Prototype Implementation of Ambient RF Energy Harvesting Wireless Sensor Networks

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***Abstract*—Energy harvesting is a key technique that can be used to overcome the barriers that prevent the real world deployment of wireless sensor networks (WSNs). In particular, solar energy harvesting has been commonly used to overcome this barrier. However, it should be noted that WSNs operating on solar power suffer form energy shortage during nighttimes. Therefore, to solve this problem, we exploit the use of TV broadcasts airwaves as energy sources to power wireless sensor nodes. We measured the output of a rectenna continuously for 7 days; from the results of this measurement, we showed that Radio Frequency (RF) energy can always be harvested. We developed an RF energy harvesting WSN prototype to show the effectiveness of RF energy harvesting for the usage of a WSN. We also proposed a duty cycle determination method for our system, and verified the validity of this method by implementing our system. This RF energy harvesting method is effective in a long period measurement application that do not require high power consumption.**

I. INTRODUCTION

A small, low-cost, wireless sensor node is important for ubiquitous sensing. However, the need for frequently replacing its battery has always been a problem, which has limited its use of WSNs. Energy harvesting is one of the key techniques used to solve this problem. We focus on using an ambient RF field as an energy source to power wireless sensor nodes. The use of this unutilized energy as a power source will not only reduce the battery replacement cost, but also enable a long period operation in WSNs. The energy generated from an energy harvester varies in time and space. Therefore the use of RF energy harvesters also requires a change in both the hardware and the software of wireless sensor nodes. Since WSNs can be applied to many types of applications such as environment and habitat monitoring, healthcare applications, and industrial process monitoring and control. Placing a large number of spatially distributed low-cost sensor nodes will increase the amount and reliability of the sensor data.

WSNs based on energy harvesting are partly in practical use. Crossbow eKo [1] is one of the solar powered WSN systems that can gather sensor data over a wireless network. Currently, the use of solar energy in energy harvesting WSNs has increased for practical applications; this is because of the fact that solar panels are easily available and they have a higher energy density as compared to other energy harvesting techniques. This high energy density allows the development of smaller sensor nodes. However, solar power strongly depends on sunlight and can therefore hardly harvest energy during the nighttime ant the amount of harvested energy depends on the weather. Hence, in order to activate a sensor node during the nighttime, it must be equipped with rechargeable batteries. These rechargeable batteries require extra recharging circuits and are usually expensive.

We propose a low cost approach using RF energy harvesting from ambient RF fields; this approach mainly relies on TV broadcast signals. TV broadcast signals that are not received by the TV viewers are generally dissipated as heat resulting in a waste of energy. This wasted energy can be utilized to power a low-power sensor node. Since the energy harvested from TV broadcasts is relatively time-invariant when compared with solar power, low-cost capacitors can be used instead of expensive rechargeable batteries in the sensor nodes. This paper introduces the prototype implementation of a WSN powered by RF energy harvesting using TV broadcast signals. First, after introducing related researches in section II, we describe the characteristics of the energy harvested from TV broadcasts in section III. Next, in section IV, we discuss the energy decrease issue caused by the daily and weekly maintenance at the radio tower. In addition, we show that the harvested energy is likely to vary in time and space. Hence, it is essential not only to apply a power-saving technique to the hardware but also implementing an energy neutral operation. In section V, we describe an adaptive duty cycle determination method to deal with the abovementioned issue. Finally, in section VI, we summarize the results of this paper.

II. REALTED RESEARCH

Passive Radio Frequency IDentification (RFID) also harvests electrical energy from the received RF signal for data transmission. However, the technical issue associated with RF energy harvesting differs from RFID in several ways. First, as in the case for RFID, a reader generates an intense radio emission, and the tag replies to the reader using the backscattered radio signal. In RFID systems, unless the reader scans the tag, the tag will maintain silence. In contrast to data transmission carried out by RFID systems, wireless sensor nodes need to actively sense the data. Moreover, since the amount of power harvested from ambient RF fields is limited, wireless sensor nodes need to operate intermittently.

An RF energy harvesting technique that converts ambient RF energy to electrical energy can be classified into a few types of techniques.

NEC's researchers have successfully reproduced 250 mW from the electro-magnetic noise generated from a fluorescent lamp and powered an RF tag [2]. Cheng et al. have also used a similar approach as that used by NEC's researchers [3]. Patel et al. have focused on the noise generated during turning on and turning off home electric appliances and discussed the feasibility of powering RFID tags with the harvested energy [4].

In contrast, Kurs et al. have explored the possibilities of achieving wireless power transfer using electro-magnetic waves [5]. This wireless power transfer is assumed to transfer energy from space to ground. On the other hand, several small wireless power transfer products that can be used in one's houses have been released, such as Powercast [6]. Powercast transmits a few watts of power, and small devices such as IR remote controllers can receive hundreds of microwatts of power.

Intel Research has conducted a research related to this topic in a project called Wireless Ambient Radio Power (WARP) [7]. 60 μW of RF energy was harvested to power a digital thermo-hygrometer using a Yagi-antenna, a rectifier circuit, and a 4-stage Cockcroft Walton voltage multiplier placed at 4km from a TV tower. Although they have succeeded in capturing a certain amount of energy, they have not discussed the feasibility of the captured energy in WSNs.

Usually, governments restrict the transfer of intense RF signals because they can block other types of radio transmissions; thus electro-magnetic fields are considered as a shared property. On the other hand, radio and TV broadcast signals are designed to cover the entire range of human activities; thus usually transmitted using intense RF signals. RF energy harvesting would be attractive if the harvested energy is sufficient for powering small devices such as widely distributed sensor nodes.

Raghunathan et al. introduced the concept of energy neutral operation[8]. This concept states that the energy overhead for charging and recharging decreases and the energy efficiency increases when the duty cycle is adapted to the harvested energy profile. They used an EWMA filter to predict the energy profile for the next day. This prediction enabled to adapt the workload to the sunrise and sunset. In this study, instead of using rechargeable batteries, we use an electrolyzed capacitor for storing energy to reduce the implementation cost. Since RF energy harvesters cannot harvest sufficient energy as compared to solar power, the duty cycle must be determined over very short intervals. The amount of energy leakage caused when using capacitors is assumed to be much greater than that caused when using rechargeable batteries. Thus, a frequent power management is required.

III. System Construction and Implementation

The amount of received RF power W_a depends on the distance decay, which can be calculated as follows; where λ, z, G_{at}, G_{ar} and W_t are, the wavelength, the distance between the transmitter and the reciever, the transmitter antenna gain, the receiver antenna gain, and transmission power, respectively.

$$W_a = \left(\frac{\lambda}{4\pi z}\right)^2 G_{at} G_{ar} W_t \tag{1}$$

This equation assumes free-space propagation. Thus, in a real environment, the amount of received power will be much less; the received power attenuates from z^{-2} to z^{-4}. Therefore, even though the transmitted power at a broadcast station is in the order of more than several kilowatts, the received power will be the order of microwatts to milliwatts. Generally, a sensor node consumes more than 10 mW of power in order to transmit a packet over a wireless link. By using a rectenna, we regenerate electricity and supply it to the MCU. We use a voltage doubler rectifier circuit for the rectifier supplying DC voltage to the MCU.

A. Rectenna Implementation

A rectenna is a rectifying antenna that consists of an antenna and a rectifier circuit. A high-efficiency rectenna has been studied assuming the use in Solar Power Station (SPS) [9]. Although TV broadcasts use VHF or UHF waves, the basis is nearly identical. By tuning the rectenna to several broadcast channels, it is possible to double and triple the amount of power.

B. Rectifier Circuit Evaluation

We evaluated the rectifier circuit, by measuring its load characteristics and frequency characteristics. First, to measure its load characteristics, we connected a signal generator and the rectifier with a load resistor (Figure 1). The output power can be calculated on the basis of the voltage across the resistor. In Figure 2, the vertical axis represents the efficiency of the rectifier circuit; it should be noted that the input power is varied from -9 dBm to 9 dBm, while the load resistor is varied from 50 Ω to 10 kΩ. Results of our evaluation show that the lower the input power is, the lower the efficiency of the rectifier circuit is. The results also show that a load resistor of 1 kΩ can extract maximum power from the rectifier circuit. Secondly, to measure the frequency characteristics, we performed another measurement using the same equipment as that used for measuring the load characteristics of the rectifier circuit. In Figure 3, the vertical axis represents the efficiency of the rectifier circuit; it should be noted that the input power is varied from -9 dBm to 9 dBm, while the input frequency is varied from 1 MHz to 1 GHz. As shown by the previous results, it is also found that the weaker the input power is, the lower the efficiency of the rectifier circuit is. RF signals ranging from 15 MHz to 800 MHz can be rectified at an efficiency higher than 50%. When the rectifier circuit is equipped with an antenna, the frequency range will be chosen.

Both results showed that when the input power was low, the efficiency of the rectifier circuit was low. Therefore, it is very important to improve the rectifier circuit in order to rectify weak RF signals at a high efficiency.

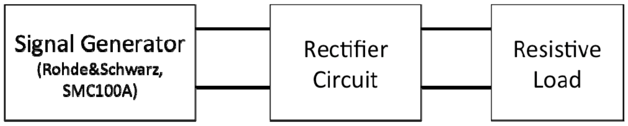

Figure 1. Schematics of signal generator, rectifier and resistive load

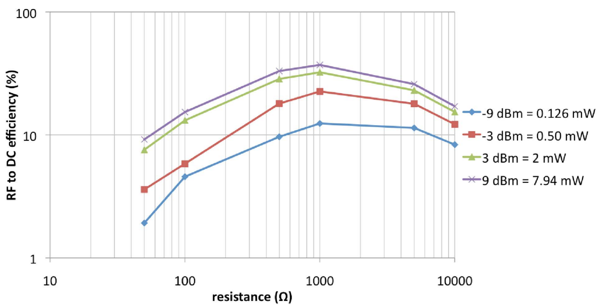

Figure 2. Rectifier efficiency with variation in resisitve load

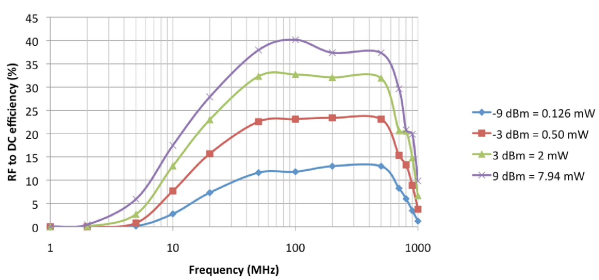

Figure 3. Rectifier efficiency with variation in input frequency

C. Prototype Implementation

We developed a sensor node prototype operating on RF energy harvesting from TV broadcast signals. This prototype consists of a rectenna, an MCU and an RF transmitter. Figure 4 shows an overview of the prototype, which includes MSP430F2274 and CC2500 both of which are included in the eZ430-RF2500 solar energy harvesting kit [10]. MSP430F2274 is a low-power 16-bit MCU; CC2500 is a low-power 2.4 GHz transceiver. The prototype stores electricity in an aluminum electrolytic capacitor to power the MCU (Figure 5). In order to avoid the node from facing energy shortage, its capacity needs to be carefully calculated. The most-power-consuming task is a radio transmission task. The minimum capacity C_{min} required for the radio transmission task can be calculated by the following equation using the transmission time T, average current I_a, rectenna output voltage V_{out}, and MCU minimum voltage V_{min}.

$$C_{\min} \geq \frac{I_a \times T}{V_{out} - V_{\min}} \qquad (2)$$

From the above equation, it can be inferred that it is preferable to use a larger capacitor. However, the capacitor should not be too large, since a large capacitor takes a long time to get charged and reach the MCU minimum voltage. On an average, the radio transmission task consumes 13.14 mA for 3.4 ms. Therefore, we chose a 100-µF capacitor. We used SimpliciTI as a network protocol to gather data from the end nodes. SimpliciTI is a proprietary network protocol provided by Texas Instruments. SimpliciTI is capable of developing a small-scale network, which includes less than 256 nodes. SimpliciTI protocol consumes less power than Zigbee with RTOS.

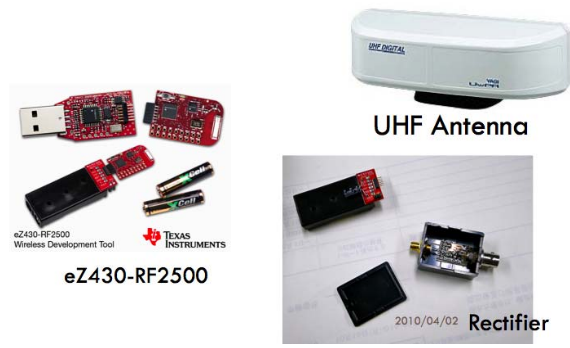

Figure 4. Equipment used for this experiment

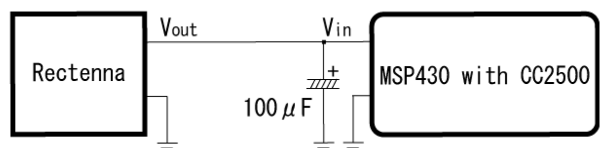

Figure 5. Simplified schematic of the RF energy harvesting node

IV. Energy Harvesting from TV Broadcasts

Ambient energy sources are usually unstable, and cannot harvest energy during a certain period of time (Figure 6). Therefore, it is important to smooth the variation of the harvested energy in order to perform a sensing task at regular intervals. As for solar power, we cannot harvest energy at nighttimes; therefore a more expensive storage must be used. RF energy harvesting using TV broadcast signals can reduce the costs because of the time-constant power supply; this is because the duration of energy decrease is shorter.

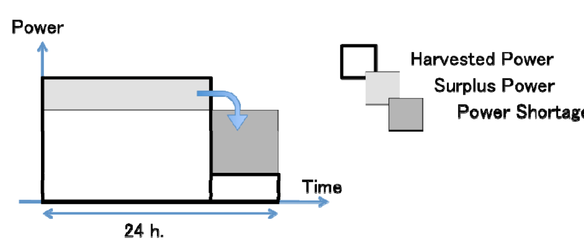

Figure 6. Concept of energy balancing

A. Characteristics of RF Energy Harvesting

RF energy from TV broadcasts is 100 times weaker than solar power [11]. In addition, as compared to solar energy that can only obtain power during daytimes in fine weather, RF energy from TV broadcasts can obtain power all day except during the maintenance period. The energy harvested from TV broadcasts could not be estimated properly because the RF power attenuated because of the multipath effect, reflection, shielding objects, etc. We conducted a 7 days measurement of the characteristics of TV broadcast RF energy harvesting. The objective of this measurement is to clarify the characteristics of RF energy harvesting and to verify that energy harvested from the ambient RF field is sufficiently stable for WSNs. Unlike solar power[1], TV broadcast signals are artificially generated; therefore they are not interfered by the weather. This measurement was performed in the balcony of our laboratory, which is located 6.6km away from the Tokyo tower; this tower broadcasts TV signals over the UHF band. Figure 7 shows the amount of power harvested over 7 days. A 1kΩ resistor was used as a load resistor; this resistor can extract maximum power from the energy harvester.

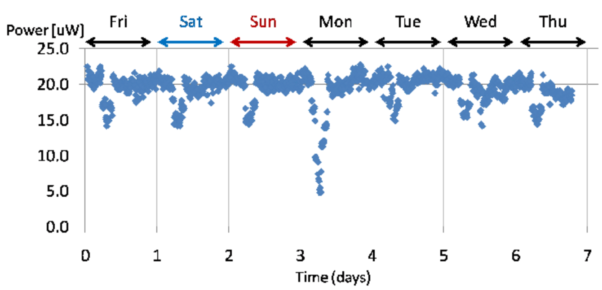

Figure 7. Energy profile for RF energy harvesting

Results show that the amount of harvested power decreases every day at midnight, i.e. from around 1:00 a.m. to 6:00 a.m.; this decrease is caused by the daily and the weekly maintenance in some broadcast stations. Except the power decrease at midnight, RF energy is rather time constant as compared to solar power which can only provide energy during the daytime and depends on the weather.

B. Evaluation of the Sensor Node Prototype

The prototype test was performed at a location that was 500m away from the Tokyo tower; this tower broadcasts digital TV signal over UHF radio frequency. Figure 8 shows the field intensity at the location where the experiment was conducted. The results show that VHF and UHF TV broadcast signals are used in majority.

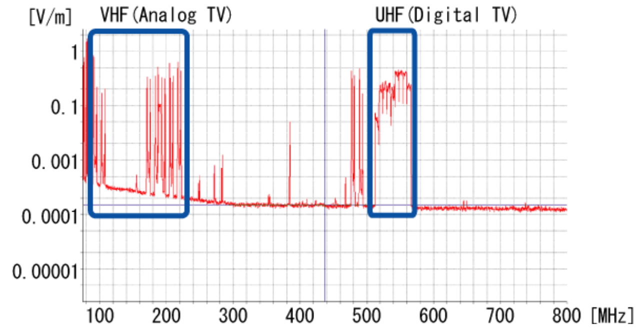

Figure 8. Field intensity at the location where the experiment was performed

An experimental network was constructed by three components, namely, an access point node connected to a PC via a USB, a battery-powered end node, and an RF-energy harvester-powered end node. The RF energy harvesting end node senses and transmits sensor data every 5 s toward the access point, while the battery powered node transmits every second over a 2.4 GHz wireless link. Sensor data is a set of 2 bytes temperature data and 1 byte of voltage data. Because the RF energy harvester only supplies several hundred microwatts of power, and data transmission consumes dozens of milliwatts of power, the sensor node has to wait for a certain period of time to charge the capacitor. Figure 9 shows the voltage across the capacitor. The voltage decreases to 2.4 V after data transmission and charges up to 2.9 V in approximately 5 s. The end node activates for 3.4 ms to transmit the sensor data toward the access point. Thus, at a location near the Tokyo tower, a sensor node can operate at a duty cycle higher than 1:1500.

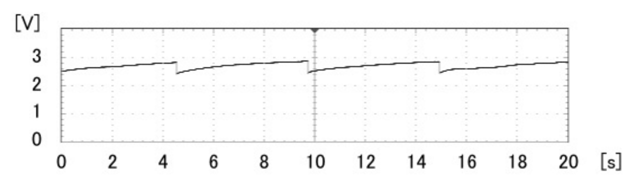

Figure 9. Capacitor voltage at the node working every 5 seconds

Since the channel propagation changes in time, and most energy harvesting WSNs consume a higher current than the charging current from the harvested energy, the harvested energy should be monitored and the system must have power management. In addition, the sensing frequency can be increased when the generated power is higher than the consumption rate.

V. ADAPTIVE DUTY CYCLE DETERMINATION METHOD

Since the harvested energy from TV broadcasts attenuates because of the multipath effect, reflection and shielding objects, it is difficult to supply a constant amount of energy. As is well known, a WSN reduces power consumption by cutting off the power supply to the unused circuits. Since the transmitter module plays the biggest role in the power consumption of the WSN, it is effective to use the RF module in the sleep mode while the sensor node is performing other tasks. Transmission and reception consumes a large amount of power. Figure 10 shows the power consumption of the sensor node prototype, which uses CC2500 as a transmitter. Starting from the left, this figure shows the time and consumption current required for sensing and calculation, PLL calibration, RF reception, and RF transmission. The power consumed during transmission is 5-6 times greater than that consumed by other tasks. Therefore, it is effective to avoid high power consumption in the transmitter module and oscillation calibration. To reduce the power consumption and achieve high power efficiency, it is very important to choose an appropriate duty cycle. In the case of energy harvesting systems, it is essential to not only save the consumed power, but also balance the harvested power with the consumed power.

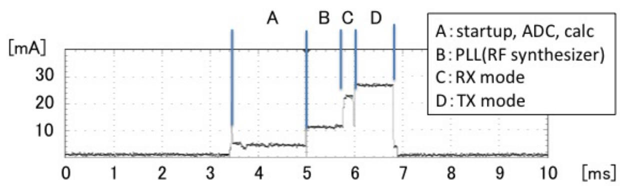

Figure 10. Example of consumption current when performing a task on MS430RF2500

The charged energy in the aluminum electrolytic capacitor can be derived from $CV^2/2$ where V is the voltage across the capacitor. The main task will only be performed when the electrolytic capacitor is sufficiently charged. Because the task performed to determine the supply voltage consumes 3% of the total energy consumed by the main task, frequent power management will lead to a large energy loss. On the other hand, if power management is not frequent enough, the node will suffer from energy shortage or some amount of energy will be wasted, which, if did not occur, could have improved the sensing frequency. We developed an adaptive duty cycle determination method that enables a low overhead power management.

By sensing the voltage V twice, we can calculate the charged energy E during a certain period using the following equation.

$$E_1 - E_0 = \frac{CV_2^2}{2} - \frac{CV_1^2}{2} \qquad (3)$$

Therefore by using the known constant C, we can estimate the time required for the capacitor to be sufficiently charged.

Figure 11 shows the pseudo code for this method. V_1 represents the voltage at the moment the voltage check while V_0 represents the voltage at the last voltage check. This method involves the following steps. First check the voltage across the capacitor, and execute the main task if the voltage is sufficiently high. If not, sleep for a certain period, and check the capacitor voltage and calculate the energy difference from the last sense. If the sleep period is sufficiently long, shorten the sleep period by a factor beta. If the sleep period is not sufficiently long, increase it by a factor gamma. Using this method, we can determine a suitable duty cycle.

```
while(1){
        volt_check(V_1);
        if((1/2*CV^2) > (MAINTASK_ENERGY + alpha)){
                t = t - beta;
                maintask();
        }else if((1/2*C(V_1^2-V_0^2)+MAINTASK_ENERGY) < 0){
                break;
        }else{
                E = 1/2*C(V_1^2-V_0^2)+MAINTASK_ENERGY;
                t' = t * MAIN / E + gamma;
                sleep(t' - t);
                maintask();
        }
        V_0 = V_1;
        sleep(t);
}
```

Figure 11. Pseudo code

Figure 12 shows the result obtained after implementing the proposed method. We connected a signal generator to the rectifier circuit and varied the input power and supplied DC voltage to the MCU (Figure 13). Figure 12 shows the results obtained when the input power increases, and sensing frequency increases.

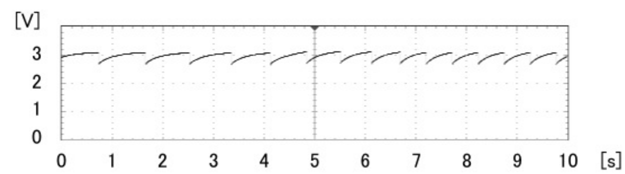

Figure 12. Activating timing prediction method (transient state)

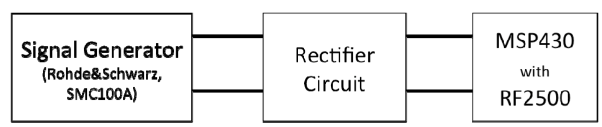

Figure 13. Schematics of signal generator, rectifier and MSP430 MCU

VI. CONCLUSION

Energy harvesting eliminates the use of dry cells, and solves the problem of frequent battery replacement. This technique helps conserving the environment by reducing battery disposal. We focus on RF energy as an ambient energy source. Although, the amount of energy reproduced from ambient RF fields is limited, sensor nodes can be operated over a long period of time when they are used. As a first step to achieve our objective, we developed a wireless sensor node prototype and implemented an adaptive duty cycle determination method. This prototype is capable of sensing and transmitting temperature data every 5 s by RF energy harvesting. An RF energy harvester consists only of a rectifier and an antenna. Therefore, its manufacturing cost is low, and hence, a large number of sensor nodes can be placed densely. This RF energy harvesting technique can be effective in long-period measurement applications that do not require high power consumption.

ACKNOWLEDGMENT

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