

Wireless Harness Inside ICT Equipments

Narihiro Nakamoto^{*1}, Hiroshi Ban*, Tomohiro Oka^{*1}, Shoichi Kitazawa*,
Kiyoshi Kobayashi*, Noriyasu Kikuchi**, Hironobu Hatamoto**, Satoru Shimizu**, and
Minako Hara***

**ATR Wave Engineering Laboratories, 2-2-2 Hikaridai, Seika-cho, Kyoto 619-0288, Japan*

*** OKI Electric Industry Co. Ltd., 3-4 Hikari-no-oka, Yokosuka-shi, Kanagawa 239-0847, Japan*

**** NTT Energy and Environment Laboratories, 3-1 Morinosato Wakamiya, Atsugi-shi, Kanagawa
243-0198, Japan*

`Nakamoto.Narihiro@ap.MitsubishiElectric.co.jp, hban@atr.jp,
Oka.Tomohiro@db.MitsubishiElectric.co.jp, {kitazawa, kobayashi}@atr.jp,
{kikuchi434, hatamoto247, shimizu706}@oki.com, hara.minako@lab.ntt.co.jp`

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 good performance even inside the ATM that has the most lossy environment among the four equipments we tested.

Keywords: wireless harness, ICT equipment, 2.4 GHz ISM band, microstrip antenna, CO₂ emission

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.

¹ They are now with Mitsubishi Electric Corporation.

In our study, we have been focusing on the wireless harness of mechatronics ICT equipments. We have reported a fundamental study on measurements and modelling 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 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 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.

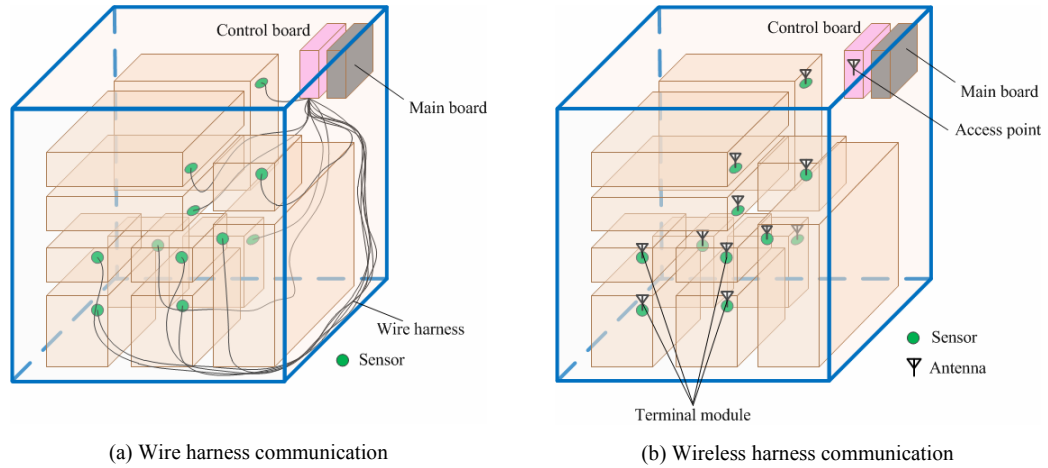


Figure 1. A conceptual picture of wire harness and wireless harness communication inside ICT equipment.

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

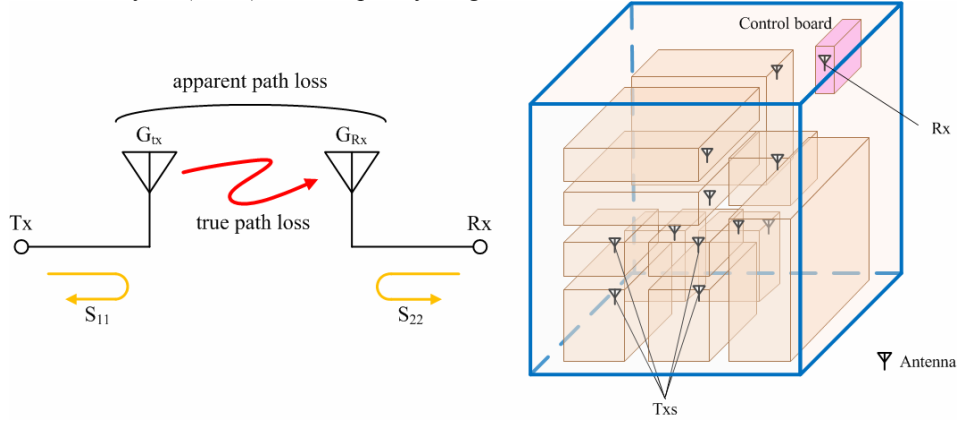


Figure 2. Setup for measurements of the propagation loss and delay inside ICT equipment.

A. Frequency Characteristics of Propagation Loss

Fig. 3 shows examples of measurement results of effective propagation loss PL_{dB} 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} is defined by

$$PL_{dB} = -P_{Rx} + L_{Tx,ref} + L_{Rx,ref} \quad (1)$$

where P_{Rx} is the received signal power and $L_{Tx,ref}$ and $L_{Rx,ref}$ are the mismatch losses of Tx antenna and Rx one, 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 functions of effective propagation losses from 2.2 GHz to 2.6 GHz in ATM are 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. Good agreements between the measurements and theories are 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 aren't 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.

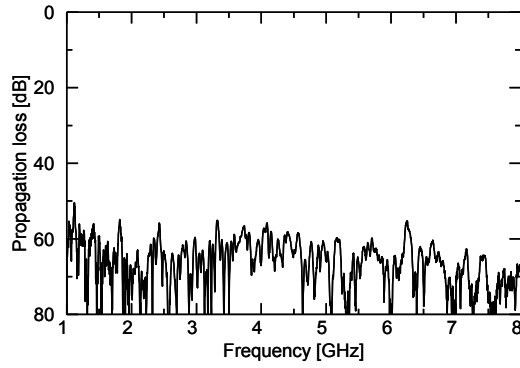


Figure 3. Measured effective propagation loss in ATM. Tx antenna is located on NLOS from Rx antenna.

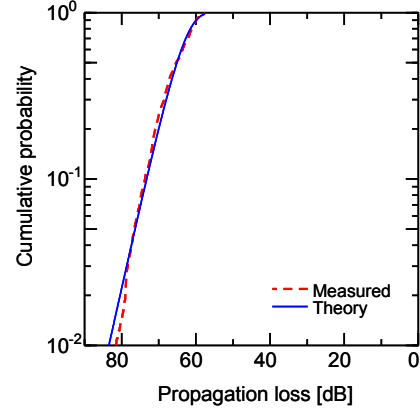


Figure 4. Cumulative probability of measured effective propagation losses from 2.2 to 2.6 GHz in ATM. Tx antenna is located on NLOS from Rx antenna.

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 multi-path propagations are observed because the insides of these mechatronics ICT equipments are very complicated and multipath-rich environment as shown 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.

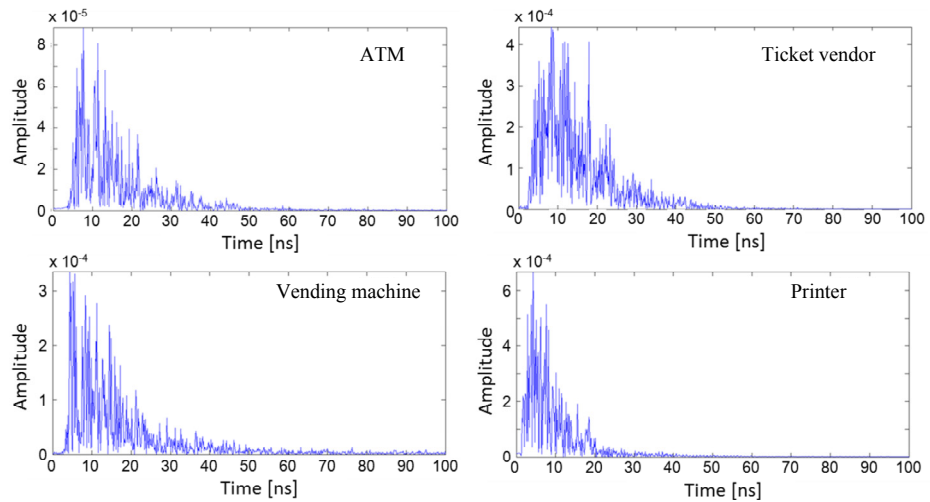


Figure 5. Measured propagation delay inside the four ICT equipments.

The measurement results and modellings of radio propagation in the four equipments are summarized in Table 1. Based on these observations we decided to treat ATM as a representative of mechatronics ICT equipment while considering broader applicability to other equipments.

TABLE 1. MEASUREMENT RESULTS AND MODELLINGS OF RADIO PROPAGATION IN FOUR ICT EQUIPMENTS

Equipment	Size(W x D x H)	Chassis	Propagation loss at distance < 1 m	Propagation Delay	Propagation loss model at far positions
ATM	57 x 104 x 120 cm	metal	20 – 70 dB	≤ 50 ns	Rayleigh
Ticket vendor	50 x 90 x 150	metal	20 – 50	≤ 50	Rayleigh
Vending machine	70 x 70 x 180	metal	20 – 60	≤ 50	Rayleigh
Printer	48 x 48 x 55	plastics	20 – 60	≤ 30	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 2 summarizes our system specifications.

TABLE 2. SYSTEM SPECIFICATIONS

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 (op. 250 kbps, 2 Mbps)

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 areal slits are as narrow as less than 1 cm. Antennas of the wireless modules inside equipment, 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 (S_{11}) 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.

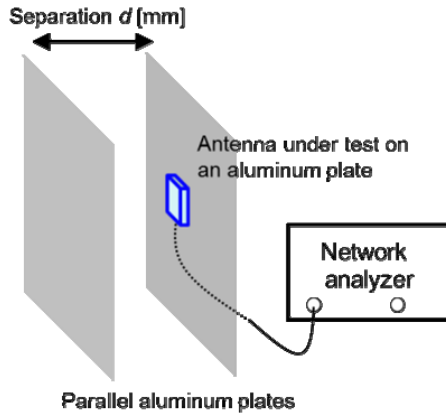


Figure 6. Measurement setup of antenna characteristics at close positions to metals.

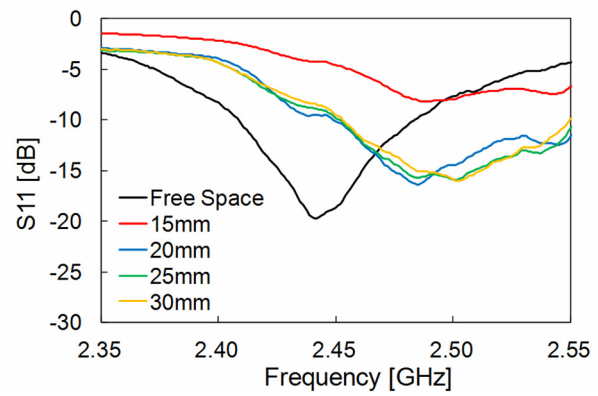


Figure 7. Measured reflection coefficient of a commercial 2.4 GHz chip antenna.

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 x 30 mm x 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).

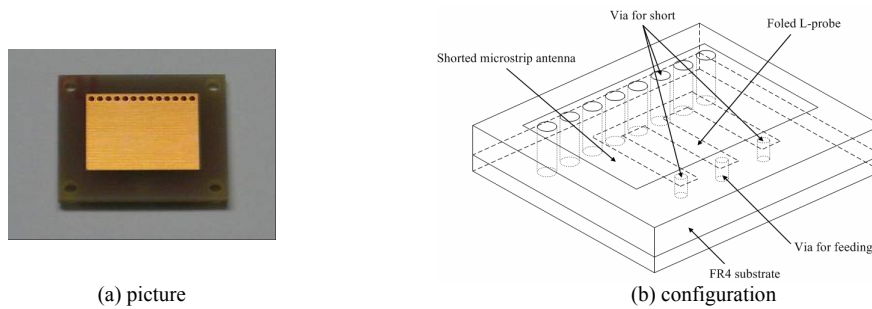


Figure 8. Configuration of developed antenna.

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. 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.

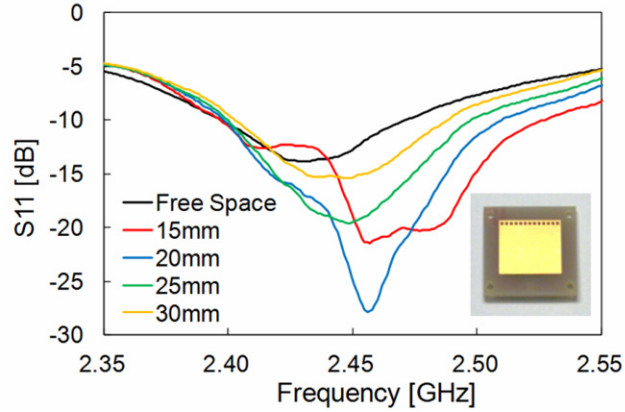


Figure 9. Measured reflection coefficient of a developed antenna with various separations between parallel aluminium plates.

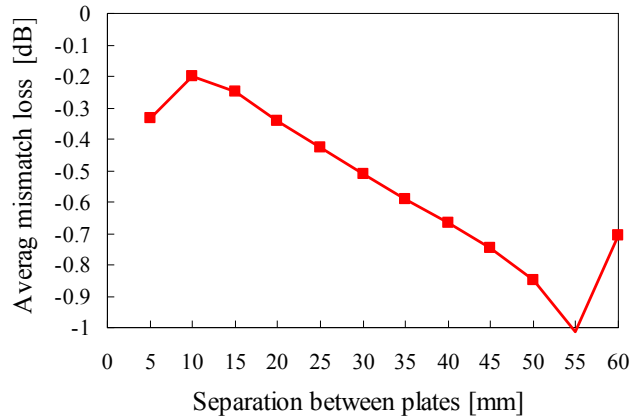


Figure 10. Measured average mismatch loss of a developed antenna.

VI. WIRELESS COMMUNICATION SYSTEM

A. Wireless Modules

To match the specifications listed in Table 2, 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 x 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.

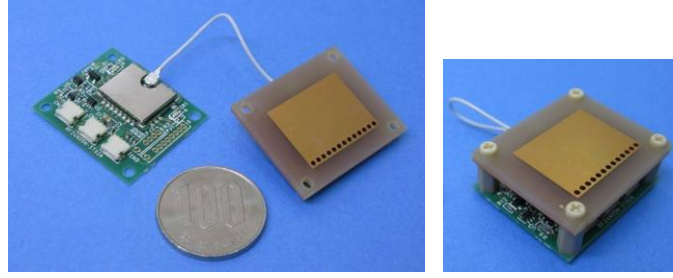


Figure 11. A pair of a wireless module and an antenna. The right picture shows an assembled state.

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.

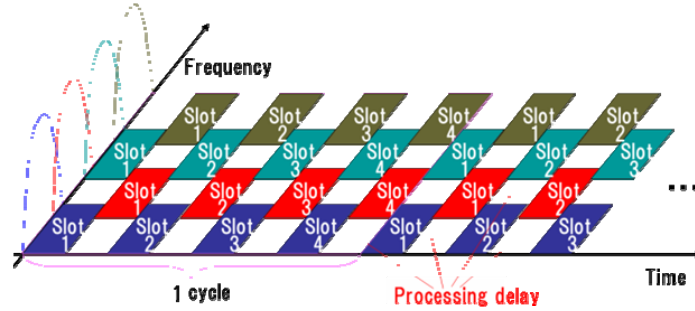


Figure 12. FTDMA protocol sequence using four slots at each frequency with checkerboard packet configuration.

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:

$$V(n, m) = \frac{-\log_{10}(PER(n, m))}{\frac{1}{N_{ch}} \sum_{k=1}^{N_{ch}} [-\log_{10}(PER(n, k))]} \quad (5)$$

where N_{ch} is the total number of frequency channels and $PER(st, ch)$ is the packet error rate (PER) of the n th terminal module at m th frequency channel. The denominator of (5) is PER characteristics averaged over all frequency channels and becomes smaller with the worse communication quality at all frequency channels. On the other hand, the numerator of (5) 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.

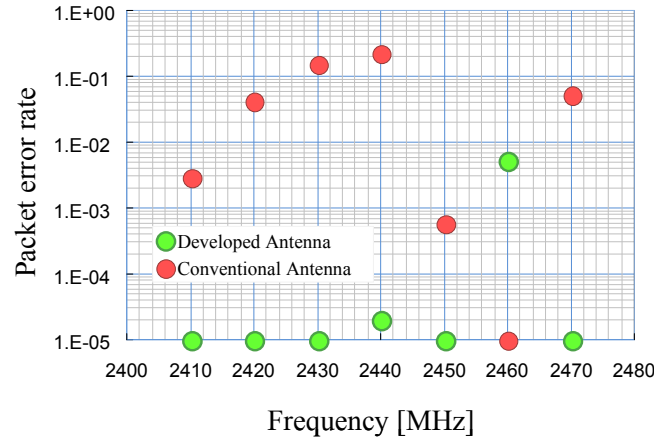


Figure 13. Comparison of packet error rates between our developed antenna and the conventional antenna.

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.

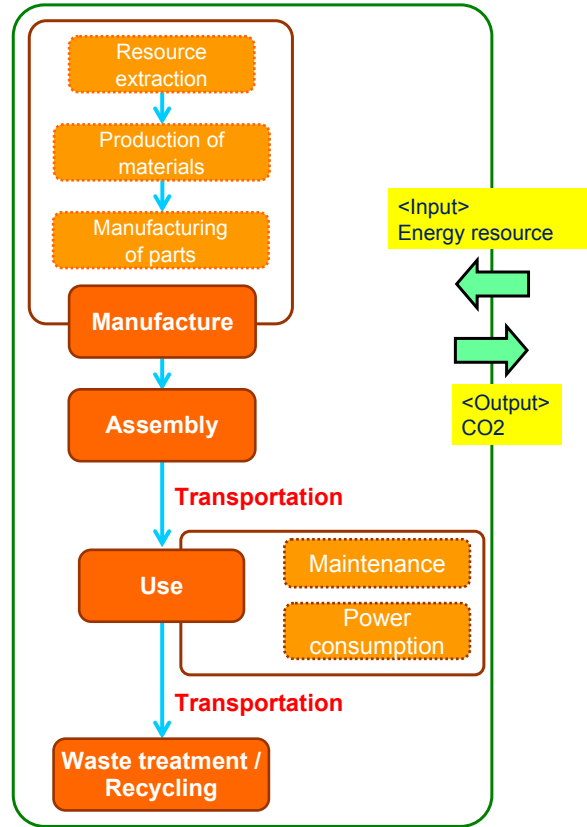


Figure 14. Evaluation boundary of our case study on the trial estimation of CO₂ emissions.

Table 3 summarizes the trial estimation of CO₂ emissions 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 between the control board and the main board of ATM taking into account the future expansion of applicability of our wireless harness technology.

TABLE 3. 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

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. CONCLUSIONS

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.

ACKNOWLEDGMENT

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Narihiro Nakamoto was born in Hyogo, Japan, in 1981. He received the B.E. and the M.E. degrees from Kyoto University, Kyoto, Japan, in 2005 and 2007, respectively.

In 2007, he joined Mitsubishi Electric Corporation, Kanagawa, Japan. From 2010 to 2012, he was with ATR Wave Engineering Laboratories, Kyoto, Japan, and was engaged in research on microstrip antennas and wireless communication system inside ICT equipment. In 2012, he returned to Mitsubishi Electric Corporation. Since then, he has been engaged in research and development on array antennas for satellite communications and radar systems.

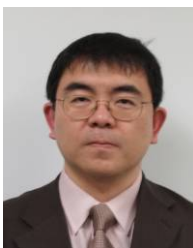
Mr. Nakamoto is a member of IEEE and IEICE of Japan.



Hiroshi Ban received the B.E., M.E., and D.E. degrees in polymer science and technology from the Tokyo Institute of Technology, Tokyo, Japan, in 1982, 1984, and 1991, respectively.

In 1984, he joined Ibaraki Electrical Communications Laboratories, Nippon Telegraph and Telephone Corporation, and started his career in research on photosensitive materials and microlithographic technologies. Since 2001, he has expanded his interest to sensor network systems, environmental assessment methodologies, and environmental ICT technologies. He moved to ATR in 2009, and is currently a head of the Department of Environment Communications of ATR Wave Engineering Laboratories. He received the Photopolymer Science and Technology Award from the Photopolymer Conference in 1998.

Dr. Ban is a member of IEEE, JSAP, and SPSJ.



Tomohiro Oka was born in Kanagawa, Japan, on August 1968. He received the B.E., and M.E. degrees from Hosei University, Japan, in 1991 and 1993, respectively.

In 1993, he joined Mitsubishi Electric Corporation, where he engaged in design and development of communication systems for government and municipal offices. Since 2010, he has been engaged in research and development of the wireless communication system inside ICT Equipment and the future mobile satellite communication systems at ATR Wave Engineering Laboratories, Kyoto, Japan. He received the prize for science and technology of the commendation for science and technology by the minister of education, culture, sports, science and technology, in 2009.

Mr. Oka is a member of IEICE of Japan.



Shoichi Kitazawa received the B.E. and M.E. degrees from Kinki University, Osaka, Japan, in 1991 and 1993, respectively, and the D.E. degree from Osaka Prefecture University, Osaka, Japan, in 2007.

In 1993, he joined Matsushita Nittoh Electric Co., Ltd., Kyoto, Japan, where he has been engaged in development on microwave filters. Since 2005, he has been with ATR Wave Engineering Laboratories, Kyoto, Japan. His current research interest includes microwave and millimeter-wave devices.

Dr. Kitazawa is a member of IEEEJ, IEEE, and IEICE of Japan.



Kiyoshi Kobayashi received the B.E., M.E. and Ph.D. degrees from Tokyo University of Science, Japan, in 1987, 1989 and 2004, respectively.

He joined NTT Radio Communication Systems Laboratories in 1989. Since then, he has been engaged in the research and development of digital signal processing algorithms and their implementation techniques including modulation / demodulation, synchronization control and diversity for satellite and personal wireless communication systems. Currently he is the director of ATR Wave Engineering Laboratories at Advanced Telecommunications Research Institute International, where he is engaged in research on advanced technologies for wireless communications. From 2012, he has been a visiting professor at Muroran Institute of Technology.

Dr. Kobayashi is a member of IEEE, AIAA and IEICE of Japan.



Noriyasu Kikuchi was born in Shizuoka, Japan, in 1976. He received the B.E. degree from Yokohama National University, Japan, in 2000, and the M.E. degree from Tokyo Institute of Technology, Japan, in 2002.

In 2004, he joined the Oki Electric Industry Co., Ltd. His research interests include wireless communication systems.

Mr. Kikuchi is a member of the IEICE of Japan.



Hironobu Hatamoto was born in Hyogo, Japan, in 1981. He received the B.E. degree in electrical and electronic engineering from Shizuoka University, Japan, in 2004, and the M.E. and Ph.D. degrees from Osaka University, in 2006 and 2011, respectively.

In 2009, he joined the Oki Electric Industry Company Limited. His research interests include digital signal processing and wireless communication systems.

Dr. Hatamoto is a member of the IEEE.



Satoru Shimizu was received the B.E. degree in electronics engineering from Kyoto University, in 1987 and Ph.D. degree from Chiba University in 1995.

He joined the Oki Electric Industry Co., Ltd. in 1987. He received the Paper Award from the Marine Acoustics Society of Japan in 1995. His current research interests are digital signal processing, wireless communication, and control systems.



Minako Hara is a Research Engineer in Green Material Project at NTT Energy and Environment Systems Laboratories.

She received the B.S. in applied chemistry from Tokyo University of Science in 1998, and M.E. and Ph.D. degrees in applied chemistry from The University of Tokyo in 2000 and 2005, respectively. During 2004-2006, as a post-doctor researcher at the Japan Science and Technology Agency, she developed a methodology of environmental impact assessment and an eco-efficiency index. She joined NTT Energy and Environment Systems Laboratories in 2006 and studied environmental assessment, including life cycle assessment and material flow analysis. She is currently studying material recovery technology.

Dr. Hara is a member of the Society of Environmental Science, Japan and the Society for Environmental Economics and Policy Studies.