Ambient-RF-Energy-Harvesting Sensor Node with Capacitor-Leakage-Aware Duty Cycle Control

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Abstract— **In this paper, we present a software control method that maximizes the sensing rate of wireless sensor networks (WSN) that are solely powered by ambient RF power. Different from all other energy harvesting WSN systems, RF powered systems present a new challenge for the energy management. A WSN node repeatedly charges and discharges at short intervals depending on the energy intake. A capacitor is used for an energy storage in the energy harvesting system because of its efficient charge and discharge performance and infinite recharge cycles. When this charging time is too short, the node is more likely to experience an energy shortage. On the contrary, if it is too long, more energy is lost because of the leakage in the capacitor. Therefore, we implemented an adaptive duty cycle control scheme that is optimized for RF energy harvesting. This method maximizes the sensing rate considering the leakage problem, a factor that has never previously been studied in this context. Our control scheme improves efficiency by aggregate evaluation of the operation reliability and leakage reduction.**

I. INTRODUCTION

Energy harvesting technologies such as solar panels, piezoelectric devices, thermocouples, and RF energy scavengers are attracting a great deal of attention. There is ample research focusing on energy harvesting devices and their operations [1]. Energy harvesting can dramatically extends the operating lifetime of nodes on wireless sensor networks (WSNs). Finally, this technology enables battery less operation and reduces the operation cost of WSN, which are mainly due to battery replacement. Thus, these technologies are important for the sustainable operations of a WSN. In this paper, we focus on RF energy harvesting, which can produce only a small amount of energy but is not affected by weather and so it is more stable than solar and wind power. Almost all energy management methods for energy harvesting are discussing solar panels, wind power, and piezoelectric devices. On another front, RF energy harvesting has the specific characteristic than other energy sources. For instance, because we rely on "ambient" RF signals which are originally intended for other communication and broadcast systems, the amount of harvested energy has both a long term fluctuation due to radio tower service schedules and human activity patterns and short term variability due to fading and noise. Therefore, we designed an energy management method that is robust against both influences. In this research, we use capacitors for energy storage because they have good charge and discharge performances. Capacitors are better than batteries in this respect and there is no limitation about the number of recharge cycles. However, capacitors allow more energy leakage compared to batteries. Thus, we have to deal with capacitor leakage problem it results in relatively large amount of energy loss in comparison to scavenging energy from a harvester.

Contributions of this paper is summarized as follows, (1) Introduction of the optimal stored energy level calculation by the aggregate evaluation of capacitor leakage and the energy shortage risk. (2) Adaptive optimal operation point tracking considering harvested energy variability. (3) Implement the duty cycle control on micro controller and evaluate it on a simulation with measured TV radio wave data. Finally we achieved 5.56% leakage reduction than without operation point tracking. Our proposed method can reduce its leakage by the determination of optimal capacitor stored energy. In addition to that, the optimal stored energy adjustment is adaptive to both the short-term and long-term transitions of harvested energy. Thanks to these energy managements, we achieve efficient energy usage and maximize sampling rate.

II. RELATED WORK

Most microprocessors used for WSN can save the current consumption by making use of the sleep state. Transition time between the active mode and the sleep mode is rather quick. Software energy managements for WSNs are typically realized by exploiting this feature and thus the goal of the energy management is to determine the duty cycle which is the ratio of the duration of the active state to the total period of a repetitive cycle. Kansal et al. introduced the energy neutral operation (ENO) concept [2]. In ENO, the duty cycle is always determined to maintain the condition that the energy consumption is always less than the harvested energy. The ENO concept achieves $B_t > B_0 \ \forall t > 0$, using an initial stored energy level of $B_0 \in [0, 1]$ and a current stored energy level of $B_t \in [0, 1]$. ENO is a requirement for system sustainability. Extending upon ENO, Vigorito et al. proposed ENO-MAX [3]. This operation aims to sustain the condition of $B_t = B_0 \ \forall t >$

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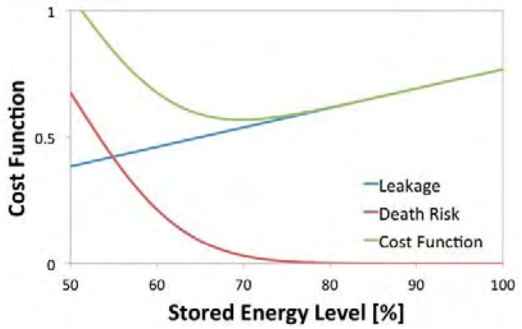

Figure 1. Aggregate cost function.

0 because if the harvested energy overshoots energy consumption, the system will not efficiently utilize the available energy. Hence, they defined an objective function as the average of $(B_t - B_0)^2\ \forall t > 0$ and applied a control method for minimizing it by linear quadratic (LQ) tracking control [4]. In short, this control method leads the system to sustain stored energy level B_t as B_0 even if the energy supply is unstable. Thus, B_0 is a significantly important parameter of this control method and should be the optimal stored energy level.

III. LEAKAGE AWARE OPERATION POINT TRACKING

In the LQ tacking control system, system operation point is represented by the stored energy level. In order to achieve an efficient operation, we should lead the operation point to track the optimal point that means operating on the optimal stored energy level. In this research, we proposed how to calculate the optimal stored energy level and a tracking method to lead the operation point to the optimal point. Applying LQ tracking control to energy harvesting systems achieves efficient energy management under unstable harvested energy supplies by the adaptive duty cycle control. However, this does not yield the optimal stored energy level alone so Vigorito et al. must be done to determine it by heuristically [3]. Our previous research aimed to calculate and to track operation point but it still contained a heuristic parameter [5]. In this section, we show how to calculate the optimal stored energy level considering both capacitor leakage and energy shortage risk. First, we discuss capacitor leakage. Capacitor leakage current is known to be kCV_c ($k{\sim}0.01$) using capacitor voltage V_c and capacitance C. Capacitor leakage energy is $P_l = kCV_c{}^2$. Then, leakage power is proportional to stored energy level B_t, that is, B_t is $\frac{V_c{}^2}{V_{max}{}^2}$ (V_{max} is maximum capacitor voltage) and is expressed by $P_l = kCV_{max}{}^2 B_t$. Finally, in T seconds, normalized leakage energy $W_l = 2kB_tT$. Note that all energies in this section are normalized by the maximum stored energy in the capacitor $\frac{1}{2}CV_{max}{}^2$.

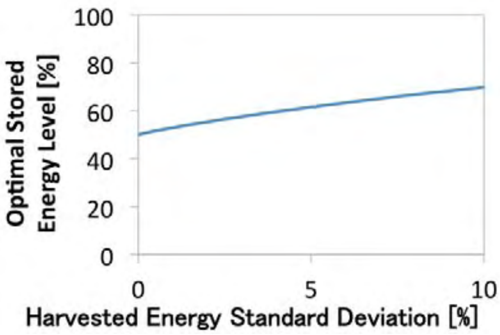

Figure 2. Optimal stored energy level.

Second, we try to evaluate the energy shortage risk and the loss when the sensor node is dead and forced to restart. Although a microprocessor only consumes several μA while it is in a sleep state, its input voltage must be always more than a specific value such as 1.9V. When the input voltage falls below the value, the microprocessor is forced to go into stop state and lose its state. Thus, we define the minimum stored energy level to operate as B_{min}. Now, the energy for restart is W_r, harvested energy is W_h and the energy used for sensing is W_c in T seconds. In this condition, stored energy B_t after T seconds will be $B_{t+T} = B_t + W_h - W_c - W_l$. $B_{t+T} > B_{min}$ is need to continue operation. Thus, when $W_h \leq W_c + W_l - (B_t - B_{min})$, the sensor node will be dead. The probability of being dead is expressed using the following probability distribution function

$$P_{dead}(B_t) = \int_0^{W_c+W_l-(B_t-B_{min})} p(W_h)dW_h$$

Thanks to LQ tracking, $W_c + W_l$ will be close to average of harvested energy $E[W_h]$. Hence, this probability can be approximated by $P_{dead}(B_t) = P(E[W_h] - (B_t - B_{min}))$ using CDF $P(W_h)$ of the harvested energy. It means variability of harvested energy is a significant parameter for dead risk. Finally, the energy lost by restart due to energy shortage is $P_{dead}(B_t)W_r$. At last, we aggregate the losses by simply summing these two terms and define that sum as a cost function$f(B_t)$.

$$f(B_t) = 2kB_tT + p_{dead}(B_t)W_r$$

The aggregated cost function is shown in Figure.1. A stored energy level that minimizes the cost function is the optimal level. As we mentioned before, the cost function depends on variability of harvested energy. Figure 2 is the relationship between standard deviations of harvested energy and the optimal level. We should select an appropriate optimal level considering harvested energy variability and this relationship. After that, we try to keep operating the sensor node at the optimal point using LQ tracking. The detail of LQ tracking adaptive duty cycle control was explained in our previous research [5] and related works [3] [4].

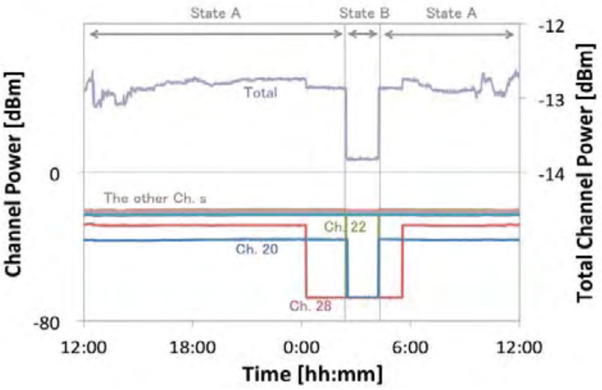

Figure 3. Channel power transition for a day.

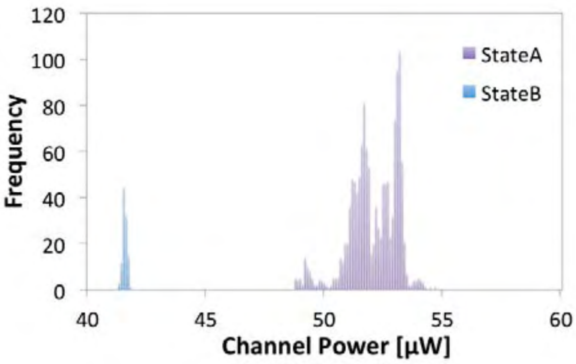

Figure 4. Channel power histogram for a day.

IV. RF ENERGY HARVESTING

There have been some previous studies of RF energy harvesting [8][6][7]. They introduced an RF energy harvesting system that aims to scavenge energy from TV broadcast radio waves, which are continuously supplied from TV radio towers almost 24 hours per day in urban areas. In Japan, TV digital signals have nine channels in the UHF band from 515 MHz to 566 MHz. Considering the circumstances, we use digital TV signals as an energy source. Figure 3 shows typical average channel power data of these channels in a day at our laboratory, 6.3km away from the transmitting tower. These data were measured at one minute interval. Each channel occupies in total 6 MHz based on ISDB-T standard. The channel power is measured by YAGI UwPA UHF antenna [9] connected to Tektronix RSA-3308B. According to the measurement result, the total channel power state can be divided into two states. This is mainly because some channels stop broadcasting service midnight for energy saving and/or maintenance purposes. It is quite hard to predict when and which channel stops sending signal. When all channels are broadcasting, state of total channel power is State A. From 12 a.m. to 2:30 a.m., only Ch. 28 is stopped, but the power does not drastically change. After that, Ch. 20 and Ch. 22 are also shut down from 2:30 a.m. to 4:15 a.m., which we define as State B. Figure 3 also shows the total power from TV radio signal consisting of 9 channels including daily fluctuation which is given by broadcasting schedules. However, these signals also exhibit short-term variability. Figure 4 is a histogram of channel powers that represents the probability distribution function of the supplied energy required for the death risk estimation. When some channels are turned off and transmitted energy decreases, the variability of harvested energy will also decrease so we should recalculate the optimal stored energy level with this transition. The current variability can be estimated by the average harvested energy, and our proposed method sets the optimal level appropriately in each state.

V. IMPLEMENTATION OF SENSOR NODE

Our sensor node with RF energy harvesting is consists of four modules: a dipole antenna on paper, a five-stage charge pump, a 100-µF capacitor as an energy storage and a Texas Instruments eZ430-RF2500 sensor node [10] that contains an MSP430F2274 micro controller, and CC2500 transceiver with SimpliciTI protocol stack and a temperature sensor. This sensor can sense temperature data and send it to the data sink using 200 µJ and only consume several microwatts in sleep mode. However, the sensor needs 1.03 mJ for initialization which is five times larger than the power needed for a sensing action. Hence, we must avoid exhausting all of the stored energy and restarting the sensor node. That is why we pay attention to death risk in the energy management design. The rectenna was designed to scavenge energy in the UHF band. Harvested energy is represented by $W_h = \eta \int_t^{t+T} P_{in}(t)\, dt$, where η is rectenna efficiency, and P_{in} is input power. The sensor node operates our proposed optimal operation point tracking and the adaptive duty cycle control. LQ tracking does not require large memory space and complex processes so even if the capability of microprocessor is limited, it can easily calculate the next duty cycle that is used in the next determination of wake-up timing.

VI. EVALUATION

We evaluated the RF energy harvesting system by both actual measurement and simulations. First we confirmed the system's operations in a realistic deployment situation. Our laboratory is on the eleventh floor of a building that is 6.3 km away from the TV tower. We can see this tower line of sight, and the rectenna can charge up to 2.82V at the location, which is enough to drive the sensor node. In this case, our sensor node could sense data and could transmit it around once per minute. Second, we will show the adaptive duty cycle control with awareness of energy supply state. When the harvested energy decreases, the system considers this event as a state transition and modifies its optimal stored energy level profile.

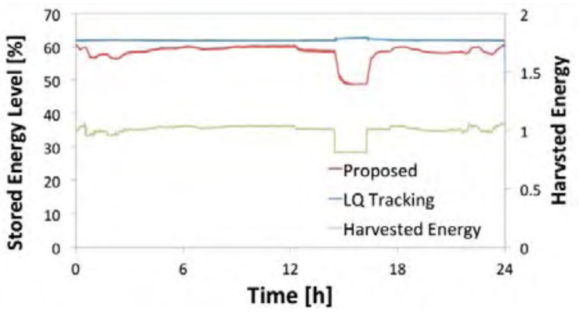

Figure 5. Simulation result: stored energy level.

This control allows the stored energy level to always be guided to the current optimal level. We evaluated the operation by simulation using measured TV channel power data in comparison to LQ tracking without state awareness. The duty cycle is adaptively chosen by the LQ tracking method so that it sustains the optimal stored energy level. Looking at the stored energy moving on Figure 5, we can see that the level was adjusted to be optimal level. Simple LQ tracking uses a static optimal stored level, so it leads the system to inefficient conditions in some states. The proposed method can adjust the optimal level in each state with the state estimation from the amount of harvested energy. The optimal level adaptation provides capacitor leakage reduction. The capacitor leakage that is proportional to the stored energy level. Thus, operating at lower levels is desirable in terms of leakage reduction. However, operating at too low of a level may cause an energy shortage and consume a large amount of energy to restart its operation. This means that balancing is quite important for efficient and stable operations. In these simulation results, the proposed method achieved an appropriate balance that can reduce capacitor leakage without spoiling sustainable operation. In order to evaluate long-term operation efficiency, we simulated this control for a week. As we show in Table 1, simple LQ tracking used 73.18% of the supplied energy for sensing operations and lost 26.81% of the energy through leakage. In contrast, the proposed method used 74.67% of its energy for sensing and lost 25.32% through leakage. This means that the proposed method achieved a 5.56% leakage reduction. State awareness enabled the system to utilize energy for sensing instead of leakage loss. As a result, this method will provide an improvement in sensing reliability and accuracy by maximizing the sampling rate of the sensing.

VII. CONCLUSION

We introduced optimal stored energy level calculations and adaptive duty cycle control by LQ tracking to sustain the optimal stored energy level under condition of unstable harvested energy. In order to calculate the optimal level, our method defines the cost function by aggregation of the capacitor leakage characteristics and energy shortage risk. Then, our method finds the optimal stored energy level that minimizes the cost function. In addition, our proposed method focuses on both long-term and short-term harvested energy transitions, which are specific characteristics of RF energy harvesting. The proposed method monitors the harvested energy and adjusts its optimal stored energy level if it detects the long-term changes. This environmental awareness provides efficient energy usage by capacitor leakage reduction. The proposed method achieves 5.56% leakage reduction compared to simple LQ tracking.

Table 1. Energy usage in long-term simulation.

Usage\Method	LQ Tracking	Proposed
Sensing	74.67%	73.18%
Leak	25.32%	26.81%

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