1-cc Computer using UWB-IR for Wireless Sensor Network

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Abstract - An ultra-small, high-data-rate, low-power 1-cc computer (OCCC) with an UWB-IR (ultra-wideband impulse-radio) transceiver was developed for a wireless sensor network. Thanks to bear-chip implementation and a flexible printed circuit board, the size of the computer is only 1 cm^3. To achieve 10-Mbps data rate, a middle-class 32-bit microcontroller, which has both a bus interface and a USB 2.0 controller, was selected. Low-power techniques, such as transition of microcontroller status to standby mode by using an external real-time clock during wait times, power shutdown of halted circuits, and detailed control of UWB-IR transceiver status, are applied. The effect of these low-power techniques is verified by measuring the time history of current consumption of the OCCC. It was confirmed that the OCCC can provide wireless communication at a transmission rate of 258 kbps over a distance of 30 m.

I. Introduction

According to Moore's Law, the number of transistors on an integrated circuit doubles every 18 to 24 months. Driven by this law, transistors have been continually and remarkably minimized since the 1960s. Accordingly, computers have also been greatly miniaturized (Fig. 1). The trend has been to miniaturize computer size by 1/100 every ten years, rather than to miniaturize gradually [1]. Desktop personal computers (PCs) with volumes of about 10 liters (10,000 cc) were widely produced throughout the 1980s and 1990s. This is about two orders of magnitude smaller than the volume of the proceeding mainframe computers. Since then, computers have been set on desks, so "everyone" can use them in his/her home or office. At the same time, laptop computers have become popular because of their compact size. Even smaller computers, such as PDAs and mobile phones with sizes of about 100 cc, have recently been developed and are now widely used in daily life. These palm-size computers are portable and used "everywhere".

The next jump in miniaturization is coming soon. In the near future, ultra-small one-cubic-centimeter computers (OCCCs) will be developed and will change peoples' lives. Huge numbers of OCCCs will be deployed everywhere to sense and control the real world. People will use these invisible-size computers "unconsciously".

The user interfaces of computers have changed along with their size. A personal computer has a keyboard and a mouse, by which data is manually entered into the computer. People use only their fingers to enter data into mobile phones or PDAs, since the keys are smaller and fewer than in personal computers. In contrast, since an OCCC is much smaller than a mobile computer, it has no interface that humans can directly operate. Instead, it uses sensors to interface with the real world. That is, an OCCC gathers real-world data via sensors without humans being conscious of it. Moreover, since OCCCs do not have space for an output interface such as a display and no space to connect wires, such as an Ethernet cable, OCCCs have both a sensor to input data, and a wireless communication device to output data.

To perform the operations described above, OCCCs contain sensors, signal processing units, and communication devices. Huge numbers of OCCCs will be embedded everywhere and gather real-world data wirelessly. The data gathered by OCCCs will enable people to understand the phenomenon of the real world. Such a system is called a sensor network. The development of OCCCs and sensor-network systems is eagerly awaited in various fields such as structural monitoring, security, logistics, nursing, healthcare, and the military (Fig. 2). The OCCC is also expected to become a driver of the chip industry in the post mobile-computer era.

In the present work, an ultra-small 1-cc computer (OCCC) with an ultra-wideband impulse-radio (UWB-IR) transceiver is presented. Its key feature is ultra-small size with no compromise on performance. In section II, the requirements for OCCCs and the strategy to realize them are introduced. In section III, the advantages of UWB-IR and the developed transceiver are presented. The design procedure and implementation of the OCCC, including both a 1-cc computer module and an access point module, are presented in section IV. In section V, measurement results are presented.

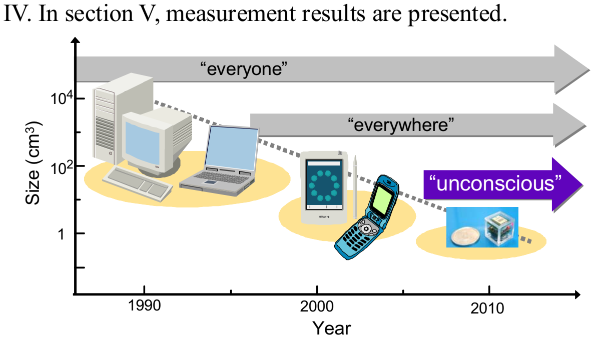

Fig. 1. Computer miniaturization trend: Miniaturization by 1/100 every ten years.

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II. Strategy to realize OCCC

A sensor network using OCCCs is expected to be applied for various applications, such as agriculture, industry, and health care. In such applications, the requirements for OCCCs are summarized in the following five points:

(1) Small size. To install OCCCs everywhere, OCCCs must be small. Since compactness is essential for widespread use, OCCCs should be in the cubic-centimeter-class or smaller.

(2) Low power consumption. Since a longer battery life leads to less maintenance, OCCCs must be low power.

(3) Robust wireless communication. To put an OCCC anywhere, the network connection must be wireless. The connection must also be stable, even in an environment with many reflectors and electromagnetic noises.

(4) High-data-rate communication. As many wireless terminals are densely deployed, the total amount of data becomes large even if that stored on an individual terminal is small. Since many terminals should share limited radio resources, high-data-rate communication is required.

(5) Location information. The location information of an OCCC is valuable from the viewpoint of both enhancing sensing-data value and efficiency of system maintenance. To distinguish between humans and objects, accuracy to within several tens of centimeters is required.

To satisfy the above requirements, a lot of research has been done on small computers with wireless communication devices and sensors. M. Niedermayer et al. developed a one-cubic-centimeter module that can operate for hours or days [2]. The computer, called ZN1, integrates a micro controller unit (MCU) and a ZigBee RF chip into a 15 x 15-mm module with an ultra-low standby current of less than 1 μA [3]. (ZigBee is a popular wireless communication standard for sensor networks.) A. Fujii et al. developed a positioning system using an ultra wideband (UWB) signal [4]. This system is configured with 30 x 50 x 15-mm tags and 100 x 100 x 40-mm access points, and achieved a locationing accuracy of 17 cm. A research team at the University of California, Berkeley developed a 38 x 25 x 8.5-mm sensor node with an efficient transmitter [5] and a power-managed protocol processor. The team also developed a localization technique based on time-of-flight measurement with accuracy of 0.5 to 2 m [6].

Although the above-mentioned researches introduce important techniques for small computers, none of these devices meets all the requirements listed above simultaneously.

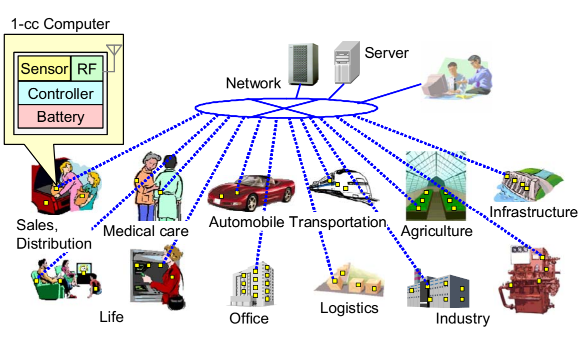


Fig. 2. Example of sensor networks. 1-cc computers will be embedded everywhere around us.

Our goal, described in this paper, is to realize an OCCC which satisfies the above requirements simultaneously. To meet the requirements, various techniques, including wireless systems, circuit design, and board implementation, must be combined. To achieve the requirements (3) to (5), we've developed a UWB-IR transceiver chip, since conventional transceivers are not capable of meeting the requirements. As for the requirements (1), (2) and (4), circuit design and implementation of an OCCC module is important. To achieve high-data-rate communication, we selected a middle-class 32-bit MCU, which has both a bus interface and a USB 2.0 controller. The most challenging issues are both (1) miniaturization and (2) power reduction using the MCU and the UWB-IR transceiver. To minimize the OCCC module, both package-less bear-chip implementation and a flexible printed circuit (FPC) board were applied to achieve 1-cc-class size. To reduce power consumption, low-power techniques, such as transition of microcontroller status to standby mode by using an external real-time clock during wait times, power shutdown of halted circuits, and detailed control of UWB-IR transceiver status, were applied. The details of the UWB-IR transceiver and the OCCC module are presented below.

III. UWB-IR communication

A. *Advantages of UWB-IR*

The developed UWB-IR wireless system has many advantages. By definition, a UWB communication system uses a broader frequency band than that of any other wireless systems. There are three major UWB systems: direct sequence spread spectrum (DSSS), orthogonal frequency-division multiplexing (OFDM), and impulse radio [7]. An impulse-radio system utilizes an intermittent impulse signal, as shown in Fig. 3. Due to the broad frequency band in the frequency domain and the ultra-short impulse in the time domain, a UWB-IR system has the following features:

(1) It does not use a carrier wave; therefore, most of the transmitter can be composed of digital circuits [8]. Chip area can thus be reduced.

(2) Because the system uses an intermittent impulse train, the transceiver can operate intermittently [9]; therefore, power can be reduced, compared with conventional wireless systems, which utilize continuous waves.

(3) Because data is diffused to ultra-wideband signals to transmit, the influence of a specific narrow band signal is small. Moreover, the multipath effect is easily distinguishable because pulse widths are as short as 2 ns. Robust communication is therefore achieved.

(4) The UWB-IR transceiver has a low-power-consumption-to-data-rate ratio. UWB-IR can thus achieve higher data rate than that of ZigBee or a weak-radio wave system, even though the power consumption is almost

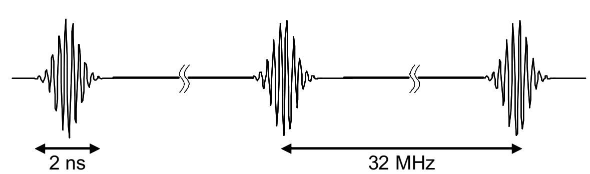


Fig. 3. Waveform of UWB-IR communication

the same.

(5) Due to its high-resolution capability in the time domain, UWB-IR achieves excellent locationing accuracy [10].

Thus, an UWB-IR system is a key device in the OCCC.

B. Developed UWB-IR transceiver

Table I lists the specifications of our UWB-IR system. A broad frequency band from 3.1 to 5.1 GHz is utilized. The -10-dB bandwidth is as broad as 1.4 GHz. The output level is suppressed to less than -41.3 dBm/MHz, which is regulated by the Federal Communications Commission (FCC) spectrum mask. A train of impulses is transmitted at a 32-MHz repetition frequency with differential binary phase shift keying (DBPSK) modulation. To spread the frequency spectrum, the width of impulses is kept short, namely, 2 ns, as shown in Fig. 3. The data rate and the communication range are variable: 10 m at 10.7 Mbps and 30 m at 258 kbps. The data rate of 10.7 Mbps is 40-times higher than that of ZigBee. The location accuracy is high, and the error is within 30 cm.

A prototype UWB-IR transceiver chip was fabricated by 0.18-μm CMOS process technology (Fig. 4). The chip includes all circuits necessary for wireless communication: a clock generator, a transmitter, a receiver, and a digital baseband circuit.

Fig. 5 shows a block diagram of the UWB-IR transceiver. The transmitter is composed of a pulse-pattern generator (PPG) and a power amplifier (PA). PPG generates an impulse train digitally, corresponding to the digital data from the baseband circuit (BB). PA amplifies the impulse train and outputs the train. To reduce power consumption, the transmitter operates intermittently [8].

The most outstanding feature of the receiver is the low sampling frequency of the analog-to-digital converters (ADCs). The sampling frequency is as low as 32 MHz, which is the same value as the pulse-repetition frequency [11]. In general, the sampling frequency of an ADC is more than 1 GHz to capture a 2-ns impulse signal. Since such a high-frequency ADC consumes a large amount of power, we utilize a low sampling frequency. The programmable divider (PDIV), which can change the period of the sampling clock slightly, is used to search for pulses. Once the sampling clock is synchronized with the pulses, the frequency of the sampling clock is fixed.

As well as the transmitter, the UWB-IR receiver can also operate intermittently. The power supply for the analog circuits, namely, a low-noise amplifier (LNA), low pass filters (LPF), and programmable gain amplifiers (PGA), is turned off between pulses [9]. The circuits operate only when pulses are acquired, so power consumption is reduced.

Fig. 6 schematically shows a location system using the developed UWB-IR technology [10]. This UWB-IR system enables location of communication devices to be accurately measured. The system consists of three access points, a synchronous point and a location server. The principle of the measurement is trilateration using time difference of arrival (TDOA). First, a node, whose location is to be measured, broadcasts a data packet. The access points measure the time difference of arrival while receiving the packet. The location server then calculates the location of the node by using the measured time differences. The synchronous point (see Fig. 6) is used to synchronize the access points. Because pulse widths are as narrow as 2 ns, the time difference is measured within an accuracy of ±1 ns. The distance that an electromagnetic wave travels in 1 ns is 30 cm. Therefore, the UWB-IR location

TABLE I
Specifications of UWB-IR Communication

Frequency band	3.1 – 5.1 GHz
Center frequency	4.1 GHz
– 10-dB bandwidth	1.4 GHz
Modulation	DBPSK
Pulse width	2 ns
Pulse repetition frequency	32 MHz
Data rate @ communication distance	10.7 Mbps @ 10 m 258 kbps @ 30 m
Location accuracy	< 30 cm

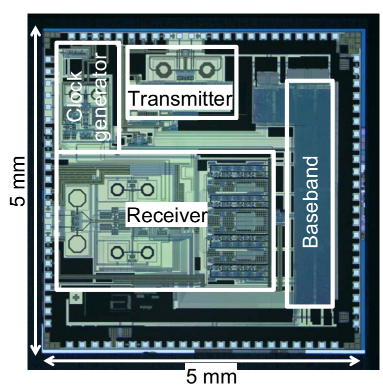


Fig. 4. Micrograph of UWB-IR transceiver

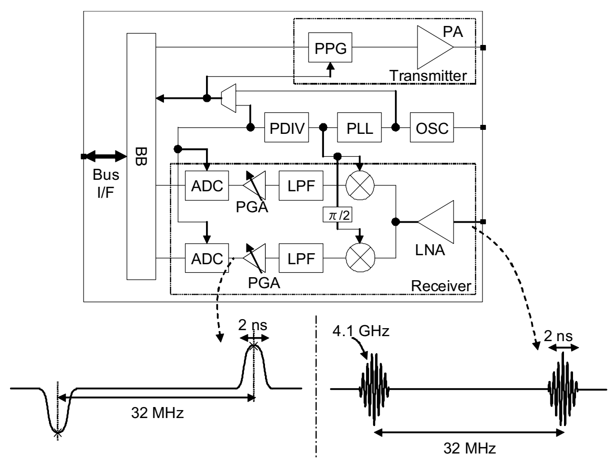


Fig. 5. Block diagram of UWB-IR transceiver

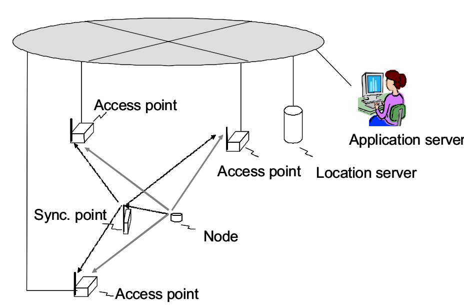


Fig. 6. Location system using UWB-IR wireless communication

system can measure the position of the node with an error of less than ±30 cm, while the locationing accuracy of ZigBee or wireless LAN is a few meters [12]. Thanks to such accurate location information, the value of sensing data increases and system maintenance becomes easy.

IV. Module design and implementation

A. Module design

To achieve ultra-small 1-cc-class size, module design is important. That is to say, there are tradeoffs between miniaturization, low power consumption, and high-data-rate communication. To meet these requirements at the same time, a 1-cc computer module was designed as follows.

First, since data rate is mainly determined by the performance of selected devices themselves, the architecture to achieve high-data-rate communication was designed. Entire communication between OCCC modules and an access point is divided into three sections: communication between wireless transceivers, communication between the wireless transceiver and an MCU, and communication between the MCU and a PC. As a wireless transceiver, a UWB-IR transceiver that achieves communication at data rates up to 10.7 Mbps was developed. As for the communication interface between the transceiver and MCU, a parallel bus interface was selected, because the data rate of a general serial interface of an MCU is about 1 Mbps at most. As for the interface between the MCU and PC, we selected USB 2.0 full speed, which achieves 12-Mbps communication, since USB is one of the most popular interfaces of a PC. We therefore selected H8SX/1653 [13] from Renesas Technology Corp. as an MCU, which has a parallel bus interface and a USB controller, to satisfy all the requirements. As a result, a data rate of more than 10 Mbps is achieved by the combination of the UWB-IR transceiver and H8SX/1653.

The next challenges are both miniaturization and power reduction using these devices. Miniaturization is achieved through bear-chip implementation and FPC board implementation. Chip size strongly depends on its package. The size of the MCU in TQFP package is 16 x 16 mm, while the size of the bear chip is 7.5 x 7.5 mm. Therefore, we adopted wafer-level chip scale packaging (W-CSP) technique to achieve 1-cc class size. W-CSP is used when high-density implementation is necessary, such as in cell phones. In a W-CSP, solder balls, which are connected to pads, are arranged in a grid on the back face of the package, and silicon chips are directly mounted onto a board via the solder balls. No external package is therefore required, reducing the size of the required area. We applied W-CSP technology to the MCU and succeeded in reducing the area it occupies by about 80%. We also applied flip-chip packaging (FCP) to the implementation of UWB-IR transceiver chip. The FCP technique enables chip scale packaging as well as W-CSP. Moreover, since there are no wires between chip and board, parasitic resistance, inductance, and capacitance are smaller than with conventional wire bonding. As a result, the electrical characteristics of the RF signal are much better than with wire bonding.

Even if bear-chip implementation is applied, it was impossible to implement all of the components on a 1-cm^2 board. Two boards, each with a size of 1 cm^2, were thus needed. Although board stacking is effective for composing a miniature module [2], connectors are necessary for stacking two boards. However, connectors occupy an area that is too large to allow them to be implemented on 1-cm^2 boards. We thus used an FPC board. FPC is a technology for building electronic circuits by depositing electronic devices on flexible, thin substrates such as plastic. All of the components were implemented on a one connector-less FPC board. We therefore used FPC board for the OCCC module to reduce the implementation area of connectors. In use, the board is bent to achieve 1-cc-class size.

To reduce power consumption, the power supply and the operational mode of peripheral circuits are controlled precisely. For example, MCU controls the power supply for the UWB-IR transceiver using an FET switch and the chip-enable pin of a regulator. This control makes it possible to completely shut down the power supply during down time. A timer function in a real-time clock (RTC) enables intermittent operation to save power. Because the timer can switch the MCU from standby mode to active mode, the MCU can transit to low-power standby mode, during which the clock in the MCU is turned off.

Based on the above design, both a 1-cc computer module for a sensor node and an access-point module were developed. In the following section, the developed modules are described in detail.

B. 1-cc computer module

Fig. 7 shows a block diagram of the prototype OCCC with a UWB-IR transceiver. The motherboard integrates an MCU, a UWB-IR transceiver, a sensor, power supply elements, and an RTC for intermittent communication. A ceramic chip antenna is implanted on the antenna board, which is connected to the motherboard via a coaxial connector. Power is supplied from a battery. The battery and the antenna board are separated from the motherboard to make replacement easy. For example, the antenna board can be easily replaced with another specific antenna, such as an isotropic antenna or a directional antenna.

The MCU, namely, H8SX/1653 from Renesas Technology Corp., is a middle-class, 32-bit microcontroller. It has a 32-bit CISC CPU core, 384 kB of ROM, and 40 kB of RAM, which are sufficient controlling peripherals and building up communications networks with access points. The MCU also has 10-bit analog-to-digital (A/D) converters for acquiring analog signals from sensors. As a wireless transceiver, the developed UWB-IR transceiver is adopted. The interface between the MCU and the transceiver is a 16-bit-data, 16-bit-address bus interface to achieve high-data-rate communication. Both the MCU and the UWB-IR transmitter have crystal oscillators (OSC). Regulators (REG) are used to provide stable voltage to the MCU and the transceiver. The voltage is also used as a precise reference voltage for the A/D converters in the MCU. A temperature sensor, for gathering temperature data in rooms, offices, homes, factories, and so on, is implemented. A temperature sensor was selected because temperature is an important environmental quality, though any other type of sensor could also have been used. To completely shut down the power supply during down time, an FET switch is inserted in the power line to the transceiver. A real time clock (RTC) is used to keep time, and a timer function in the

RTC enables intermittent operation of the OCCC to save power.

Fig. 8 shows the fabricated OCCC module. The motherboard, built from FPC board, covers an area of 10 x 25 mm. The layout of the components is important from the viewpoint of noise suppression. The noise-susceptible RF components are separated from the digital components to prevent degradation of RF performance. The bent motherboard and a 10 x 10-mm antenna board are connected by a coaxial cable. With this configuration, a 1-cc-class size is achieved (without battery).

C. *Access point*

An access point controls a huge number of sensor nodes and gathers a large amount of data. Since the gathered data are transmitted to a data server, the access point must have high-speed throughput. Fig. 9 is a block diagram of the access-point module, which is based on the same architecture used in the OCCC module. In addition, it has several PC interfaces and a sensor port. To connect with a PC with high data rate, a USB 2.0 interface is implemented. Moreover, an interface for an emulator, as well as a serial interface, is implemented for debugging the firmware of the MCU.

Fig. 10 shows fabricated the access-point module, which is composed of a motherboard and an interface board. The size of the motherboard and the interface board are 25 x 50 mm and 25 x 40 mm, respectively. A USB connector is implemented in the interface board. Power is supplied by either an AC adaptor or USB bus power. The size of the access-point module is only 25 x 70 x 5 mm. The volume is about 9 cm^3.

The motherboard of the access point is also used as a stand-alone sensor node. It is more extensible than the OCCC, since it has a sensor port, which is connected to the analog and digital I/O pins of the MCU. Sensors or an arbitrary circuit can be connected to the sensor port. While operating as a stand-alone device, the module powered by a battery.

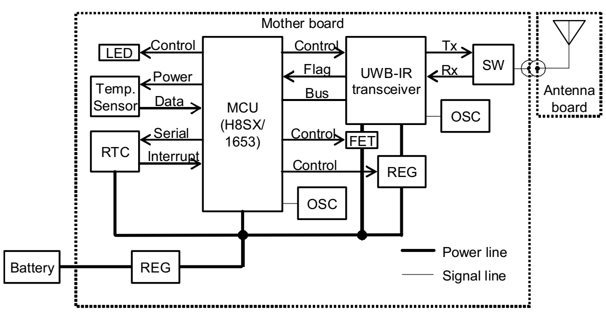
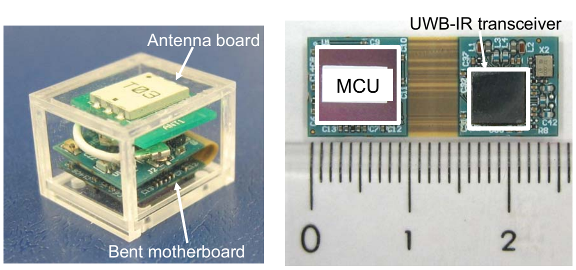


Fig. 7. Architecture of 1-cc computer with UWB-IR transceiver



(a) Whole view (b) Motherboard

Fig. 8. Micrograph of UWB-IR transceiver module: (a) whole view and (b) motherboard

V. Measurement results

Communication performance of the developed modules was measured. Fig. 11 shows dependence of packet error rate on attenuation value between the transmitter and the receiver. At a 258-kbps data rate, a communication distance of up to 30 m was achieved.

Fig. 13 shows an example of the time history of current consumption of the OCCC. The power of the UWB-IR transceiver is shut off while sensing and processing data packets. During sending of a data packet to an access point, only the transmitter is on, while the receiver is off. When sending is finished, the transmitter is turned off, and the receiver is turned on. Then, as soon as the OCCC finishes receiving an acknowledge packet from the access point, the power of the transceiver is turned off. When this operation sequence is finished, the MCU transits to low-power standby

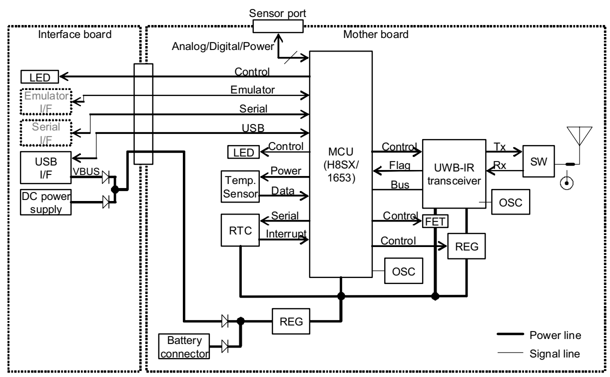
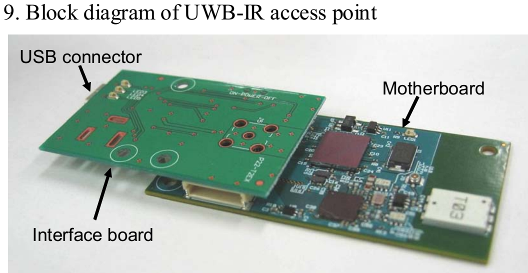
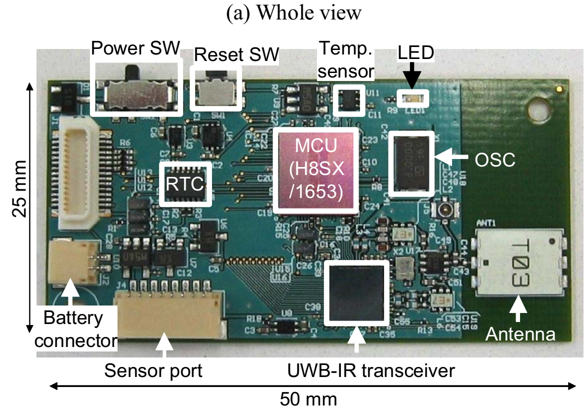


Fig. 9. Block diagram of UWB-IR access point



(a) Whole view



(b) Motherboard

Fig. 10. Micrograph of UWB-IR access point module: (a) whole view and (b) motherboard

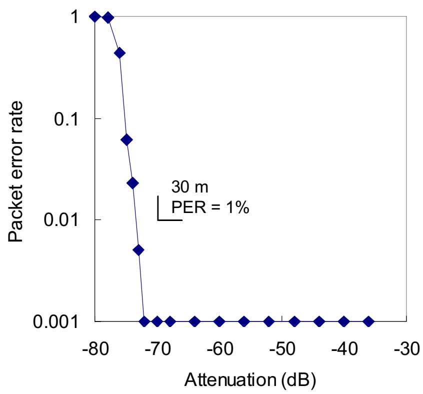


Fig. 11. Packet error rate dependence on attenuation level between transmitter and receiver

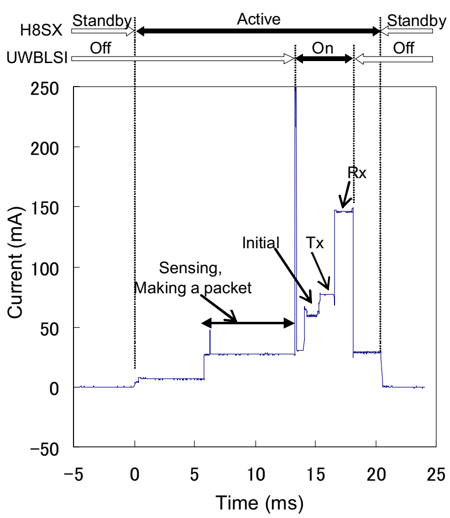


Fig. 12. Example of time variation of operating current of the OCCC

mode. The operation of OCCC was verified, as shown in the figure.

VI. Summary

An ultra-small, high-data-rate, low-power OCCC and an access-point module with an UWB-IR transceiver were developed for a wireless sensor network. The size of OCCC and the access-point module are only 1 cm^3 and 9 cm^3, respectively. To achieve high-data-rate communication, a H8SX/1653, which is configured with a parallel bus interface and the transceiver, and a USB 2.0 controller are used for the MCU. To minimize OCCC, both bear-chip implementation and a flexible printed circuit (FPC) board are applied. Power is reduced by techniques such as transition of microcontroller status to standby mode by using an external real-time clock during idle time, power shutdown of halted circuits, and detailed control of UWB-IR transceiver status. The effect of these techniques was verified by measuring the current-consumption history of the OCCC. It was confirmed by experiments that the OCCC can provide wireless communication with transmission rate of 250 kbps over a distance of 30 m.

Acknowledgements

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