FEASIBILITY STUDY ON MICROWAVE POWER TRANSMISSION TO A ZIGBEE DEVICE FOR WIRELESS SENSOR NETWORK

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Keywords: Wireless power transmission, ZigBee, Wireless sensor network

Abstract: The objective of the present study is to drive or charge a ZigBee device wirelessly by microwave power transmission. Wireless sensor network is expected to monitor several systems in order to control various infrastructures, such as electric power consumption, actively. However, power supply for sensor terminals is a critical problem to realize a fruitful wireless sensor network system. Primary batteries needs to be changed soon or later, wired power supply confines their installation location, and natural energy utilization like solar cells limits their regular operation. We therefore suggest wireless power supply for the sensor terminals by microwave power transmission. We adopt a ZigBee device as a wireless sensor terminal because of its low power consumption. We experimentally investigated electromagnetic compatibility between ZigBee and microwave power transmission, and found that there were some frequencies and power levels of microwave power transmission not to interrupt ZigBee. We also developed a microwave power receiving system which consists of a receiving antenna, a rectification circuit, a dc-dc converter, and a power storage circuit or a secondary battery. Finally we succeeded establishment of ZigBee network while driving a ZigBee device without batteries by microwave power transmission. Through the experiments, we found out intermittent microwave power transmission was preferable to CW microwave power transmission with respect to electromagnetic compatibility and rf-dc efficiency.

1 INTRODUCTION

Wireless sensor network is becoming an attractive application for monitoring systems such as energy conservation systems of buildings and houses, traffic management systems, environment monitoring systems etc. A vast number of wireless sensor terminals are scattered over a wide area, and send and receive monitoring information through ad hoc network. The collected information will be utilized to control various infrastructures, such as electric power consumption, actively.

One of the critical issues of the wireless sensor network is the way to supply electric power for sensor terminals. Primary batteris need to be changed soon or later even though power consumption of the sensor terminals is quite small. That will make the running cost of the wireless sensor network expensive. Wired power supply can provide stable operation of the sensor terminals; whereas it confines their installation location and burdens the wireless sensor network with wired cost. Natural energy utilization like solar cells with a charging system will drive the sensor terminal permanently; however their installation location and regular operation are limited because the natural energy is quite unstable.

We therefore suggest wireless power supply to the sensor terminals by microwave power transmission (MPT), in order to realize a fruitful wireless sensor network. MPT is able to provide a stable power for the sensor terminals, transmits power even for a long distance, supplies the power for multiple terminals simultaneously, and even drives the terminals without batteries. By utilizing MPT for the wireless sensor network, we can provide new applications of the wireless sensor network as well as the envisioned ones. A great potential application is a wireless sensor network system for disaster relief, as shown in Figure 1. Wireless sensor terminals located in any places normally sleep but work in emergency situations by receiving the power from vehicles or helicopters via

Mitani T., Ichihara T., Suzuki N. and Shinohara N.
FEASIBILITY STUDY ON MICROWAVE POWER TRANSMISSION TO A ZIGBEE DEVICE FOR WIRELESS SENSOR NETWORK.
DOI: 10.5220/0005413500290034
In *Proceedings of the First International Conference on Telecommunications and Remote Sensing (ICTRS 2012)*, pages 29-34
ISBN: 978-989-8565-28-0

long-range MPT. The activated terminals can collect and send disaster information via short-range wireless communication. Another application is "energy harvesting" from radio communication (Kawahara, 2009). The energy harvesting system by receiving VHF or UHF energy from TV towers were reported in 2009 (Sample, 2009). Mobile communication systems and wireless local area network systems, as shown in Figure 2, will be potential candidates as energy harvesting source in microwave band.

The objective of the present study is to drive or charge a wireless sensor terminal by MPT. We adopt a ZigBee device as wireless sensor terminal because of its low power consumption. In this paper we describe our current status of MPT to a ZigBee device, including our previous studies on development of a microwave power receiving circuit (Suzuki, 2010), and feasibility of intermittent MPT (Ichihara, 2012).

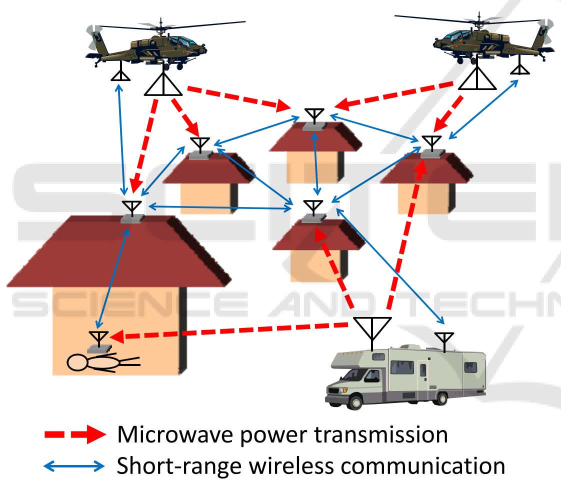

Figure 1: A conceptual image of a wireless sensor network system for disaster relief.

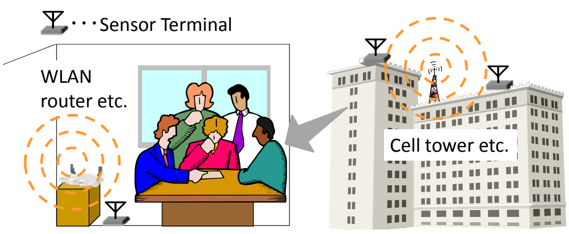

Figure 2: A conceptual image of energy harvesting from radio communications in microwave band.

2 OUTLINE OF MPT SYSTEM TO ZIGBEE DEVICE

2.1 Zigbee Device

ZigBee is one of the radio communication standards and appropriate for the sensor network for the following reasons: its power consumption is lower than wireless LAN and Bluetooth, its production cost is low, and its network capacity is large. Its low power consumption is beneficial for a MPT system from the viewpoint of electromagnetic compatibility between MPT and ZigBee.

In the present study, we are using IEEE802.15.4/ZigBee Evaluation and Development Kit TWE-EK-001 produced by Tokyo Cosmos Electric Company (TOCOS) as ZigBee devices. ZigBee network consists of the coordinator, a router and an end device. The coordinator is only one in a ZigBee network system and it coordinates the network. The router has the function of relaying data from other routers and end devices as well as monitoring. The end device only has the function of monitoring and data sending. Therefore the power consumption of the end device is lower than the coordinator and the router. Table 1 shows measured average power consumptions of a router and an end device of this kit. The power consumption of the router is stable whether or not it joins in the network; whereas the power consumption of the end device is quite small when it joins in the network. We have studied on MPT to an end device in the present paper.

In our configuration, the router and the end device sent data for nearly 2 milliseconds every 1.14 seconds. The coordinator decided to drop them from its network if it had not received data from them for 15 seconds. When it had dropped out of the network, the device was requested to join in the network again.

Table 1: Measured average power consumption of ZigBee devices.

Device type	Joining	Not joining
Router	57.4 mW	57.1 mW
End device	9.46 mW	61.8 mW

2.2 Microwave Power Receiving Circuit

Figure 3 shows a schematic of a microwave power receiving circuit. The microwave power receiving circuit consists of a receiving antenna, a rf-dc rectifier, a power storage circuit, and a dc-dc converter. The combination of the receiving antenna and the rf-dc rectifier is called “rectenna”. The power storage circuit can be omitted when the transmitted microwave power is large enough to drive a ZigBee device directly. The dc-dc converter converts the rectenna output voltage to a regulated voltage for a stable ZigBee device operation.

We adopt 2.4 GHz ISM-band, which is the same frequency band as ZigBee, as MPT frequency, from the viewpoint of efficient frequency usage. In this study, continuous or intermittent microwave without modulation transmits power to the receiving circuit.

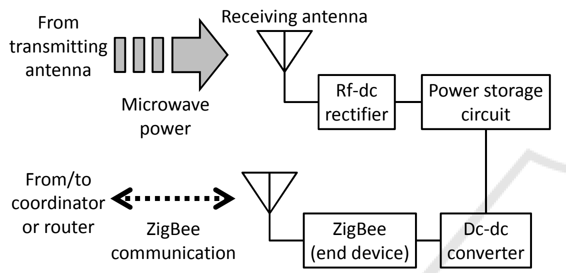

Figure 3: A schematic of microwave power receiving circuit.

3 EXPERIMENTAL STUDY ON COMPATIBITITY BETWEEN MPT AND ZIGBEE

We firstly conducted experimental measurements of electromagnetic compatibility between MPT and ZigBee, in order to investigate how MPT affected ZigBee. Also the measurements contributed to fix the frequency and maximum transmitting power of MPT in our study.

We defined and evaluated two indices on MPT power density: communicable power density (CPD) and joinable power density (JPD). CPD is the threshold of MPT power density which does not affect ZigBee. A ZigBee device can communicate with the other one under the CPD when it has already joined in the network. JPD is the threshold of MPT power density under which a ZigBee device can join in the network. The CPD is generally larger than the JPD.

3.1 Measurement Setup

Figure 4 shows the experimental configuration. The ZigBee frequency was set to 2.46 GHz (22 ch), and the network had just two devices of the coordinator and an end device. First, the coordinator, which was put behind the transmitting horn antenna, established communication with the end device. Then, the end device was irradiated with non-modulated microwave as alternative to MPT. We measured CPD with increasing the non-modulated microwave power until the communication was disabled. After that, we measured JPD with reducing the non-modulated microwave power until the coordinator established communication with the end device again.

We investigated two types of non-modulated microwave irradiation: CW microwave irradiation and intermittent microwave irradiation. During the intermittent microwave irradiation, the non-modulated microwave turned on and off under the conditions of a pulse frequency and a duty ratio.

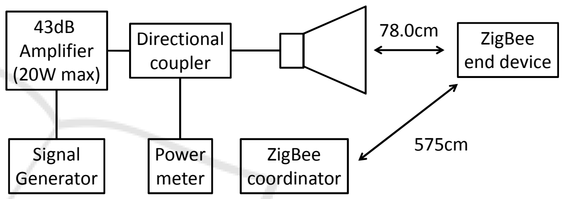

Figure 4: Experimental configuration of electromagnetic compatibility between MPT and ZigBee.

3.2 Measurement Results

3.2.1 CW microwave irradiation

We conducted CW microwave irradiation to a ZigBee end device, with changing the frequency from 2.4 GHz to 2.5 GHz (20 MHz step). We measured the maxima of the CPD and JPD at all the frequency points.

Experimental results of the CPD and JPD are shown in Figure 5. At all the frequency points, the CPDs were lower than 1 mW/cm^2 – the maximum power density determined by International Commission on Non-Ionizing Radiation Protection (ICNIRP, 1998). Around the ZigBee frequency, the power density of 5 pW/cm^2 even interrupted ZigBee. From these results, CW MPT is quite difficult to be compatible with ZigBee, in order to supply enough power wirelessly for a ZigBee device. Although we have not checked yet, CW MPT at another frequency band except 2.4 GHz band might be compatible with ZigBee.

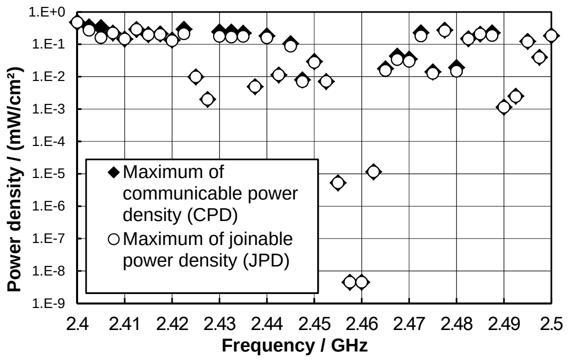

Figure 5: Measurement results of the CPD and JPD when the ZigBee end device was irradiated with CW microwave.

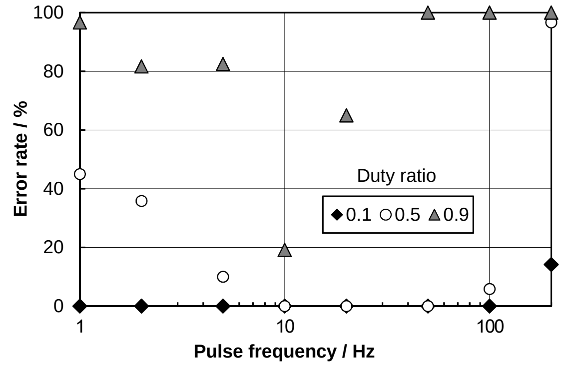

Figure 6: Measurement results of error rates when a ZigBee end device was irradiated with intermittent microwave under the peak power density of 1.91 mW/cm^2.

3.2.1 Intermittent microwave irradiation

Under the same condition as shown in Figure 4, we conducted intermittent microwave irradiation to a ZigBee end device. We fixed the intermittent microwave frequency of 2.46 GHz, at which we obtained the lowest maximum of the CPD and JPD in the CW microwave irradiation case. The end device was irradiated with intermittent microwave, within the pulse frequency range from 1 Hz to 200 Hz and the duty ratios of 0.1, 0.5 and 0.9.

From experimental results, 1.91 mW/cm^2 of the peak power density with any duty ratios allowed the end device to participate in the network and communicate with the coordinator. This means the CPD and JPD of the intermittent microwave is more than 10^8 times larger than those of CW microwave, when the MPT frequency is the same as the ZigBee frequency.

We also measured error rates of ZigBee during the intermittent microwave irradiation. Experimental results under the peak power density of 1.91 mW/cm^2 are shown in Figure 6. Since we fixed the peak power density in the measurements, the average power density was dependent on the duty ratio: 0.191 mW/cm^2, 0.955 mW/cm^2 and 1.72 mW/cm^2 at the duty ratios of 0.1, 0.5 and 0.9, respectively. The experimental results show that the ZigBee end device could communicate with the coordinator almost perfectly at the duty ratio of 0.1; whereas it seemed difficult for the ZigBee end device to send data stably at the duty ratio of 0.9.

In the measurements, interference would occur stochastically because we made the period of intermittent microwave irradiation irrelevant to that of ZigBee. Therefore, it is important to build a scheduling rule between intermittent MPT and ZigBee for a robust wireless sensor network with MPT.

4 DEVELOPMENT OF A RECEIVING CIRCUIT

4.1 Rectenna

Rectenna consists of a receiving antenna and a rf-dc rectifier. As with the experiments in Section 2, we focused on the MPT frequency of 2.46 GHz.

Circular patch antenna was adopted as receiving antenna. Figure 7 shows a photograph of the circular patch antenna. The measured antenna gain was 6.5 dBi.

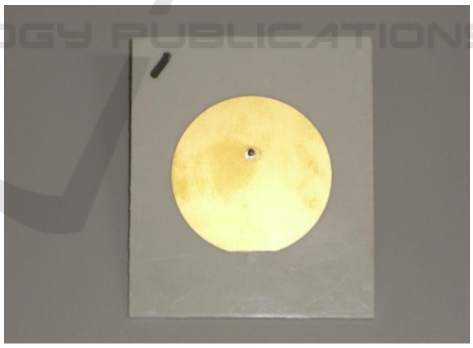

Figure 7: Photograph of the circular patch antenna.

We developed a single-shunt type rf-dc rectifier, whose photograph is shown in Figure 8. We adopted Schottky barrier diode (Avago HSMS-2860) as rectifier diode. Measurement results of rf-dc conversion efficiency are shown in Figure 9. The rectifier provided the maximum rf-dc conversion efficiency of 65 % at 2.46 GHz when the output load was 138.1 ohms, in the CW microwave case (Suzuki, 2010). The rf-dc conversion efficiency started to be dropped at an input power of 180 mW. This drop in conversion efficiency is related to the breakdown voltage of the diode.

We also investigated rf-dc conversion efficiency when the intermittent microwave was input to the rectifier. The duty ratio of the intermittent microwave was changed from 1 (CW) to 0.1, the pulse frequency was 1 kHz, and the average input power was 16 mW, 65 mW and 101 mW. Since we fixed the average input power, the peak input power was dependent on the duty ratio. The peak input power was equal to the average input power at the duty ratio of 1; whereas it became 10 times larger than the average input power at the duty ratio of 0.1. Figure 10 shows measurement results of rf-dc conversion efficiency in the intermittent microwave case. Of great interest is that the rf-dc conversion efficiency depended on the peak input power. Even if the average power is small, one can obtain the maximum rf-dc conversion efficiency by adjusting the duty ratio of intermittent microwave. The rf-dc conversion efficiency dropped down at low duty ratios when the average input power was 65 mW and 101 mW, because the peak input power became over the input power of 180 mW, where the rf-dc conversion efficiency started to be dropped.

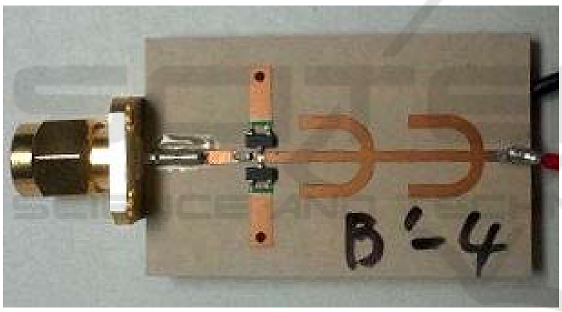

Figure 8: Photograph of the rf-dc rectifier (Suzuki, 2010).

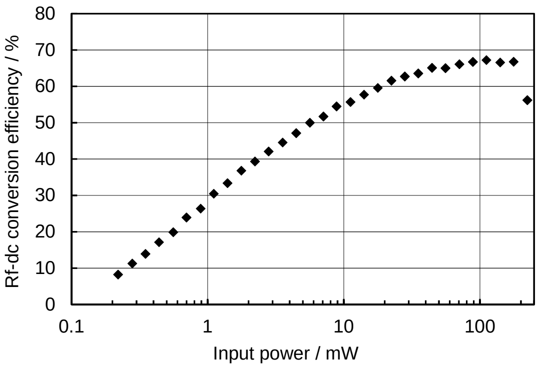

Figure 9: Rf-dc conversion efficiency of the rectifier in the CW microwave case.

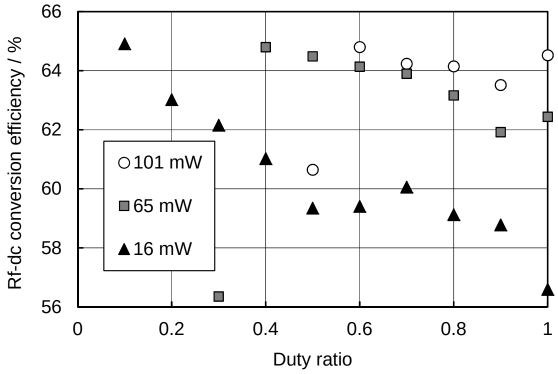

Figure 10: Rf-dc conversion efficiency of the rectifier in the intermittent microwave case.

4.2 Dc-dc converter

The rectenna output voltage became over 4 V at the input microwave power of 180 mW from the measurement results; whereas the ZigBee input voltage should be in the range from 2.7 V to 3.6 V. We therefore adopted a step-down dc-dc converter (Texas Instruments TPS62120) as dc-dc converter. This dc-dc converter provided an efficiency of over 90 % in an output voltage range around 3 V.

5 INTERMITTENT MPT DEMONSTRATION TO ZIGBEE DEVICE

We conducted demonstration experiments of power supply to a ZigBee end device by intermittent MPT. A demonstration configuration and a photograph of the demonstration are shown in Figure 11 and Figure 12, respectively. The MPT frequency was 2.46 GHz, and the pulse frequency was changed from 1 Hz to 50 Hz. Three rectennas were connected in series. The ZigBee end device had no batteries, that is, it was driven only by intermittent MPT. In this demonstration, we fixed a peak power density of 2.4 mW/cm^2 at the rectenna position.

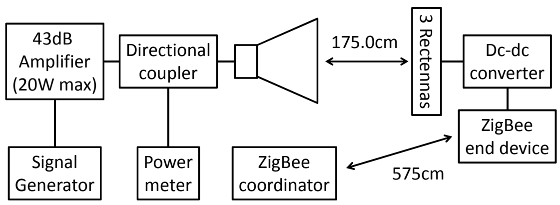

Figure 11: Configuration of intermittent MPT demonstration to a ZigBee end device.


Figure 12: Photograph of intermittent MPT demonstration to a ZigBee end device.

From the demonstration experiments, the end device was driven by intermittent MPT at any pulse frequency when the duty ratio of the intermittent MPT was above 0.4. We therefore succeeded battery-less operation of the ZigBee device by MPT. Moreover, when the pulse frequency was 10 Hz, the end device could communicate with the coordinator with no error, while its power was being supplied by MPT.

6 CONCLUSIONS

We succeeded MPT to a ZigBee device which was driven without batteries. Intermittent MPT was preferable to CW MPT because of the following reasons: ZigBee was better compatible with MPT, and higher peak power of MPT was allowed. The latter factor contributed to higher rf-dc conversion efficiency of the rectifier even at the low average power. Moreover we confirmed that the ZigBee end device worked and communicated correctly with the coordinator while its power was being supplied by intermittent MPT.

As future works, we will study on scheduling management between MPT and ZigBee. Although we succeeded intermittent MPT demonstration to a ZigBee device as a feasibility study, scheduling management will be essential for realizing a fruitful wireless sensor network. Also we will have to study how to transmit microwave power to multiple ZigBee devices in a wide area.

ACKNOWLEDGEMENTS

A part of the present study is supported by The Japan Prize Foundation.

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