Solar Biscuit: A Battery-less Wireless Sensor Network System for Environmental Monitoring Applications

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Abstract

This paper describes the design and implementation of a battery-less wireless sensor network system that uses the combination of an electric double layer capacitor equipped with a small solar cell as its energy source. Although it is easy to drive sensor nodes with such energy sources on the hardware level, long-interval communication remains an important problem. Since the amount of energy obtained from a solar cell is small, a sensor node should wait until a sufficient amount of energy is charged in the capacitor before sensing or wireless communication. Thus, sensor nodes wait for a long period for capacitor charging and then communicate over a short period. This behavior by the node seriously affects the design of the communication mechanism in battery-less sensor network systems. In order to address this problem, we have designed a communication mechanism that is suitable for such behavior of battery-less sensor network nodes based on a practical application scenario of environmental monitoring applications. We also implement the newly designed communication mechanism on custom hardware and evaluate the performance of the mechanism trough several experiments.

1 Introduction

One important application of sensor networks is environmental monitoring, which involves the use of several sensor nodes scattered over a target field, such as a large area farmland or forest. In particular, the wireless sensor network (WSN) enables easy construction of such a large monitoring system because of the flexibility of wireless communication technology. However, in order not to restrict the advantages of the WSN, each sensor node usually has a battery for its energy source. This is problematic in that dead battery replacement is then required for a huge number of WSN devices. Therefore, various energy saving techniques, including energy-efficient routing protocols [1], medium access control schemes [2][3], special operating systems [4] and system-on-chip technology [5], have been proposed.

Although these techniques are useful for extending the battery life of WSN nodes, none of these techniques offer an essential solution to the battery replacement problem. This is because the energy consumption of a node can never be reduced to zero, even if we use extremely efficient energy saving technologies. Moreover, self-discharge is an inherent problem of batteries. Therefore, as long as battery-powered nodes are used, we will have to replace an enormous number of dead batteries, and performing such maintenance is unrealistic. Of course, in specific application scenarios such as military applications, WSN nodes can be assumed to be disposable. However, in many cases, disposable devices are not acceptable. For example, WSN nodes used to monitor temperature in plastic green houses can not be left in the environment because the dead nodes and batteries will become obstacles and may be harmful to the products grown therein.

On the other hand, various kinds of energy conversion devices have been developed that can provide electric power without batteries. For example, thermoelectric devices can produce electric power from temperature changes, micro generators can convert vibrations to electric power, and solar cells can produce electric power from light sources. If these devices can be used to drive WSN nodes, the problem of battery replacement for WSN systems can be eliminated. In other words, we can realize a perpetual WSN-based environmental monitoring system that maintains its availability semi-permanently.

However, driving WSN nodes with such devices is more difficult than it seems. Basically, a WSN node consumes around 0.01-0.1 W, depending on the clock speed of the microprocessor and the wireless communication device. Compared to this power consumption, conversion devices can usually provide only 0.001-0.01 W. Of course, these values depend on the physical size of the conversion device, where lager devices can provide higher electric power. However, smaller WSN nodes are preferable when considering the practical application of WSN. Thus, WSN nodes should store obtained energy by some means of electric storage, such as electric double layer capacitors (EDLCs), until the stored energy level becomes sufficient for sensing and communication. As a result, WSN nodes should wait for a long period of time, and then run their task in a short period of time. For example, if a small solar cell is used to drive a WSN node, then the node should wait for approximately ten seconds and then transmit data via an RF communication device for approximately one second.

This long intermittent behavior of WSN nodes seriously affects the performance of WSN systems, especially with respect to communication, causing long delays and degrading the reliability of multi-hop communication. Moreover, this behavior makes difficult the use of various energy-efficient routing protocols designed for conventional WSN. However, if a good communication mechanism and application scenarios that are suitable for the above-mentioned behavior can be found, then battery-less WSN systems can be enabled.

We investigated battery-less WSN systems from this point of view, and implemented a prototype system called Solar Biscuit (SB) that utilizes solar cells for its energy source. Although a previous study has examined the use of solar cells for driving WSN nodes [6], this previous study proposed a modified version of an existing energy-efficient routing protocol and does not consider the important behavior of battery-less WSN systems. Since our goal is to prove the concept of the SB system and determine the essential problems regarding practical application of battery-less WSN systems, we designed the SB system through implementation and experimentation, rather than through computer simulation.

The present paper describes the design, implementation, and initial experimental results obtained using the SB system as follows. In Section 2, we describe the requirements of the system based on a typical application scenario of environmental monitoring. In Section 3, we describe the system design, focusing on the communication mechanism, and propose a primitive protocol that is suitable for long intermittent communication. Section 4 describes a prototype implementation of the system and an evaluation of its basic performance in a practical environment. Finally, the findings of the present study are summarized in Section 5.

2 Application Scenario and Requirements

Generally, sensor network systems are categorized into two types. The first type is general-purpose systems that are designed for research and development of sensor networks. For example, MICA Mote [7] and SmartIts [8] are the most famous systems in this category. The second type is special purpose systems that are designed for specific applications. For example, the i-bean network [9] is designed mainly for monitoring applications in indoor environments and employs star-mesh topology for its communication network. In our opinion, the development of practical sensor network systems requires hardware and software design for application specific systems. In other words, the requirements for a specific application should define the design of the sensor network. Based on this consideration, we investigate the characteristics of the environmental monitoring applications and clarify the requirements for designing the battery-less WSN system in this section.

Basically, driving WSN nodes without a battery on the hardware level is not particularly difficult. However, as stated in Section 1, the long intermittent communication behavior of the nodes seriously affects the communication performance of battery-less WSN system. Thus, long delay and low reliability of communication is unavoidable. In addition, although battery life is not a concern of WSN nodes, the obtained energy of a node may be insufficient in order to execute various tasks. This means that it is difficult for battery-less WSN systems to maintain routing information of sophisticated routing protocols, whereas environmental monitoring requires multi-hop communication in order to archive wide-area monitoring system.

However, when the general characteristics of environmental monitoring applications are considered, almost all of these restrictions are allowable. In many environmental monitoring applications, each sensor node reports sensed data to a destination node, and the sensing target is usually a slowly changing physical parameter, such as temperature, humidity, or the concentration of some kind of agricultural chemical. In this case, real-time sensing and communication

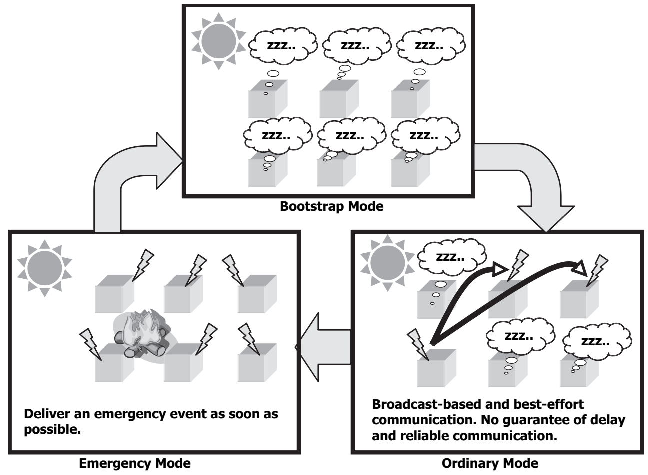

Figure 1: Three Basic Modes in the Solar Biscuit System

for on-the-fly data processing are not necessary, and a delay of a few minutes will likely be acceptable. Therefore, long communication delays do not affect such applications. Loss of sensed data is also acceptable in environmental monitoring applications because various mathematical techniques can be used to interpolate missing data. In addition, high-density redundant sensor nodes can be used to improve communications reliability.

Based on the above discussion, we can assume that environmental monitoring applications are not sensitive to communication delay or reliability problems when nodes are monitoring a slowly changing target under ordinary conditions. On the other hand, once a node detects an emergency event, such as detection of an unusual temperature, these assumptions become invalid. In such cases, fast and reliable communication is required in order to deliver the emergency event to a destination as soon as possible. All nodes in the monitoring application must contribute to relay the events, and the energy condition of each node must not be a concern.

Therefore, a battery-less WSN system for environmental monitoring applications should satisfy the following three requirements. First, the system should support both an ordinary monitoring mode and an emergency event delivery mode. Second, although long delay and low reliability is acceptable, a simple, lightweight and energy-adaptive multi-hop communication protocol is required for use in the ordinary monitoring mode. Third, when an emergency event is detected at a node, the system changes its mode and reliably reports the event to a destination as soon as possible.

3 Design

3.1 Conceptual Design

Based on the above discussion, we designed the SB system as shown in Figure 1. In order to embody the scenario outlined in the previous section, we designed bootstrap mode, ordinary mode, and emergency mode as the basic states for the SB nodes. In the bootstrap mode, the SB node charges energy obtained from an energy conversion device to electric storage. Since light sources can be found almost everywhere, we used a solar cell for the energy source of the SB node in

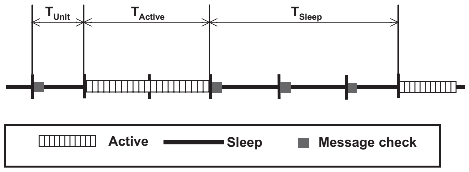

Figure 2: Timing Sequence of Communication for the SB Node

order to support a wide variety of monitoring applications in the current implementation. The solar cell is equipped with an EDLC in order to store the obtained electric power temporary. When a sufficient amount of energy is charged in the EDLC, the SB node enters ordinary mode. In this mode, the node reports a sensed data to a destination node within a certain period, depending on its energy level. For example, if the node can obtain sufficient energy from the solar cell, then it transmits the sensed data over a short interval, whereas if the energy condition of the node is poor, then sensing and communication is performed over a long period.

Once an emergency event is detected at an SB node, all nodes in the SB system enter emergency mode. In this mode, the node that detected the event wakes up all nodes, and the nodes transmit the event to the destination as soon as possible. Since every nodes continuously contributes to event transmission in emergency mode, the nodes will consume all of their energy in a few seconds. After this, the nodes are restarted in bootstrapping mode. In this way, the SB system supports the application scenario described in the previous section.

3.2 Communication Protocol

One of our goals in designing the SB system is to develop a novel communication mechanism that satisfies the requirements of the above-mentioned scenario. Generally, we have to consider both a medium access control (MAC) protocol and a routing protocol in designing a communication protocol for WSN systems. In the SB system, we use Carrier Sense Multiple Access (CSMA) for a MAC protocol. For a routing protocol, although several sensor network protocols have been proposed, we designed a simple flooding-based protocol from scratch because conventional communication protocols do not consider the long intermittent communication behavior of nodes.

Figure 2 illustrates the basic timing sequence of a SB node. Sensing and communication of the SB node are performed in a unit time of T_{Unit}, and the node repeats the active state and sleep state for T_{Active} and T_{Sleep}, respectively, where T_{Active} and T_{Sleep} are determined as multiples of T_Unit. In the SB system, all nodes have same active time T_{Active} and T_{Sleep} is changed depending on the existence of an energy condition. The SB node measures the voltage level of the EDLC, and if the measured voltage is higher than a threshold value V_{Th}, then the node adds a unit time T_{Unit} to T_{Sleep}, otherwise T_{Unit} is subtracted from T_{Sleep}.

Figure 3 shows the multi-hop communication protocol in ordinary mode. This figure assumes that the start points of the time when SB nodes become active are uniformly

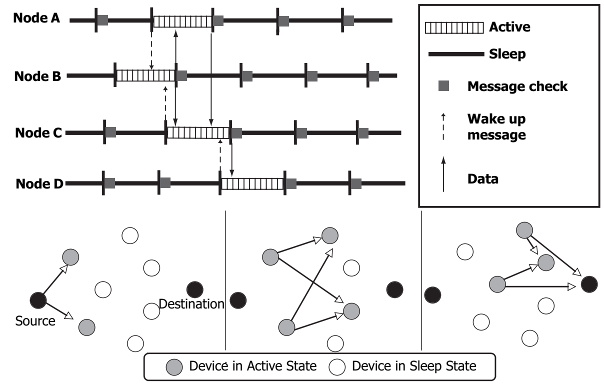

Figure 3: Communication Strategy of the SB system

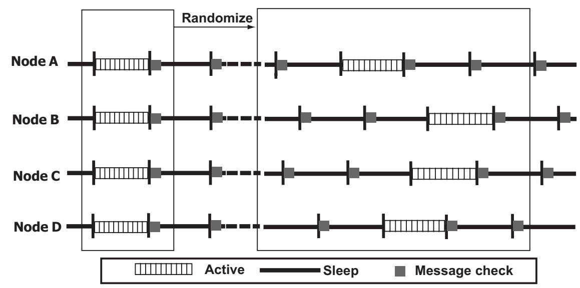

Figure 4: Randomization Algorithm

randomized. We then consider node B to be a sender of a sensed data and node D to be a destination node (sink node). Every time a node becomes active, it broadcasts a wake-up message via an RF transceiver. In this example, node B can receive wake-up messages from node A and node C and so recognizes that node A and node C have become active. Since the active time T_{Active} of all nodes is identical, this guarantees that both nodes A and C are active when node B enters the sleep state. Then, node B broadcasts the sensed data before entering the sleep state. As a result, the sensed data is duplicated and stored in nodes A and C. In the same way, node A broadcast the sensed data when it enters the sleep state. In this case, node C receives the same data from nodes B and A, and so ignores the data from one node. Here, if node D becomes active while node C is active, then the destination can receive the sensed data. In this way, sensed data is delivered to the destination node. The sensed data is transmitted with Time to Live (TTL), and if the TTL becomes zero, then the packet is discarded.

The key point of the communication protocol is that broadcast-based and best-effort data forwarding is performed among a limited number of nodes by creating a situation in which several nodes become active when one node is active. In order to create this condition, we designed an algorithm that randomizes the start points of the active mode, as shown in Figure 4. When a node in the active state has received n wake-up messages, the node performs a trial to determine whether the node can obtain "1" with probability $1 - 1/n$ and "0" with probability $1/n$. If the node obtains

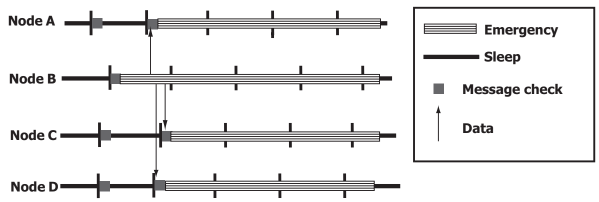

Figure 5: Communication in the Emergency Mode

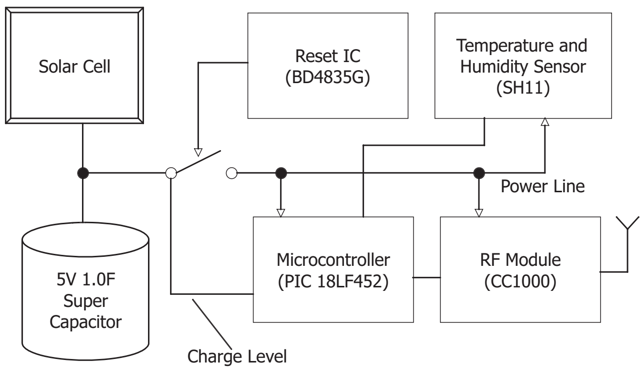

Figure 6: Block Diagram of the SB Node

"1", then one unit time T_{Unit} is added to T_{Sleep}, and the trail is repeated. If the node obtains "0", then the nodes terminate the trial. Using this algorithm, the start points of all nodes in the system can be randomized.

Once an emergency event has occurred, the SB system enters emergency mode, as shown in Figure 5. In emergency mode, node B, which has detected the event, continuously broadcasts an emergency message. In ordinary mode, all nodes in the system check for messages at every T_{Unit}. If the emergency event is detected by other nodes, then these nodes also enter emergency mode and broadcast the emergency message. Eventually, all nodes enter emergency mode, and the emergency event is delivered to the destination. Message broadcasting continues until the nodes consume all of their energy.

The above mentioned simple communication protocol is designed based on the philosophy that the sensed data will eventually be delivered to the destination in ordinary mode. In contrast to ordinary mode, in emergency mode, all nodes contribute to deliver the important event as soon as possible. Although this protocol is very simple, it is not the optimal protocol for battery-less WSN systems. However, we believe that the basic concept of our protocol is appropriate. Further improvement of the protocol will be considered in future studies.

4 Implementation and Evaluation

4.1 Hardware Implementation

In order to prove the concept of the proposed system, we developed a prototype system. Figure 6 shows a block diagram of a SB node. We implemented a one-chip MPU (MICROCHIP PIC 18LF452, 7.3728 MHz), a 315-MHz RF module (ChipCon CC1000), and a temperature and humidity sensor (Sensiron SH11) on a 5 cm x 5 cm main circuit board. A 5 cm x 5 cm solar cell (SHELL SOLAR, Monolithic Silicon Solar Cell) is connected to a low internal impedance EDLC (5 V, 1.0 F, NEC Tokin, FT0H105Z). The EDLC is also connected to an internal A/D converter of the MPU so that the SB node can determine the sleep time as stated in the previous section. If the charge level is less than 3.5 V, then a CMOS reset IC (ROHM BD4835G) shuts down the MPU (i.e., the MPU must enter the sleep mode before the charge level becomes less than 3.5 V) in order to avoid unexpected behavior of the node. If the charge level becomes 3.675 V, then the reset IC restarts the MPU.

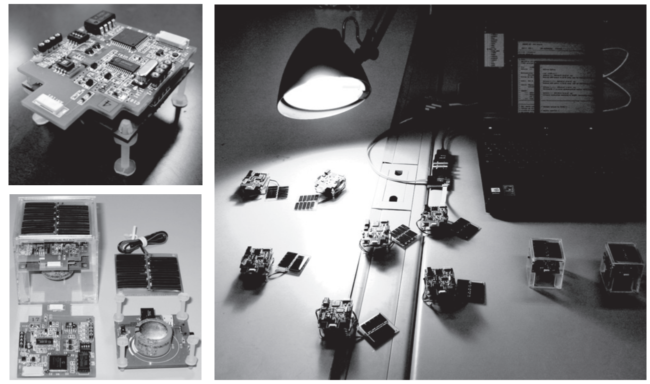

Figure 7: Hardware Implementation

Sensing and communication software of the node are developed using the C language. We used Manchester encoding, Cyclic Redundancy Check (CRC), and pure CSMA for the lower layer of the communication protocol. On top of these mechanisms, we implemented the broadcast-based routing protocol described in the previous section.

When the device is continuously sending data via the RF module, the maximum power consumption of the SB node is approximately 30 mA, because the RF module consumes over 25 mA in the highest transmission power mode. On the other hand, the solar cell can provide approximately 20 mA in fine weather. Therefore, the performance of the SB device is good in an outdoor environment. However, in an indoor environment, driving the SB node by solar cell is not possible due to current leakage of the main circuit board. Currently, we are designing the next version of SB node, which will have improved performance in both outdoor and indoor environments.

4.2 Performance Evaluation

We performed several experiments in order to evaluate the prototype system. We first observed the behavior of an SB node in order to confirm whether the node can perform the expected action according to the application scenario described in Section 2. Figure 8 shows an example of the EDLC voltage change reflecting the activity of the SB node. Here, we set T_{Unit}=1 second and T_{Active}=1 second, and V_{Th}, which determines the ratio of the active state to the sleep state, was set to 4.0 V. After turning on the SB node, the node stores obtained energy to the EDLC, waiting until the charge level rises to a level that is sufficient to drive the MPU (bootstrap mode). When the charge level becomes 3.675 V,

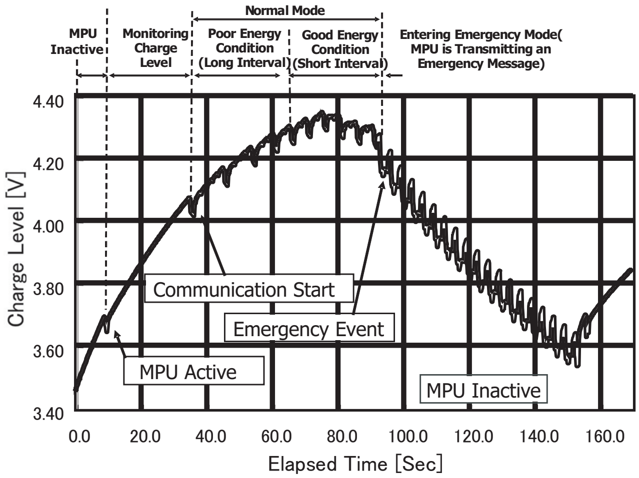

Figure 8: Activity of the SB Node

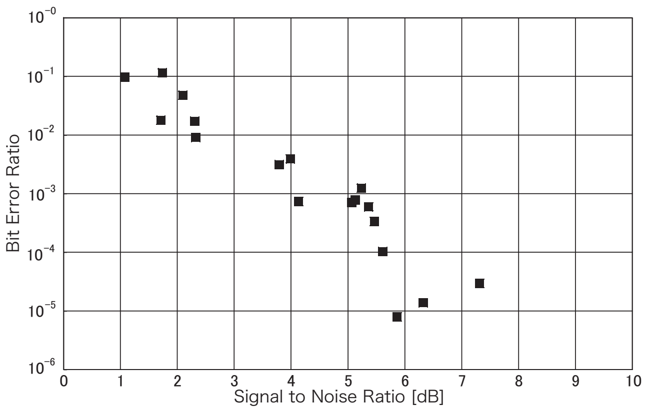

Figure 9: Bit Error Rate

the MPU wakes up and enters sleep mode until the charge level becomes V_{Th}. Once the charge level exceeds V_{Th}, the MPU begins sensing and communication in a certain interval, depending on the energy condition (normal mode). Since the energy condition of the node is poor for 40 seconds to 60 seconds in Figure 8, the interval of sensing and communication is approximately 20 seconds. After an elapsed time of 60 seconds, the energy condition becomes good and the interval changes to 5 seconds. After an elapsed time of approximately 90 seconds, the node detects an emergency event and enters emergency mode. Since the node continuously transmits the emergency event in emergency mode, the charge level quickly drops. If the charge level falls below 3.5 V, then the node stops its activity and enters bootstrap mode again.

Next, we placed two SB nodes in an outdoor environment and measured the Bit Error Rate (BER) by changing the distance between the two nodes, as shown in Figure 9. The signal-to-noise ratio (SNR) is computed as $log(P_{RSSI}/P_N)$, where P_N is background noise and P_{RSSI} is the received signal strength obtained from the RF transceiver. At a distance of 20 m, the BER was approximately 10^{-5}.

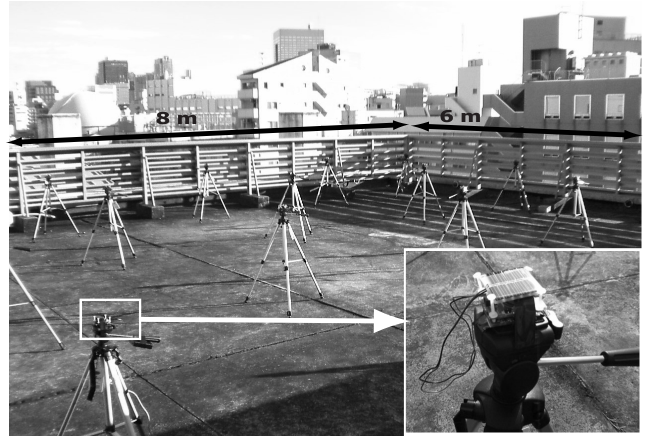

Figure 10: Experimental Setup

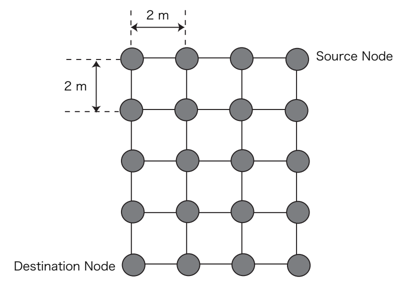

Figure 11: Node Placement

Finally, we measured the delay and success ratio of communication. In this experiment, we placed 20 nodes in an 8 m × 6 m rectangular area at intervals of 2 meters, as shown in Figures 10 and 11. A destination node and a source node were placed at opposite corners of the area. Since the performance of the proposed communication protocol was expected to depend on the TTL and the sensing interval, we varied these two parameters during the measurement.

Figures 12 and 13 show the measured success ratio and communication delay. When the sensing interval is set to 15 seconds, a peak success ratio exists at TTL = 3. In the case of TTL = 2, the success ratio of communication was 48% and the communication delay was 2.1 seconds. This result indicates that the sensed data is dropped in the SB network because TTL = 2 is too small to deliver the sensed data to the destination. On the other hand, at TTL = 4, the success ratio was only 31% and the average communication delay was 4.8 seconds. This is because TTL = 4 yields numerous duplicate data and causes congestion in the network. These results show that the value of TTL should be carefully chosen depending on the network size. When the sensing interval was set to 60 seconds, both the success ratio and the communication delay were greatly improved. In this case, since the TTL is sufficient for delivering the sensed data to the destination and the congestion of the SB network is negligible, the success ratio was 90% and average delay was only 0.89 seconds.

Although we succeeded in implementing the SB system

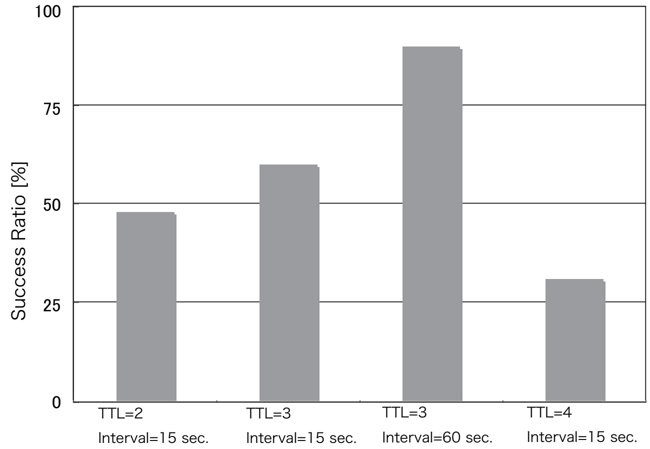

Figure 12: Success Ratio of Communication

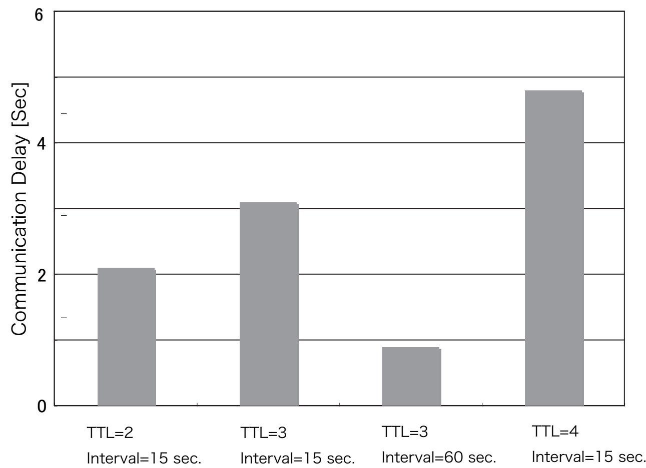

Figure 13: Average Communication Delay

to demonstrate the concept of a battery-less WSN system, the performance of the system was less than expected. In the future, we should consider the application of a mechanism by which to control the number of duplicate data.

5 Summary

This paper described the design and implementation of a battery-less sensor network system as well as its performance evaluation. We designed the system as a specialized system for supporting a typical scenario of environmental monitoring applications. Although the concept of the system was successfully proven, the performance of the system was less than expected because of inefficiency of the designed communication protocol.

We believe that a success ratio of 90% for the sensing interval of 60 seconds may be acceptable for a limited number of applications, such as temperature monitoring. However, improvement of the performance is required in order to support a wider variety of applications. Therefore, we intend to employ geographic routing techniques or a message aggregation technique in order to avoid message explosion in communication.

Another problem is the insufficiency of MPU resources to handle critical tasks such as CRC and preamble processing in lower layers of the communication protocol. This limitation causes instability of the SB network and affects the communication performance of the SB system. We intend to use a high-speed variable-clock MPU for the next version of the SB network.

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