A Neighbor Discovery Method for Wireless Sensor Networks

Shigeru TERUHI and Shuichi YOSHINO and Masashi SHIMIZU
NTT Network Innovation Laboratories, NTT Corporation
Email: {teruhi.shigeru, yoshino.shuichi, shimizu.masashi}@lab.ntt.co.jp

ABSTRACT

One requirement of wireless sensor networks is network organization protocol that can provide robust and energy-efficient communications. Although turning off the radio when it is not needed is an important strategy for energy conservation, the low duty cycle (<0.1%) operation leads to a relatively large overhead for network organization, such as the synchronization and maintenance of routing information. We propose new neighbor discovery method that realizes a self-organization network with low power consumption and verify the optimal value of the parameters for our method. We show that the power consumption of this method with the computed optimal parameters is not dependent on the duty cycle and decreases, especially in networks where nodes frequently join and leave.

***Key Words*: wireless sensor networks, neighbor discovery, self-organization**

I. Introduction

Recently, advances in Micro Electro Mechanical Systems (MEMS) and Wireless Personal Area Network (WPAN) technologies have enabled the realization of the wireless sensor networks to monitor environmental conditions. In wireless sensor networks, each node deployed over a large area is required to discover a neighbor node and adaptively construct a wireless multi-hop network. The wireless sensor networks are designed to use short-range radios, such as weak radio waves or specified low power radios for wireless sensor nodes. These need wireless ad hoc networking techniques to expand the network area.

The other important constraint on wireless sensor networks is the low power consumption requirement. Sensor nodes carry limited, generally irreplaceable, power sources.

We describe a new neighbor discovery method that consumes less power and verify the best parameters for applications to wireless sensor networks.

II. Intermittent Idle and Sleep

In general, radio modules are classified into four operation modes, transmit, receive, idle listening, and sleep. Idle listening mode occurs when the radio module is monitoring the channel for data. The cost of idle listening depends on the Radio Frequency (RF) and operation, but can reach the same order of magnitude as the receive and transmit costs for short-range radios (0.5 km or less). For example, the power consumption ratios of idle listening, receive, and transmit are 1:1:1.41 on the Mica2 mote at 433 MHz with a 1-mW RF signal power in transmit mode [1]. Therefore, idle listening is a key factor in power consumption for low duty cycle operations. In other words, the most obvious way to conserve energy is to turn the transceiver off when it is not required. However, for low duty cycle operations, a new problem arises, in which neighbor discovery become relatively time consuming.

III. Conventional Neighbor Discovery Methods

A. ZigBee

ZigBee [2] is a wireless communication standard aimed at energy conservation. ZigBee adopts IEEE802.15.4 standards [3] in the physical and the media access layers, and provides the security service and application interface for the network layer to achieve a secure multi-hop network. Both beacon and non-beacon modes are provided for in the media access layer to meet IEEE802.15.4 standards. In the non-beacon mode, all nodes need to constantly be in standby mode to connect with other nodes. In contrast, all nodes can be powered off by synchronizing with the regularly transmitted beacon from the coordinator when there is no data to send in beacon mode. Thus, we will focus on beacon mode in our discussion because we examine MAC protocol on the premise of intermittent listen and sleep operations.

Each node recognizes the superframe structure between frame beacons using information included in the receive beacon and controls operation based on each time period in the superframe. Figure 1 shows ZigBee's superframe structure. The superframe is located between the frame beacons, and the active portion of the superframe has a Contention Access Period (CAP) and Contention Free Period (CFP) with Guaranteed Time Slots (GTSs).

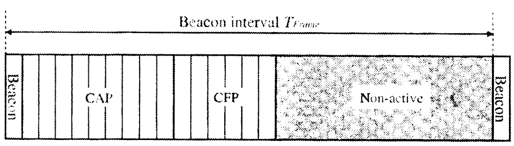

Fig. 1. ZigBee superframe structure.

B. Estimate cf Power Consumption

The IEEE802.15.4 standards defined two physical device types, a full function device (FFD) and a reduced function device (RFD). A FFD can be a network coordinator that manages the network and router for multi-hop communications, while an RFD cannot be a network coordinator and communicates only with a network coordinator. In a hierarchical network, the entire network load concentrates on the cluster heads so that they can advertise themselves to guide the clustering of the sensor networks. This load concentration on the cluster heads is not considered in the IEEE802.15.4 standards, because the FFD's cluster head is assumed to be connected to the power supply. However, for this paper we estimated the power consumption, including the amount of FFD, because restricting the power supply to the FFD is a major barrier to setting up the sensor node.

When all the sensor nodes are in intermittent listen and sleep modes, and the wake-up signal [4] does not exist on another channel, a new node needs to detect the neighbor node until the coordinator wakes up and transmits the beacon (as shown in Fig. 2). In this method, the energy consumed for neighbor discovery comprises most of the consumed energy, because it takes a long time to discover a neighbor node in low duty cycle operations.

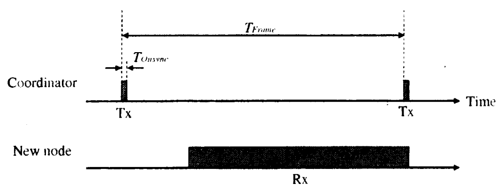

Fig. 2. Conventional method.

The energy consumed for network organization is divided into P1, to maintain the transmit beacon, P2 to discover neighbors, and P3 to synchronize with the coordinator. The P1 that results from the transmission frequency in the network life T_{Run} is multiplied by the beacon transmitting energy once. T_{Frame} and T_{Onsync} each indicate the time interval between frame beacons and the beacon transmission time.

$$P1 = \frac{T_{Run}}{T_{Frame}} \cdot P_{tx} T_{Onsync} \tag{1}$$

The $n-1$ nodes organized in network once are assumed to leave the network during the network life T_{Run}. In this case, the new node has to scan only half of the beacon interval time T_{Frame} once on average. $P2$ is shown as follows.

$$P2 = P_{rx} \cdot \frac{T_{Frame}}{2} \cdot (n-1) \tag{2}$$

TABLE I

MAIN PARAMETERS

Parameter	Value [unit]
T_{Run}	5 [years]
T_{Onsync}	10 [msecs]
T_{Frame}	0–3600 [secs]
n	20
P_{tx}	25 [mA]
P_{rx}	20 [mA]

A new error margin δT_{Frame} is caused every beacon interval when the RTC clock accuracy is assumed to be δ. Therefore, the error margin of the clock between the coordinator and the slave node becomes $2\delta T_{Frame}$ at maximum. On average, the slave node should scan for δT_{Frame} every beacon interval to correct this error margin. $P3$ is shown as follows.

$$\begin{aligned} P3 &= \frac{T_{Run}}{T_{Frame}} \cdot P_{rx} \delta T_{Frame} (n-1) \\ &= P_{rx} \delta T_{Run} (n-1) \end{aligned} \tag{3}$$

As shown, $P3$ does not depend on the beacon interval T_{Frame}. Therefore, the sum of $P1$ and $P2$ is defined as the total energy P consumed in the entire network to organize the network. Next, we discuss P in the low duty cycle network.

$$P = P1 + P2 \tag{4}$$

The changes in $P1$, $P2$, and P depending on the beacon interval T_{Frame} are shown in Fig. 3. Table I shows various evaluation parameters. $P1$ decreases along with T_{Frame} because the transmission frequency for the selected network life decreases. In the meanwhile, $P2$ increases along with T_{Frame} because it takes time for a new node to discover the neighbor node. P decreases in the high duty cycle field, but increases in proportion to T_{Frame} in the low duty cycle field because the neighbor discovery load is predominant when T_{Frame} is larger than 500 seconds.

IV. PROPOSED NEIGHBOR DISCOVERY METHOD

Table II shows the power consumption features of the Mica2 mote. For long-distance radios, the transmission power is large predominantly compared with the idle listening and receive powers. In contrast, no difference is seen in the power consumption between the receive, idle listening, and transmission powers for short-range radios. Therefore, P, which is mostly dominated by $P2$, increases along with the T_{Frame} shown in Fig. 3. Then, P can be reduced by obtaining the best balance between $P1$ and $P2$. We propose a new neighbor discovery method, in which the coordinator continuously transmits multiple beacons and the new node repeats scanning

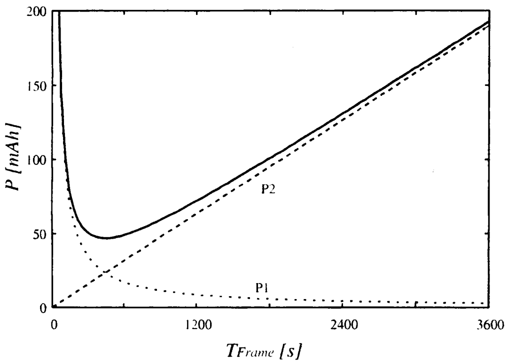

Fig. 3. Power consumption for network organization (Conventional method).

intermittently during the continuous transmission time cycle, (as shown in Fig. 4). Intermittent scanning reduces the new node's load by continuously transmitting the beacon increases the coordinator's load. We examined the technique to obtain the best balance between the beacon transmission and neighbor discovery loads. In our proposed method, the coordinator transmits continuously k times P1 increases to k times of the conventional method.

$$P1 = \frac{T_{Run}}{T_{Frame}} \cdot P_{tx} T_{Onsync} k \quad (5)$$

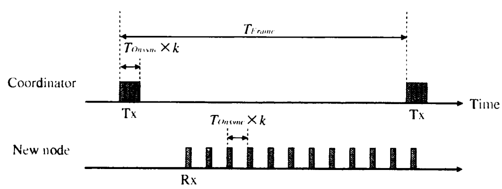

Fig. 4. Proposed method.

On the other hand, we assumed that new $n - 1$ nodes organized in network once don't leave the network during network life T_{Run}, and the scanning time to receive the beacon for slave node is the same length duration as the beacon transmission time T_{Onsync}. In this case, $P2$ is 1/k times smaller than the conventional method.

$$\begin{aligned} P2 &= P_{rx} T_{Onsync} \cdot \frac{T_{Frame}}{2kT_{Onsync}} \cdot (n-1) \\ &= P_{rx} \cdot \frac{T_{Frame}}{2k} \cdot (n-1) \end{aligned} \quad (6)$$

TABLE II

CURRENT SENSOR NODE CONSUMPTION

Operation Mode	Current Consumption [mA]
Idle/Receive	7.5
Transmit 0 dBm	10.4
Sleep	0.001

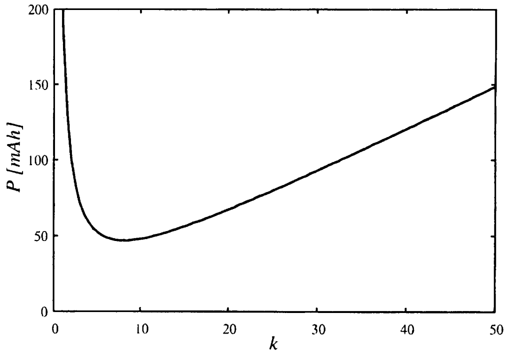

Fig. 5. Relationship between k and P.

Here, the change in P depending on k is shown in Fig. 5. We obtained an optimized number k_{OPT} of beacon transmissions when we minimized P as follows.

$$\begin{aligned} \frac{\partial P}{\partial k} &= \frac{T_{Run}}{T_{Frame}} \cdot P_{tx} T_{Onsync} \\ &\quad - P_{rx} \cdot \frac{T_{Frame}}{2k^2} \cdot (n-1) \\ k_{OPT} &= \sqrt{\frac{(n-1) P_{rx} T_{Frame}^2}{2 P_{tx} T_{Run} T_{Onsync}}} \end{aligned} \quad (7)$$

The change in k_{OPT} depending on the number n of sensor nodes is shown in Fig. 6, based on the current consumption features of the two kinds of devices. One is CC 1020 [5] with an RF power signal of 10 dBm, and the other is CC 1000 [6] with 0 dBm. The CC 1000 installed in the Mica2 mote is an RF device in which the current transmission circuit consumption, including the oscillator, is greatly reduced. The k_{OPT} increases with the n so that the neighbor discovery load ratio for the entire load increases along with n. In addition, k_{OPT} increases more in devices in which the current transmission circuit consumption is reduced.

Next, we show P and the reduction rate of P with k_{OPT} in Fig. 7. The reduction rate of P is limited to around 37%, using a device in which 60% reduces the current transmission circuit consumption by 60%, regardless of n. This shows that the ratio of $P2$ in P is not small.

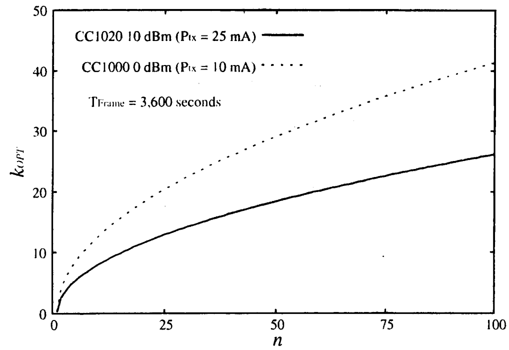

Fig. 6. Relationship between n and k.

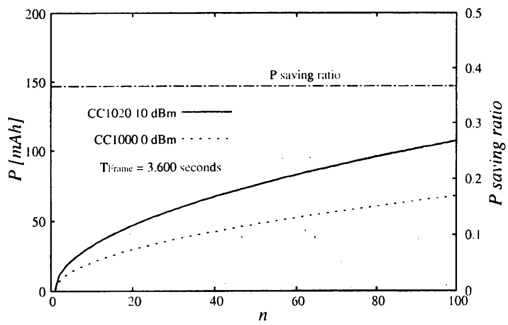

Fig. 7. Relationship between n, P and reduction rate of P.

V. Effect of Proposed Method

A. Without considering the coordinator's leave process:

Here, we assume that once organized in the network the new node doesn't leave during the network life (as shown in Fig. 8). The Table I shows the main parameters. As previously shown, P increases in proportion to T_{Frame} in the conventional method where T_{Frame} is more than 500 seconds. On the other hand, we realize a low power consumption regardless of T_{Frame} by Eq. (5), (6), (7) using the optimized parameter k_{OPT} in the proposed method. However, it has the same features as the conventional method, where the T_{Frame} is small, so that the k_{OPT} provided from Eq. (7) is less than 1. As a result, we can conserve energy using the proposed method when the T_{Frame} is large enough. For example, P is suppressed to about 1/4 compared with the conventional method, where T_{Frame} is 3,600 seconds.

On the other hand, many loads depend on the proposed method in which the coordinator transmits the beacon. Figure 9 shows the proportion of $P1$ in P. The coordinator must bear 50% of P using Eq. (5), (6), (7) regardless of the number of nodes n and the beacon interval T_{Frame}, when K_{OPT} is selected. Therefore, we need some load balancing

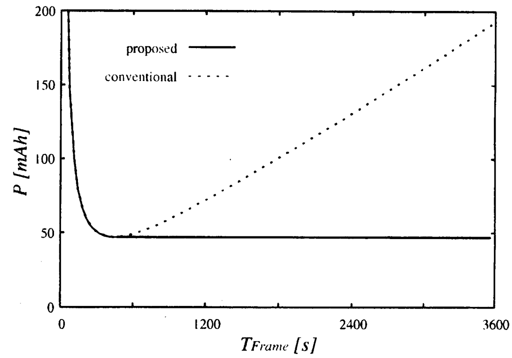

Fig. 8. P comparison using proposed method and conventional method.

mechanisms, like LEACH (Low-Energy Adaptive Clustering Hierarchy) [7], in which the coordinators (cluster heads) change randomly over time in order to balance the energy dissipation of the nodes.

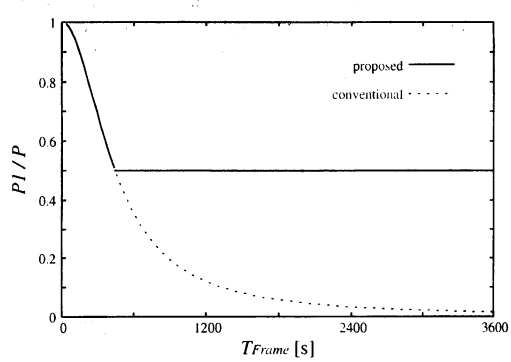

Fig. 9. Proportion of $P1$ in P.

B. Considering the coordinator's leave process:

Next, we assume that new nodes organized in the network leave the network. The Table III shows the main parameters. As previously shown, the coordinator has a short life compared to the other nodes in our method. Then, the average period the coordinator functions is assumed to be T_{Ref}. In addition, it is assumed that the slave node that detects the coordinator leaving becomes the coordinator. Here, the leave level M of the coordinator is defined to standardize T_{Ref} in the network life T_{Run} and shows the leave possibility of the coordinator (as shown in Fig. 10).

$$M = \frac{T_{Run}}{T_{Ref}} \quad (8)$$

TABLE III
SIMULATION PARAMETERS

Parameter	Value [unit]
T_{Run}	5 [years]
T_{Onsync}	10 [msecs]
T_{Frame}	3600 [secs]
n	20
P_{tx}	25 [mA]
P_{rx}	20 [mA]
k	8
M	0.5–8

The change in P depending on the leave level M of the coordinator is shown in Fig. 11. Consequently, we know that the energy conservation of our method improves when there is a high leave level M. For example, P is suppressed to 1/7 or less of the conventional method as compared to the proposed method where the leave level M is 8. This is because the opportunity to discover the neighbor node increases for slave nodes when the coordinator leaves during network life.

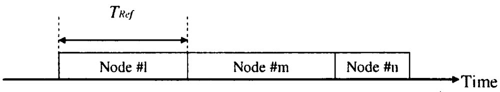

Fig. 10. Period function as coordinator T_{Ref}.

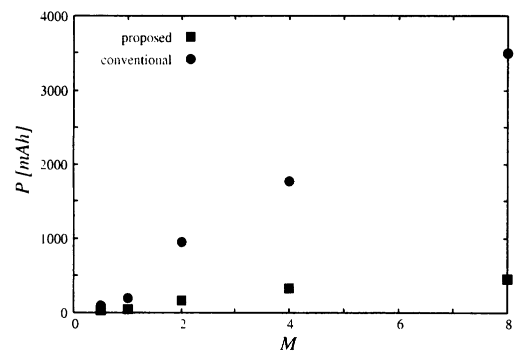

Fig. 11. P with considering coordinator's leave process.

VI. CONCLUSIONS

We proposed a new neighbor discovery method that can improve power consumption in wireless sensor networks and verified its parameters. We verified that the proposed method is effective under long beacon interval T_{Frame} conditions and in which the nodes frequently join and leave. Although the duty cycle demand for each node is application specific, we assumed the duty cycle of each node to be designed low enough to extend the drive time without changing the batteries. Our results show that our method can be effective in wireless sensor networks.

REFERENCES

[1] W. Ye and J. Heidemann, "Medium Access Control in Wireless Sensor Networks," USC/ISI Technical Report ISI-TR-580, Oct. 2003.

[2] ZigBee Alliance, http://www.zigbee.org/.

[3] IEEE Std. 802.15.4, Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low Rate Wireless Personal Area Networks (WPANs).

[4] C.Schurgers, V.Tsiatsis, and M.B.Srivastava, "STEM: Topology Management for Energy Efficient Sensor Networks," Proceedings of the IEEE Aerospace Conference, pp.78–89, Mar. 2002.

[5] Chipcon Inc., http://www.chipcon.com Chipcon CC1020 Data Sheet (rev. 1.5).

[6] Chipcon Inc., http://www.chipcon.com Chipcon CC1000 Data Sheet (rev. 2.2).

[7] Wendi Rabiner Heinzelman, Anantha Chandrakasan, and Hari Balakrishnan, "Energy-efficient communication protocols for wireless microsensor networks," Proceedings of the Hawaii International Conference on Systems Sciences, Jan. 2000.