Wireless Harness Inside ICT Equipments

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***Abstract*—We have been investigating point-to-multipoint wireless communication suitable for the use inside Information and Communication Technology (ICT) equipments to accommodate demands for weight saving, environmental lifecycle CO2 reduction and improvement of assembly/maintenance efficiency by means of replacing communication wire harnesses with wireless technology, that is wireless harness. Through the radio propagation measurements inside four equipments of automatic teller machine (ATM), ticket vendor, vending machine, and printer, a consistent specification applicable to them has been determined. Based on this specification, a test wireless system has been developed. It showed a good performance even inside the ATM that has the most lossy environment among the four equipments we tested.**

***Keyword*—2.4 GHz ISM band, ICT equipment, radio communication equipment, radio propagation, wireless harness**

I. INTRODUCTION

ONE of recent trends in wireless technology is machine-to-machine communication (M2M) using short range devices. As an expansive application of M2M, wireless communication inside machines has been recently receiving much attention aiming for the improvement of assembly/maintenance and weight savings. Several works have focused on these benefits of replacing wire harnesses with wireless communication, that is wireless harness, and reported its potential applicability in various vehicles and equipments such as automotive [1], [2], aircraft [3], spacecraft [4], [5], personal computers [6], and so on, through fundamental radio propagation measurements and feasibility tests.

Such utility of wireless harness also seems effective as a green technology to reduce CO2 emissions of machines. The reduction of CO2 emission is a big issue regarding with the global warming and has been challenged at all the sectors and various scenes in Japan. In accordance with these movements we have been studying the application of wireless harness to Information and Communication Technology (ICT) equipments that have a considerable amount of wire harnesses inside them. In addition, our study also covers the clarification of how effective the wireless harness of ICT equipments is on the reduction of CO2 emission. As a method to estimate the CO2 emission, we here employ a lifecycle assessment methodology that converts both the consumption of resources and energy into the amount of CO2 emissions during the whole lifecycle of the equipment. In our study, we have been focusing on the wireless harness of mechatronics ICT equipments. We have reported a fundamental study on measurements and modeling of radio propagation in four mechatronics ICT equipments; automatic teller machine (ATM), ticket vendor, vending machine, and printer [7], [8].

In this paper, we first show briefly the concept of the wireless harness of the mechatronics ICT equipments and review the radio propagation characteristics inside the above four equipments. Secondly, we show our dedicated wireless communication test system for mechatronics ICT equipments and discuss its performances inside the mechatronics ICT equipment. In order to understand an effect of the wireless harness on the reduction of CO2 emission, a trial estimation of CO2 emissions related to wire and wireless harness in the case of ATM is also presented.

II. CONCEPT OF WIRELESS HARNESS

Figs. 1(a) and (b) show the conceptual picture of the wire harness and the wireless harness communication inside the ICT

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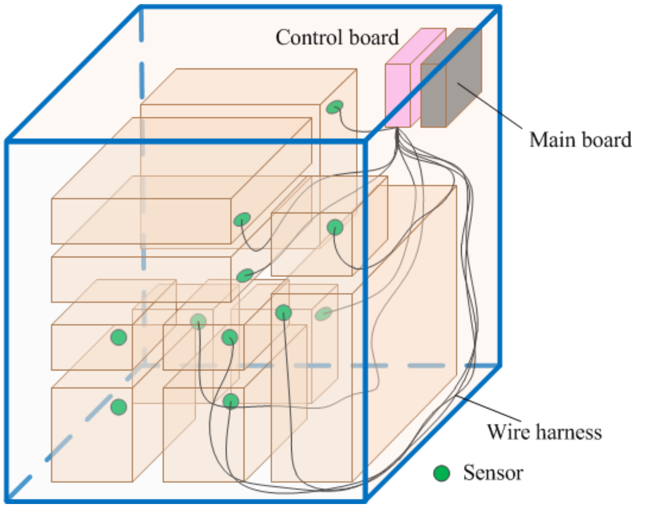
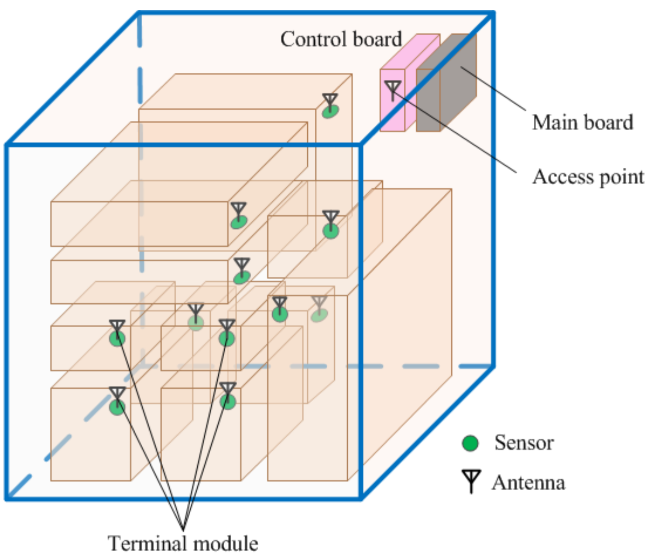


(a)



(b)

Fig. 1. Conceptual pictures of wire harness and wireless harness communication inside ICT equipment. (a) Wire harness communication and (b) wireless harness communication.

equipment, respectively. The ICT equipment, especially mechatronics ICT equipment, has a lot of sensors inside itself so as to monitor mechanical states in various positions such as transfer tracks and stockers in real time. As shown in Fig. 1(a), all these sensors are connected to a control board with wire harnesses in the present equipment. For example, ATM has about 200 sensors for monitoring and the total weight of the harnesses connecting sensors to control boards and a main board goes up to more than a couple of tens kilograms. Since the internal structure of ATM is so complicated and densely packed, the harnesses are swirled along with the frames and modules inside the chassis, resulting much longer than the straight-line distance. This increases technical difficulties in the assembly/maintenance processes. As shown in Fig. 1(b), the wire harnesses communication between sensors and the control board is replaced with wireless communication between

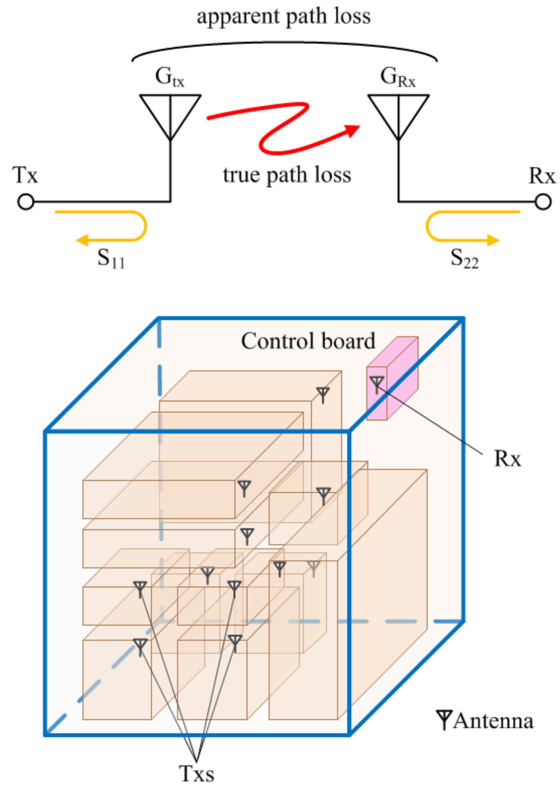


Fig. 2. Setup for measurements of the propagation loss and delay inside ICT equipment.

transmit antennas of terminal modules connected to sensors and a receive antenna of the access point on the control board. The application of the wireless harness into mechatronics equipments is very effective in assembly/maintenance load reduction as well as weight saving. As a whole, these must contribute to the reduction of the lifecycle CO2 emissions.

III. Radio Propagation inside Tested Equipment

The radio propagation environment inside densely packed mechatronics ICT equipments is significantly different from conventional outdoor and indoor ones. Through the challenge to apply wireless harness to mechatronics ICT equipments, we found out that the radio channel inside the equipment closely depends on its internal structure more than we expected. In order to understand the radio propagation characteristics inside such equipments, we measured propagation losses and delays inside four mechatronics ICT equipments [7], [8]. Now we show the typical examples of those measurement results.

The measurement setup for the radio propagation is shown in Fig. 2 Both transmit (Tx) antenna and receive (Rx) antenna are commercial 2.4GHz chip antennas (TAIYO YUDEN AH-316M245001) or ultra wide band (UWB) antennas (TAIYO YUDEN AH-086M555003). Tx antennas are placed at various positions near the sensor positions and the Rx one is fixed near the control board. The number of the measured Rx

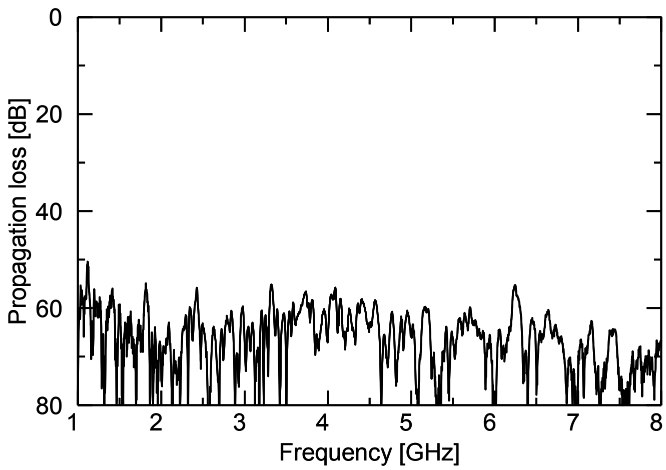


Fig. 3. Measured effective propagation loss in ATM. Tx antenna is located on NLOS from Rx antenna.

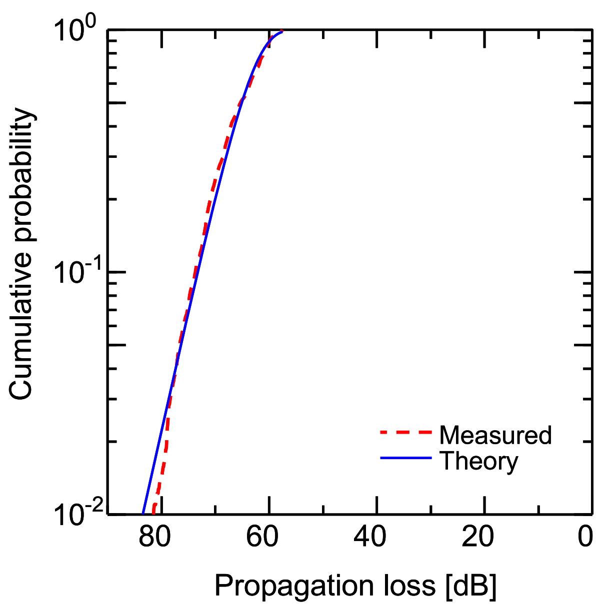


Fig. 4. Cumulative probability of measured effective propagation losses from 2.2 to 2.6 GHz in ATM. Tx antenna is located on NLOS from Rx antenna.

positions is about 40 to 70. The S-parameters of two ports are measured by a vector network analyzer (VNA). The frequency range is set from 1 to 8 GHz.

A. Frequency Characteristics of Propagation Loss

Fig. 3 shows an example of measurement results of the effective propagation loss in ATM as a function of the frequency. In Fig. 3, the Tx antenna is located on a non-line-of-sight (NLOS) from the Rx antenna. The effective propagation loss PL_{dB} in decibels is defined by

$$PL_{\mathrm{dB}} = -P_{\mathrm{Rx}} + L_{\mathrm{Tx,ref}} + L_{\mathrm{Rx,ref}} \tag{1}$$

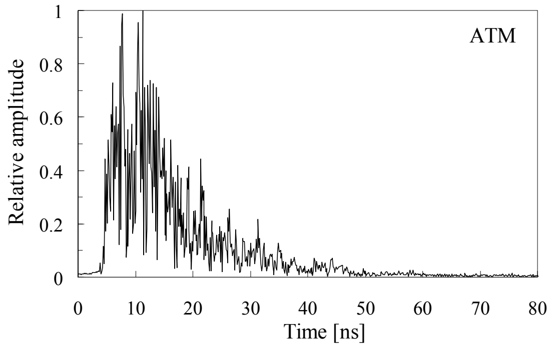
where P_{Rx} is the received signal power in decibels and $L_{\mathrm{Tx,ref}}$ and $L_{Rx,ref}$ are the mismatch losses of Tx antenna and Rx one in decibels, respectively. The gain and the reflection characteristics of the antenna may be changed when the antenna is located near metallic or dielectric components. The gains of antenna are involved in the effective propagation loss. This is because it is difficult to remove the effective gains from the measured data at each measurement point. The reflection characteristics of the antennas are de-embedded from P_{Rx} as shown in (1). As seen in Fig. 3, a lot of deep nulls of effective propagation loss are observed in the measured frequency range. Frequencies and depths of these nulls depend on and are sensitive to the position of the antennas.

The cumulative distribution function of effective propagation losses from 2.2 GHz to 2.6 GHz in ATM is shown in Fig. 4. In Fig. 4, the Tx antenna is located on a NLOS from the Rx antenna. The theoretical curve is the Rayleigh probability distribution. A good agreement between the measurement and theory is observed.

Such measured characteristics show that the inside of the ATM are typical multipath-rich environments and the propagation loss distribution for NLOS obeys the Rayleigh model. We also confirmed that these propagation loss characteristics are almost same in ticket vendor and vending machine. Though we omit the detailed measurement results here, in the case of printer, the propagation loss distribution for NLOS obeys the Nakagami-Rice model because the printer has a fewer components causing the shading and reflection of the radio wave inside itself than the other equipments. This indicates that the multipath waves are not always the dominant components inside equipment with few components causing the shading of the radio wave and the stationary wave with larger amplitude to be the dominant component exists among the multipath waves.

B. Propagation Delay

Fig. 5 shows examples of the measurement results of the propagation delay inside four equipments. As shown in Fig. 5, the complex multipath propagations are observed because the insides of these equipments are very complicated and multipath-rich environment as mentioned before. The observed propagation delays are less than 50 ns in various positions in ATM, ticket vendor, and vending machine. Their chassis are mainly made of metal. However, they have slits and windows, so that the radio wave easily dissipates from the inside. This helps the propagation delay be in the same range of that observed in a chassis of personal computer [6]. On the other hand, the printer that has a plastic chassis shows a shorter propagation delay, and which is less than 30 ns. This indicates the dissipation of the radio wave for printer is larger than the other equipment. The measurement results and the models of radio propagation in these equipments are summarized in Table I. Based on these observations we decided to treat ATM as a representative of mechatronics ICT equipment while considering broader applicability to other equipments.



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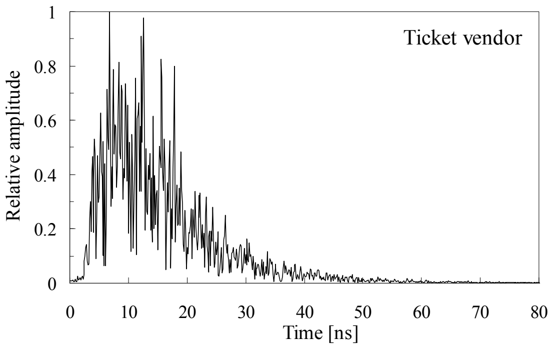

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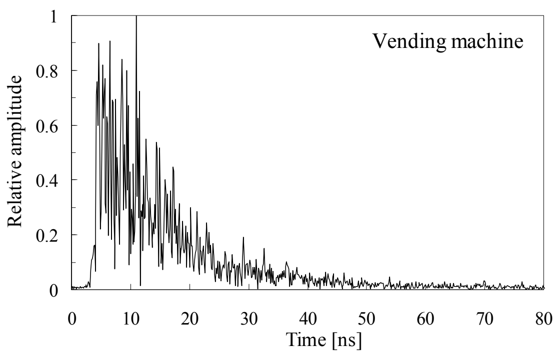

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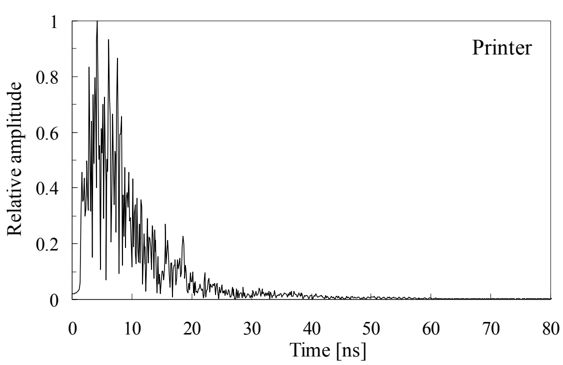


(d)

Fig. 5. Measured propagation delay inside the four ICT equipments: (a) ATM, (b) ticket vendor, (c) vending machine, and (d) printer.

TABLE I
MEASUREMENT RESULTS AND MODELS OF RADIO PROPAGATION IN FOUR ICT EQUIPMENT

Equipment	ATM	Ticket Vendor
Size (cm) (width × length × height)	57 × 104 × 120	50 × 90 × 150
Chasis	Metal	Metal
Propagation loss for distance < 1 m	20 – 70 dB	20 – 50 dB
Propagation delay	≤ 50 ns	≤ 50 ns
Propagation loss model at far positions	Rayleigh	Rayleigh

Equipment	Vending machine	Printer
Size (cm) (width × length × height)	70 × 70 × 180	48 × 48 × 55
Chassis	Metal	Plastics
Propagation loss for distance < 1 m	20 – 60 dB	20 – 60 dB
Propagation delay	≤ 50 ns	≤ 30 ns
Propagation loss model at far positions	Rayleigh	Nakagami-Rice

IV. SYSTEM DESIGN AND SPECIFICATIONS

Although there were a couple of candidates among commercialized products such as Bluetooth [9], ZigBee [10], and UWB [11] systems and actually some of them were tested inside our equipments at an early stage of our work [12], we decided to make a custom system based on a commercialized radio frequency integrated circuit (RF-IC) running at 2.4 GHz Industry, Scientific, and Medical (ISM) band. Some of the reasons for this are to satisfy our primary requirements that the system shall simultaneously collect status data from as many as 200 sensor transmitters, each of which runs with 1 kHz sensing frequency and with a system latency of 1 ms. These requirements are mainly derived from a current wired system of ATM as a case reference. The existing technologies such Bluetooth and ZigBee seemed hardly applicable to meet with these requirements without deep level modification. Though UWB is a fascinating high-speed technology, we have to consider power consumption of sensor transmitters and the radio wave regulation of Japan that limits UWB to indoor use at present. Thus we decided to design a point-to-multipoint custom system. Table II summarizes our system specifications.

V. ANTENNA

Since a lot of metals and dielectric components are closely arranged inside mechatronics ICT equipment, extra free spaces available for additional placement of wireless modules are not so large. The distances between adjacent components look 2 to 5 cm at best. In some places aerial slits are as narrow as less than 1 cm. Antennas on the wireless modules inside equipment,

TABLE II
SYSTEM SPECIFICATION

Num. of sensor modules (transmitters)	up to 200
Sensor data	0/1 (bit datum)
Sensing frequency at each sensor	1 kHz
Radio communication frequency	2.4 GHz ISM band
Modulation	GFSK
Access protocol	FTDMA
Communication speed	1 Mbps

therefore, have to be inevitably placed close to the components. In order to know how the antenna performance is affected by adjacent metals, we first measured variations of the reflection coefficient (S11) by employing a setup shown in Fig. 6. An antenna under test was placed on the surface of one aluminum plate and the other aluminum plate was brought to closer to the antenna. Fig. 7 shows the measured reflection coefficient of a commercial 2.4 GHz chip antenna with various separations between two aluminium plates. As shown in Fig. 7, the reflection characteristic of the chip antenna easily varies and degrades when the aluminum plate was closely placed. Compared to the free space condition, the reflection coefficient at 2.45 GHz got worse to -10 dB at 20 - 30 mm and -5 dB at 15 mm. Though these results are specific examples of the antenna performance degradations, we also observed almost same antenna performance degradations inside the mechatronics ICT equipments.

In order to obtain stable antenna performance inside mechatronics ICT equipments, we designed a dedicated antenna to have better performance when a metal plate exists at around 20 mm and to be insensitive to the environmental change. Fig. 8 shows a picture and a configuration of the developed antenna. We adopt the shorted microstrip antenna (shorted MSA) in our wireless harness communication system because it may be suitable for use in a narrow space such as the inside of mechatronics ICT equipment because of its low-profile structure. Moreover, shorted MSA has a ground plane on its back face and is expected to be less sensitive to the proximity of the metals to the ground plane side. The dimensions of the antenna are 25 mm × 30 mm × 2.5 mm. The wide and depth are same as the board size of terminal module described later. The height of the antenna is about 1/50 of the wavelength at the center frequency 2.44 GHz. In order to enhance the bandwidth of the antenna, we use the double folded L-probe proximity feeding structure [13] as shown in Fig. 8(b).

Fig. 9 shows the measured reflection coefficient of a developed antenna with various separations between two aluminium plates. As shown in Fig. 9, the antenna exhibited much more stable characteristics than the conventional one shown in Fig. 7. The averaged reflection coefficient keeps better than -11 dB from the free space to the distance of 15 mm in the range of 2.4 to 2.5 GHz.

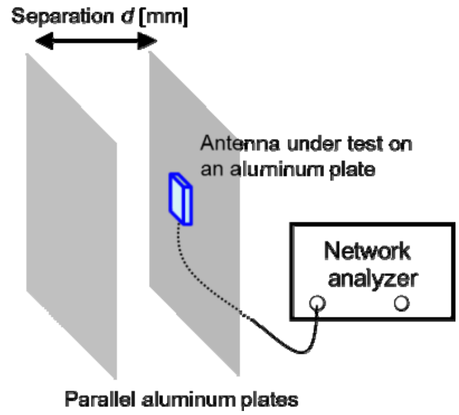


Fig. 6. Measurement setup of antenna characteristics at close positions to metals.

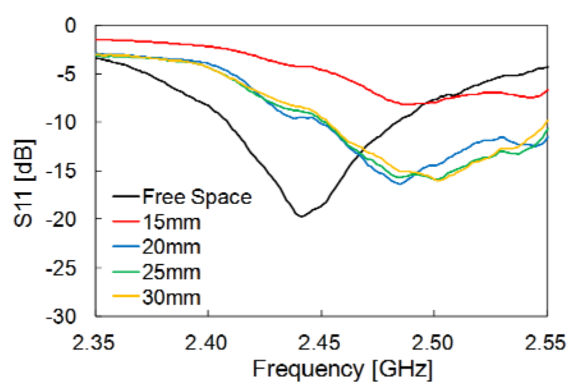
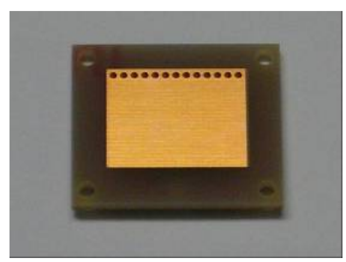


Fig. 7. Measured reflection coefficient of a commercial 2.4 GHz chip antenna.



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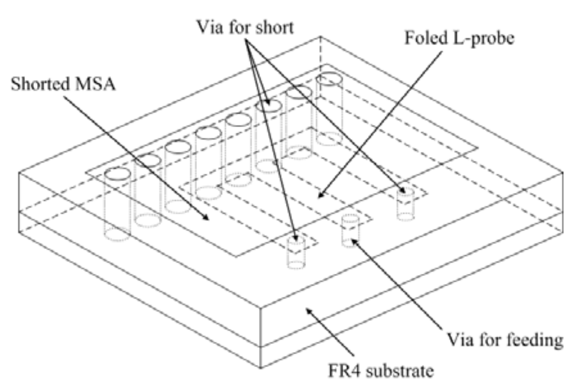

(b)

Fig. 8. Configuration of the developed antenna. (a) Photo. (b) Configuration.

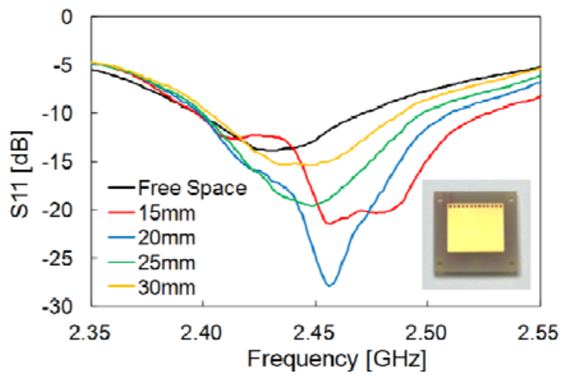

Fig. 9. Measured reflection coefficient of a developed antenna with various separations between parallel aluminium plates.

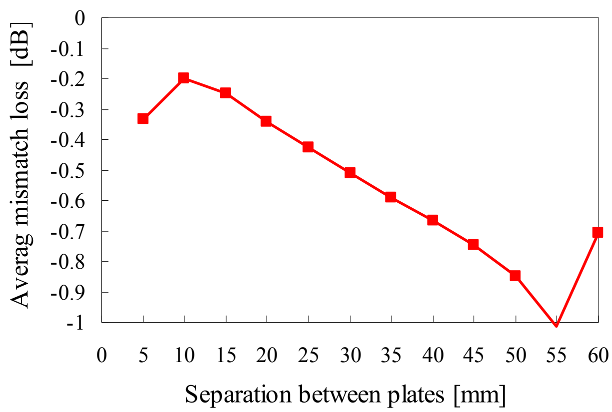

Fig. 10. Measured average mismatch loss of a developed antenna.

Fig. 10 shows the measured average mismatch loss (averaged between 2.4 and 2.5 GHz) of our developed antenna. As seen in Fig. 10, the average mismatch loss becomes the minimum at the separation d = 10 mm and is less than -0.4 dB for d < 20 mm. As can be seen from these results, our developed antenna has a stable and good antenna performance between the metallic plates. Though these measurement results only show the antenna performances in the ideal situation such as in the parallel metallic plate, we observed our developed antenna also shows a good performance in the mechatronics ICT equipments.

VI. Wireless Communication System

A. Wireless Modules

To match the specifications listed in Table II, we made a custom wireless module based on a commercially-available RF-IC produced by Nordic Semiconductor. Fig. 11 shows a terminal module coupled with an antenna developed. It has two connector ports to sensors and a board size of 25 mm × 30 mm. In this module custom protocols described next are embedded. The combined wireless module shown in Fig. 11 is a kind of functional test version.

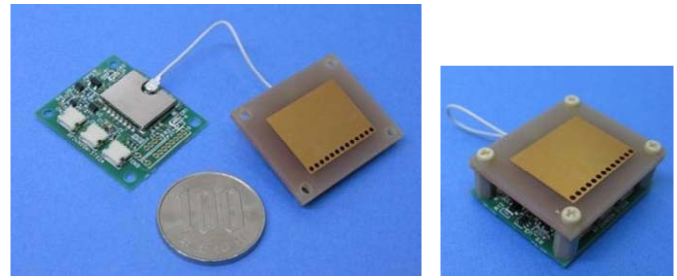

Fig. 11. A pair of a wireless module and an antenna. The right photo shows an assembled state.

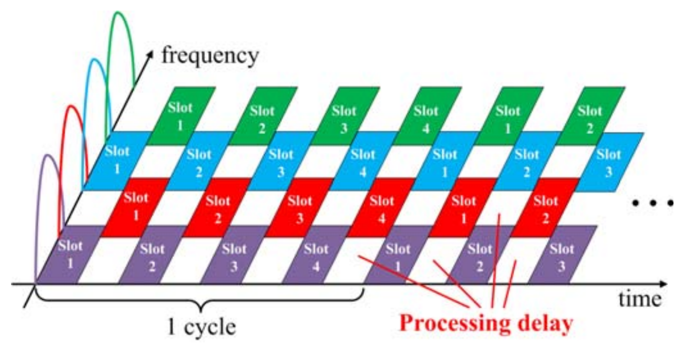

Fig. 12. FTDMA protocol sequence using four slots at each frequency with checkerboard packet configuration.

B. Protocols

Fig. 12 shows a frequency and time division multiple access (FTDMA) protocol sequence which is implemented on the RF-IC as an access protocol inside mechatronics ICT equipments. The system is designed to utilize 73 frequency channels with 1 MHz bandwidth in the range of 2400 MHz to 2480 MHz and each channel has four time slots. A guard time is set for compensating the processing delay of RF-IC and guard frequency band is prepared to avoid the interference from adjacent frequency channels. Therefore, the guard time is allocated to the transmission time of both the adjacent frequency channels in order to use frequency band efficiently.

The allocation of frequency to each terminal module is pre-processed at initial setting to avoid severe multi-path interference and functionalize frequency diversity effect. The allocation of frequency is decided based on the following evaluation value V of n th terminal module at m th frequency channel:

$$V(n,m) = \frac{-\log_{10}\left(PER(n,m)\right)}{\frac{1}{N_{ch}}\sum_{k=1}^{N_{ch}}\left[-\log_{10}\left(PER(n,k)\right)\right]} \qquad (2)$$

where N_{ch} is the total number of frequency channels and $PER(n,m)$ is the packet error rate (PER) of the n th terminal module at m th frequency channel. The denominator of (2) is PER characteristics averaged over all frequency channels and

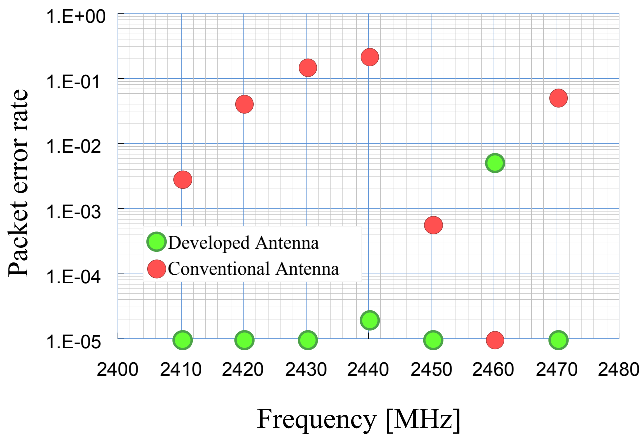

Fig. 13. Comparison of packet error rates between our developed antenna and the conventional antenna.

becomes smaller with the worse communication quality at all frequency channels. On the other hand, the numerator of (2) is PER characteristics at a certain frequency channel. Therefore, higher V is obtained when the communication quality is bad over all frequency channels and comparatively good at a certain frequency channel. The frequency channels are allocated according to the magnitude of V , in order from the terminal module with highest evaluation value V . Currently we utilized a pre-installed packet format for communication, and thus put a couple of sensor data into one payload to transmit. Though the packet has a length of 72 bits, that is too long for datum length of each sensor and even for a couple of sensors, the total data volume of 200 sensors with 1 kHz repetition can be successfully transmitted to the access point (Rx) with using FTDMA, running at 1 Mbps in each channel.

C. *Performance*

Performances of our developed wireless module and antenna were measured in ATM. An access point was placed near the backside of the front panel, and the terminal module was placed close to the rear panel. The straight-line distance of them was more than 50 cm. The arrangement was where the propagation obeys Rayleigh distribution and the propagation loss was about 60 dB. Fig. 13 shows the measurement results of PER against 7 frequency channels from 2400 MHz to 2480 MHz. In Fig. 13, green and red dots mean performances of our developed antennas and conventional 2.4 GHz meander-line inverted-F antennas that the RF-IC supplier recommended, respectively. As shown in Fig. 13, PER with the developed antennas achieved 10-5 level in the wide range of channels. The degradation of PER at 2460 MHz seems to be due to the severe multi-path interference and a steep increase of propagation loss, which is sensitive to the position of the terminal module. As shown in Fig. 13, average to say, our developed antenna showed better performance in ICT equipment.

In our early measurement of bit error rates (BER) at various positions inside ATM, about 10% of the positions exhibited very lossy conditions probably due to the environmental reason and multi-path interference and suggested difficulty to achieve BER being 10^{-6} level or better. Fig. 13 is only one example and we can also achieve BER < 10^{-6} (corresponding PER is about 8.1×10^{-5}) at dozens of sensor positions we measured inside ATM by adopting our developed antenna and FTDMA based channel allocation.

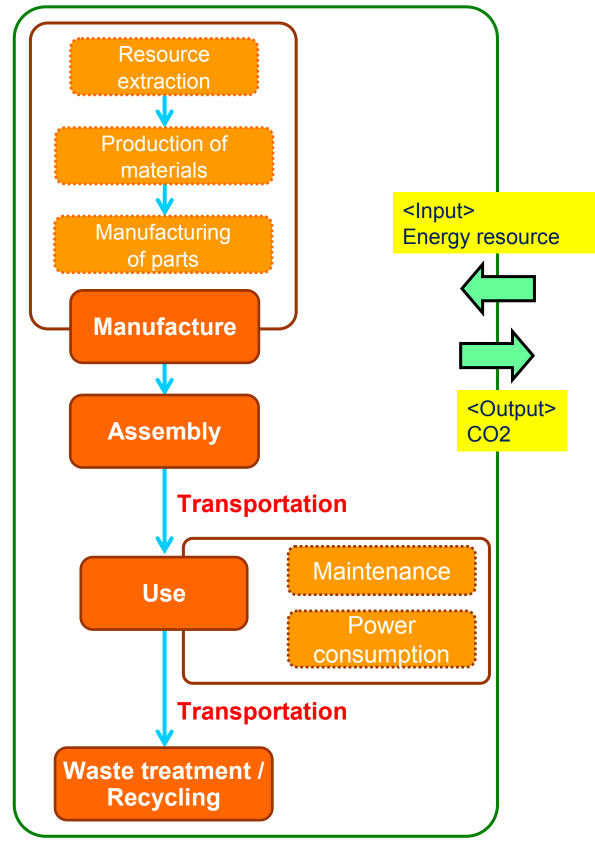

Fig. 14. Evaluation boundary of our case study on the trial estimation of CO2 emissions.

VII. Green Effect

The benefit of the wireless harness in terms of lifecycle CO2 reduction has been estimated [14]. The difficulties in such estimation at an early stage of test development phase include the collection of appropriate primary units of elemental parts and the framework of evaluation.

Fig. 14 shows the evaluation boundary of our case study. The manufacture process includes the resource extraction, the production of materials, and manufacturing of parts (cables and connectors / wireless modules). The assembly process means assembling the equipment with wire harnesses or wireless modules. In the use process, power consumptions by wireless modules and by the movement of workers for maintenance are included. In the waste treatment and recycling process, shredding process of equipment is only evaluated. In our study, the transportation of products and wastes is only considered and that of resources, materials, and parts is neglected.

Table III summarizes the trial estimation of CO2 emissions

TABLE III
CALCULATED CO2 EMISSION
(a) Wire harness. (b) Wireless harness. (Kg-CO2/unit)

Lifecycle process	(a)	(b)
Manufacture of cables and connectors	288	0
Manufacture of wireless modules	0	145
Assembly	74	41
Transportation	69	54
Use	12	0
Waste treatment and recycling	3	2
Total	444	241

related to wire and wireless harness in the case of ATM. In the estimation of the wireless harness, CO2 emissions are calculated in a case where the wireless harness is applied to the wire harness not only between sensors and the control board but also between the control board and the main board of ATM taking into account the future expansion of applicability of our wireless harness technology.

In the case of wire harness, the major process of the CO2 emission is found to be the manufacture of cables and connectors. It occupies 65% in the total CO2 emission. In the case of wireless harness, it is found that the manufacture of wireless modules process occupies 60% of the total CO2 emission and the CO2 emission of the use process, that is CO2 emission due to the power consumption by wireless modules, is negligibly smaller than that of the other processes. This result indicates that the manufacture of cables and connectors and wireless modules are more important than other factors. Although the assembly, transportation, use and waste treatment and recycling processes have been addressed as distinct loads and speculated to have considerable CO2 emissions, they occupies 35% to 40% of the total.

Though these estimated values seem to have considerable errors at current stage, the estimated amount of CO2 reduction by replacing the harness with wireless harness becomes 203 kg CO2 per a unit and is not negligible. This indicates the wireless harness almost certainly has a very good effect to the reduction of CO2 emissions when it is applied to ICT equipments that have a lot of wire harnesses in them.

VIII. CONCLUSION

Based on the measurement results of radio propagation inside ICT equipments, we settled down a consistent specification to fit for use of sensor data acquisition, and built up a test system of point-to-multipoint wireless communication. The system runs with 73 channels using 2.4 GHz ISM band. It enables to connect 200 sensor-transmitter modules and retrieve sensor data with dedicated packet protocols. The test system exhibited good performance even inside ATM, the inside of which is the most severe environment for radio propagation among the equipments we tested. The application of wireless harness to ICT equipments seems to offer wider variety of merits such as weight saving, slim-design, abatement of assembly/maintenance, and reduction of lifecycle CO2 emission as a result.

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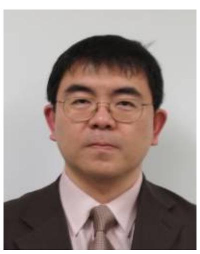

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