Experiment of Power Supply Method for WLAN Sensor Using Both Energy Harvesting and Microwave Power Transmission

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Abstract. This paper proposes to improve effectiveness of supplying a sensor with energy using microwave power transmission (MPT) and energy harvesting (EH). The MPT duration should be as short as possible to avoid serious interference between the MPT and wireless local area network data transmission when co-channel operation of both microwave power transmission (MPT) and wireless data transmissions is performed. To shorten the MPT duration, we use multiple power sources such as an MPT source and an EH source to supply a sensor with power. Here, an overcharge or an energy shortage could occur at the sensor if the power supplied by both the MPT and EH sources is not adjusted appropriately. To solve this problem, the power supplied by multiple sources should be estimated precisely. In this paper, we propose a scheme for estimating the power supplied by multiple sources on the basis of an existing MPT scheduling system and then conducted an experiment using the scheme. From the experimental results, it is confirmed to estimate the power supplied by multiple sources successfully. In addition, the required MPT duration when the EH source is used is reduced compared to that when it is not used. Moreover, it is confirmed that the sensor station successfully estimates the power supplied by an MPT source and that by an EH source and adequately configures the MPT duration.

1. Introduction
The wireless sensor network (WSN) [1] is a technology for collecting various types of information by using many wireless sensors; it will be used in applications such as medical care or smart grids. Because the number of sensors connected to the network is expected to increase, it would become costly to replace the batteries. Thus, batteryless wireless sensors should be used to reduce the need for maintenance. As the technology to realize batteryless sensors, microwave power transmission (MPT) [2] and energy harvesting (EH) are cited. In this paper, we have studied how to power a sensor using both EH and MPT. We assume that a photovoltaic cell is alternately used as the EH source.

When we supply a sensor with power using MPT, the problem is serious interference between MPT and wireless local area network (WLAN) data transmission during co-channel operation of MPT and WLAN communication [3]. Therefore, a scheduling scheme for time division operation of MPT and WLAN communication has been proposed [4] to avoid the interference.
In this paper, on the basis of an existing MPT scheduling system [4], we propose a scheme for estimating the power supplied by multiple sources such as an MPT source and a photovoltaic cell and then conducted an experiment on it.

There are many studies on sensors for WSNs. In [5], a simulation of the power consumed by sensor network applications is described. In [6], the energy replenishment process and storage constraints of a rechargeable battery are discussed in terms of the design of efficient transmission strategies. In addition, a multipowered platform solution for wireless devices is presented in [7].

2. Experimental Setup

Fig. 1 illustrates the experimental setup, which consists of three devices: a sensor station (SS), an energy source (ES), and an access point (AP). In addition, Fig. 2 shows the SS and the horn antenna of the ES. We explain the detail of each device as follows.

- The SS consists of a rectenna (a patch antenna and a rectifier), a photovoltaic cell, two diodes for preventing reverse current, a capacitor, a DC-DC converter, a microcontroller board, a sensing device, and a WLAN module. The microcontroller board and the WLAN module operate on energy stored in the capacitor of the SS. The capacitor is charged with the photovoltaic cell and the rectenna.
- The AP is compatible with IEEE 802.11g WLAN. The AP periodically broadcasts beacon frames to manage the network. If the AP receives a data frame from the SS, the AP will forward the data frame to the ES.
- The ES consists of a horn antenna, an amplifier, a radio frequency signal generator, a microcontroller board, a laptop, and a WLAN module. The microcontroller board determines whether the ES transmits microwave power or not. In addition, the microcontroller board forwards data frames transmitted from the SS via the AP to the laptop. Here, the laptop is used only to display data frames transmitted from the SS via the AP, not to control the MPT.

3. Proposed Estimation Scheme for Using Multiple Sources

In this section, we explain the scheduling scheme used in this experiment and the proposed scheme of estimating the power supplied by multiple sources.

3.1. Scheduling scheme

Fig. 3 illustrates the operation of the SS, and the definitions and values of the symbols used in Fig. 3 are summarized in Table 1.

The operation of the SS is explained in detail as follows. The microcontroller board of the SS measures the capacitor voltage of the SS and then calculates the energy stored in the capacitor.
Using the information on the energy, the microcontroller board determines the MPT duration using the scheme described in Sect. 3.2. The microcontroller board switches the WLAN module from sleep mode to active mode and forwards the transmitted data to the WLAN module. The data are transmitted to the ES when the WLAN module is switched to awake mode for receiving beacon frames, which contain delivery traffic indication map (DTIM) information, called DTIM beacon. The DTIM beacon is broadcasted at predetermined intervals. After transmitting the data frame and receiving the DTIM beacon, the WLAN module is switched to sleep mode. The microcontroller board is switched from sleep mode to awake mode after the MPT duration, and then the SS measures the capacitor voltage.

The operation of the ES is explained as follows. The ES receives data frames from the SS and then transmits microwave power during the MPT duration determined by the SS such that microwave for MPT does not influence on data transmission. In addition, the ES also acts as a data sink.

3.2. Estimation of power supplied by multiple sources and determination of MPT duration

In the proposed scheme, the SS operates to make the capacitor energy converge to a predetermined target value \( E_{\text{target}} \). The reason is to prevent overcharging and energy shortage.

First, we define the symbols used in our proposed scheme. Let \( V_{SS,k} \) and \( e_{SS,k} \) denote the voltage of the capacitor and the energy stored in the capacitor at the time of \( k \)-th data frame transmission of the SS, respectively. In addition, we let \( p_{\text{micro},k} \) and \( p_{\text{solar},k} \) denote the power supplied by the MPT source and EH source, respectively, estimated at the time of the \( k \)-th data transmission, and also let \( n_{t,k}^{*} \) denote the coefficient for determining the MPT duration \((n_{t,k}^{*}+1)T_{\text{DTIM}}\).

Next, we explain our proposed scheme. The SS measures \( V_{SS,k} \) and uses it to calculate \( e_{SS,k} \). Here, the SS has information on \( e_{SS,k-1}, p_{\text{micro},k-1}, p_{\text{solar},k-1}, \) and \( n_{t,k-1}^{*} \). In our proposed scheme, the following equation is satisfied:

\[
e_{SS,k} - e_{SS,k-1} = p_{\text{micro},k-1} \cdot n_{t,k-1}^{*} \cdot (T_{\text{DTIM}} - T_{p}) + p_{\text{solar},k-1} \cdot (n_{t,k-1}^{*} + 1)T_{\text{DTIM}} - \dot{e}_c(n_{t,k}),
\]

where \( \dot{e}_c(n_{t,k}) \) represents the power consumption during the \((k-1)\)-th and \(k\)-th data transmissions. The SS estimates the power supplied by either the MPT or photovoltaic generation assuming that the other type of supplied power has not increased or decreased since the last estimated value. In other words, we assume that if \( k = 0 \) then \( p_{\text{micro},k} = 0 \), if \( k \) is even and \( k \neq 0 \) then \( p_{\text{micro},k} = p_{\text{micro},k-1} \), and if \( k \) is odd then \( p_{\text{solar},k} = p_{\text{solar},k-1} \). On this assumption we calculate the value for the other type of power using (1).
Table 1. Definitions and values of parameters.

| Symbols    | Definitions                                               | Values         |
|------------|-----------------------------------------------------------|----------------|
| $E_{c,DTIM}$ | Energy consumption of SS for DTIM reception               | 17.4 mJ        |
| $E_{ct}$   | Energy consumption of SS for data frame transmission      | 21.51 mJ       |
| $T_{DTIM}$ | DTIM interval                                             | 10.24 s        |
| $T_{rec}$  | Duration of SS energy consumption to receive DTIM beacon  | 40 ms          |
| $T_{p}$    | MPT guard time for data transmission                       | 2.0 s          |
| $T_{act}$  | Duration of active mode of SS                              | 90 ms          |
| $P_{sleep}$| Power consumption of SS in sleep mode                      | 6.6 mW         |

Finally, we explain a method to determine MPT duration. The SS determines $n^*_t$ using the following equation:

$$
\Delta(n_{t,k}) = E_{target} - [e_{SS,k} + \hat{e}_t(n_{t,k}) - \hat{e}_c(n_{t,k})],
$$

$$
n^*_t := \begin{cases} 
0 & \text{if } k=0, \\
0 & \text{if } k \neq 0 \text{ and } \Delta(n_{t,k}) \leq 0, \forall n_{t,k}, \\
\arg\min_{n_{t,k} \in N} \Delta(n_{t,k}) & \text{otherwise,}
\end{cases}
$$

where $N = \{n | \Delta(n_{t,k}) > 0, n = 1, \ldots, N\}$, $\hat{e}_t(n_{t,k})$ represents the power supplied during the $(k-1)$-th and $k$-th data transmissions, and $N$ represents the predetermined maximum value of $n^*_t$. The SS also informs the ES of the MPT duration $(n^*_t + 1)T_{DTIM}$. Then $\hat{e}_t(n^*_t)$ and $\hat{e}_c(n^*_t)$ in the above equation are defined as

$$
\hat{e}_t(n_{t,k}) = (n_{t,k} + 1) \times p_{solar,k} \times T_{DTIM} + n_{t,k} \times p_{micro,k} \times (T_{DTIM} - T_p),
$$

$$
\hat{e}_c(n_{t,k}) = E_{ct} + P_{sleep} \times (T_{DTIM} - T_{act}) + n_{t,k} \cdot [E_{c,DTIM} + P_{sleep} \times (T_{DTIM} - T_{rec})].
$$

4. Experiment

4.1. Experimental parameters

Fig. 4 illustrates the position of each device, the distances between each pair of antennas, and the power density at each antenna. Here, the input power of the horn antenna is 10.3 W when the ES transmits microwave power. The SS is positioned in front of the horn antenna of the ES. The WLAN modules of the ES and the AP are positioned behind the horn antenna to prevent interference with data communication.

The SS, ES, and AP transmit data using 2.446–2.468 GHz bands, while microwave for MPT uses the 2.457 GHz band. The antenna gain of the horn antenna and the patch antenna is 16.1 dBi and 7.7 dBi, respectively. The capacitance of the capacitor of the SS is 10 F, and the withstand voltage of the capacitor is 2.7 V. In addition, $E_{target}$ is set to be 31.25 J and $N$ is set to be 5. The DC–DC converter is used to convert the capacitor voltage to 3.3 V, which is required for operating both the microcontroller board and the WLAN module.

4.2. Experimental results

Fig. 5 shows the transition of $e_{SS}$ when a photovoltaic cell is used, and Fig. 6 shows the results without a photovoltaic cell. The shaded areas in the figures illustrate the MPT duration. Figs. 5
and 6 show that $e_{SS}$ successfully converged to $E_{target}$. These results indicate that the power supplied by the MPT source and the photovoltaic cell was successfully estimated. In addition, compared with Fig. 6, the MPT duration after convergence of $e_{SS}$ to $E_{target}$ in Fig. 5 was reduced.

5. Conclusion
In this paper, we proposed a scheme for estimating the power supplied by an MPT source and that of an EH source on the basis of the existing MPT scheduling scheme and then conducted an experiment in which a sensor is powered with multiple sources. We confirmed the feasibility of the scheme; that is, compared with the MPT duration for a sensor without a photovoltaic cell, that for a sensor with a photovoltaic cell is reduced. Thus, by using a photovoltaic cell, serious interference between the MPT and WLAN data transmission is avoided more effectively.

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