fig. 10 confirms that it is necessary to retransmit the system at least once in the industrial Ethernet part. Considering the retransmission, two retransmissions of the wireless LAN part are enough. The reason for this is that when there are 32 communication terminals, the maximum number of times of communication per terminal in one cycle of the wireless LAN is 6 times (1 + 5 times). On the other hand, considering one system retransmission, it can be said that 3 times (1 + 2 times) is enough for the maximum number of communication times in the wireless LAN part. This is because the system retransmission guarantees 6 times (3×2 times) of communication to guarantee reliability. From the above verification results, the reliability of the system was able to obtain the error probability from the formulated formula and evaluate the conditions that satisfy the reliability.

V. Conclusions

In this paper, we have presented an implementation of the proposed fast iWLAN including MAC and PHY layer on hardware. The proposed system can control four motors using a cable in the experimental results. The time transmission results observed on an oscilloscope for four motors have shown that the control time for each motor is 750 *us* in the worst case. It can prove that the system has a fast transmission which is less than 1 *ms* compared to PROFINET. In addition, this paper has evaluated the reliability of an industrial wireless LAN system that supports communication with multiple terminals.

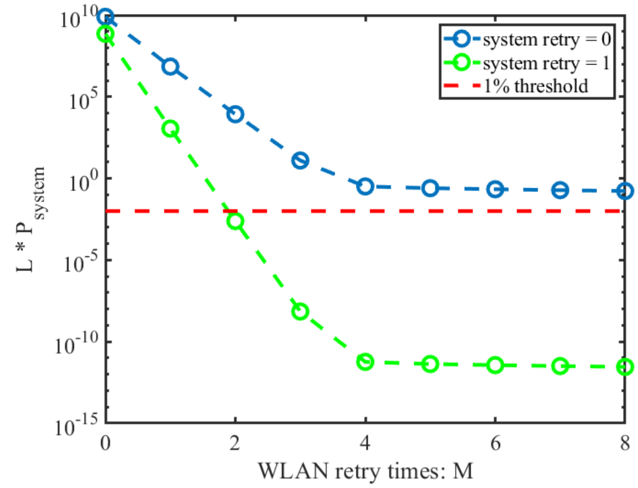

Fig. 10. Reliability of proposed system in 80 *MHz* band $N \times P_{\text{system}}$

As a result of verification, at least one system retransmission is required to guarantee the reliability of the industrial Ethernet part. Considering the system retransmission, it was confirmed that the number of retransmissions in the wireless LAN part is two times. As a result, assuming communication in a factory in the actual manufacturing field, we performed calculations and simulations that formulated the error probability of the proposed system, and we were able to determine the conditions necessary for building a reliable system. Future plans include the construction of a system that combines PHY and MAC actually to control iRB wirelessly as well as considers noise and burst errors caused by external factors.

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