Energy Effective Time Synchronization in Wireless Sensor Network *

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Abstract

Advance in processor, memory and wireless communication technique have led to an increase of economical and small wireless sensor nodes. To provide the right responses quickly for the diverse events, wireless sensor nodes have cooperation with together. For successful cooperation, the time synchronization among sensor nodes is an important requirement for application execution. In wireless sensor networks, message packets are used for the time synchronization. However, the transmission of message packets dissipates the battery energy of wireless sensor nodes. Since wireless sensor nodes works on the limited battery capacity, the excessive use of message packets has a negative impact upon their lifetime. In this paper, reference interpolation protocol is proposed for reducing the number of message packets for the time synchronization. The proposed method performs time interpolation between the time of reference packets and the global time of the base station. The proposed method completes the synchronization operation with only two message packets. Due to the simple synchronization procedure, our method greatly reduces the number of synchronization messages. From the decrease in the transmission of message packets, the convergence time among wireless sensor nodes is shortened and the lifetime of wireless sensor nodes is also prolonged as much as the amount of saved battery energy.

1. Introduction

Based on recently the amazing growth of subminiature, low-cost and low-powered hardware, the wireless sensor network is strongly researched for the various application areas. The wireless sensor nodes have cooperation with together to support the right and quick responses for the diverse events. However, to perform the cooperation between sensor nodes, time synchronization operations between sensor nodes are an important requirement to provide the correct operations. In particular, some spotlight applications performing the functions such as the location search, data collection in mobile sensors, event awareness in the complex area and highly privileged security are based on the precise time synchronization of wireless sensor nodes. Without time synchronization function, the time-ordering in triggered events cannot be distinguished but also the duplicated data driven from same events cannot be handled.

In the case of NTP and GPS method, when the timestamp in messages is broadcasted to exploit as a global time, the sending time and the access time of messages incurs time delay problem for time synchronization [1, 2, 3]. To solve this problem, the Reference Broadcast Synchronization (RBS) method is proposed. The RBS does not perform time synchronization activities based on the global time value. This method is based on the relative time difference of reference message packets arrived in each wireless sensor node. The RBS has an advantage that it greatly reduces the time period for the message sending and access. However, as the number of sensor nodes is increased, the number of message for time synchronization is highly increased. In wireless sensor nodes, the message transmission via the RF antenna takes a major part of the energy consumption. Therefore, in the RBS method, the increase of messages for time synchronization results in a significant energy waste in wireless sensor nodes.

In this paper, to address the energy waste problem occurred in the previous RBS method, Reference Interpolation Protocol (RIP) method is proposed. The RIP method uses the broadcast messages come from both reference packet transmission nodes and a base station node. In this way, wireless sensor nodes receive two reference packets from two source nodes. After that, each sensor node synchronizes its local time by interpolating the time difference be-

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tween two packets. The RIP does not use the synchronization message with timestamp values so that it reduces the errors occurred in MAC layer transmission. In addition, since each sensor node receives only two messages within the single-hop range for its own time synchronization, the number of message for total time synchronization is reduced tremendously. The decrease of messages also reduces the amount of energy consumption in the wireless sensor nodes so that their lifetime would be prolonged. In addition, the reduced messages results in greatly shorten the convergence time of all wireless sensor nodes performing the time synchronization.

The rest of this paper is organized as follows. Section 2 describes the common errors occurred in the time synchronization methods and the classification of the time synchronization and the existing time synchronization techniques in the wireless sensor networks. In section 3, the Resource Interpolation Protocol is proposed to reduce the number of message transmitted for the timing synchronization. In section 4, the performance of our RIP is measured and evaluated throughout compared to the RBS protocol. Section 5 concludes the paper.

2. Related Work

2.1. Sources of the inaccurate time synchronization

The non-deterministic delay characteristics of the network communication cause the inaccuracy in time synchronization activities. To get accurate time synchronization, these sources should be analyzed and alternative methods should be considered to alleviate the effect of the synchronization error. The Fig. 1 shows the inevitable delay times occurred in transmitting the messages between the sender and the receiver.

Based on this phenomenon, the non-deterministic factors for the network communication are classified as follows [4].

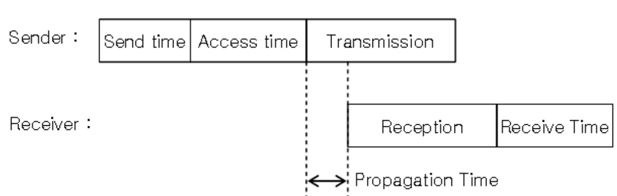


Figure 1. Delay Times for Transmitting Messages

Send Time It is actually exhausted time when applications send the data over the system operations. This time include the kernel processing time, context switching time and system call processing time. It depends on the amount of current sender system's workloads.

Access Time It is the time required to access the wireless channel after ready to transmit in the sender node. It depends on the amount of the current network workloads.

Propagation Time It is the necessary time until the radio signal transmits from the sender to the receiver. It depends on the distance between the sender and receiver. When compared to the send time and the access time, its exhausted time is trivial.

Receive Time The time it takes for the received data to reach the application level.

2.2. RBS Time Synchronization

The RBS(Reference Broadcast Synchronization) method performs the time synchronization based on the received time of messages. Firstly, the reference packet sender transmits reference packets to its neighbor nodes. For the time synchronization, all sensor nodes receive reference packets and exchange their local times each other. Reference packets are broadcasted and the neighbor sensor nodes are stored their relative time from the received referenced packets. Thus, the RBS method performs the time synchronization with the time difference offset values between sensor nodes. The RBS model has several advantages compared to the global time based time synchronization such as NTP, GPS.

Since the RBS method does not perform the time synchronization depending on the global time transmission such as the server-client models, it eliminates the errors from the unexpected sending time and access time. In the global time based time synchronization, these errors usually have occurred in the packet transmission procedure. In addition, since the reference packets do not include timestamp values, time synchronization is easily done by the several broadcast methods such as the RTS/CTS. However, the RBS method should keep the clock information of neighboring sensor nodes. In addition, the number of messages exchanged for the time synchronization rises sharply according to increasing the number of sensor nodes. Since RF using takes a major part of energy consumption, the increased messages cause the wireless sensor nodes to exhaust their battery power. As a result, it is inevitable that the lifetime of sensor nodes is shortened.

3. Reference Interpolation Protocol

3.1. Basic Operations in Single Hop

The existing RBS method performs the time synchronization based on reference packets. After received reference packets, sensor nodes broadcast their received time. In this method, as the sensor nodes are added in the sensor network, not only the messages for the time synchronization but also the amount of memory usage for sustaining the received time value of reference packets are highly increased. In addition, since a reference packet sender node does not participated in time synchronization activities and just relative time offsets between sensor nodes are used, the global time value can not exist in the sensor network.

In this paper, we propose the RIP(Reference Interpolation Protocol) to reduce the number of messages for time synchronization in wireless sensor networks. The reduction of messages causes the sensor nodes to prolong their lifetime and also to shorten the convergence time for synchronizing. In our RIP, since all sensor nodes including reference packet sender nodes and a base station node are participated in time synchronization activities, the global time can be sustained in working sensor networks.

The RIP method uses reference packets to synchronize all sensor nodes that are exploited in the previous RBS method. When compared to the previous NTP method based on time stamp packets, the use of reference packets takes advantage of eliminating the synchronization errors due to the nondeterministic characteristics of the send time and the access time occurred in the sender. The factors of inaccuracy in the RIP method are the propagation time and the receive time. However, the propagation time can be ignorable as sensor nodes are deployed densely.

The Fig. 2 shows the sequence diagram of the RIP method suggested in this paper. From this figure, the reference packet sender broadcasts reference packets. The neighbor sensor nodes 1 3 and the base station node store their local time when they receive reference packets. The reference sender node writes the sending time of reference packets. After the base station receives reference packets, the time of receipt of reference packets is broadcasted. This message is include the global time maintained in the base station. Based on the global time data sent by base station node, adjacent sensor nodes and a reference packet sender node interpolate their local time. By these procedures, the local time of the reference packet sender node and all sensor nodes synchronize with the global time of the base station node.

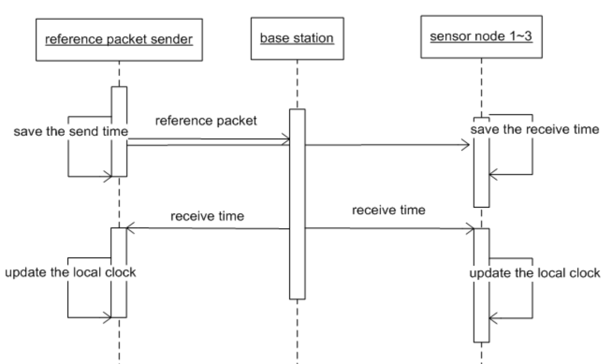


Figure 2. Sequence Diagram of RIP Method

3.2. Operations in Multiple Hops

The wireless sensor nodes in the sensor network are usually worked on the multiple hop communication features. The Fig. 3 shows the brief diagrams for the topology of the wireless sensor network. As shown in this figure, the A, B and C node represent the reference packet sender node. The node 2 and 3 are the gateway node synchronized by the reference packet sender in either side. For example, if the node 1 is a base station node and our RIP method is worked on the multi-hop mode, the steps for time synchronization are next;

Step 1: The base station send a packet to start the time synchronization

Step 2: The node A broadcast the Reference Packet (RP) after it received the start message from the base station

Step 3: Each node write its local time received the reference packet.

Step 4: The node 1 as a base station broadcasts the time of receipt of the reference packet.

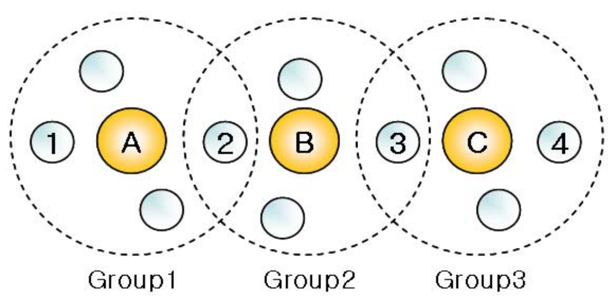


Figure 3. Interpolation Protocol in Multiple Hops

Step 5: Each node interpolates its local time based on the time information broadcasted by the node 1.

Step 6: The gateway node 2 change its role as a base station and performs the procedure from the step 1 to the step 5.

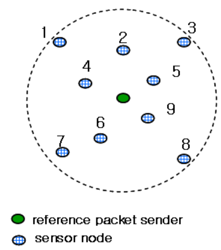
Based on the Fig. 3 and the above 6 steps, the number of message can be calculated to complete the time synchronization. In the RIP method, only the 2 messages are exchanged each other within one hop group and the 2 x G messages are needed in the multiple hops with G groups. On the other hand, if the number of sensor nodes is n, the RBS method described in the Section 2 takes the n x (n - 1) messages in a single hop. Thus, in the multiple hops composed of the G groups, the n x (n -1) x G messages are come out. As the number of sensor nodes is increased, the RBS method suffers from highly increased messages for time synchronization. Its big-O is O(n^2). Otherwise, the RIP method is O(G).

3.3. Convergence Time for Synchronization

The convergence time means the exhausted period until all sensor nodes complete their time synchronization. Since the RIP method completes the time synchronization by the broadcast of 2 messages, its convergence time is greatly shorter than that of RBS method. In the case of the RIP method using the multiple hops, after finishing the synchronization in upper level groups, lower level groups can perform their time synchronization. However, the RBS method commences the time synchronization as flooding the ignition message from the base station into sensor networks. After that, since a reference packet sender node establishes the random time for the synchronization, all sensor nodes perform the time synchronization after this designated time.

Due to the sequence processing in RIP method, the long convergence time may be supposed. However, since the RIP method uses very fewer messages, the speed of the time synchronization is greatly fast over our expectation. On the other hand, in the RBS method, when sensor nodes are deployed densely, many messages causes the high contention to occupy the network bandwidth between sensor nodes. As a result, the increase of convergence time is inevitable.

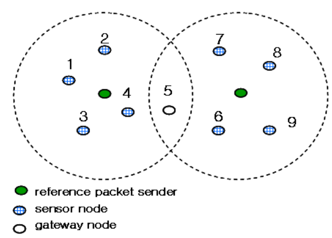
The wireless sensor nodes are composed of very limited computing resources such as low CPU ability, small memory capacity, lack of IO devices and low network bandwidth. Since sensor nodes are worked on the limited resources, even in the time synchronization activities, it would be better to use a small amount of memory if possible.



Offset table of node 9

Node ID	1	2	3	4
Offset	−98	+11	0	−9
Node ID	5	6	7	8
Offset	+24	+5	−32	0

Figure 4. Table and Sensor Deployment in Single Hop RBS



Offset table of node 1

Node ID	2	3	4	5
Offset	−8	−21	+3	−2

Offset table of node 5

Node ID	1	2	3	4
Offset	+2	+6	+19	+5
Node ID	6	7	8	9
Offset	−14	+6	−2	0

Figure 5. Offset Table and Sensor Deployment in Multiple Hop RBS

3.4. Resource Usage in Sensor Nodes

In the RBS method, each sensor node keeps the time of receipt of the reference packet to all neighbored sensor nodes. As the number of sensor nodes is increased, the amount of memory usage rises up highly to maintain the time offset data of all sensor nodes. The Fig. 4 shows the example of offset table when the RBS method is working on the single hop environment. This network is composed of 9 sensor nodes except the reference packet sender node. This figure shows the offset table located in the 9^{th} sensor node. As shown in this table, the time offset values for 8 neighbored nodes are stored in the memory. If the sensor network is composed of N nodes and the time offset value takes K bytes, the memory size to maintain the time offset in each sensor node is [(N-1) x K] bytes. Thus, total memory size of a group is [N (N-1) x K] bytes. The Fig. 5 shows the time offset tables in multiple hops. In particular, the 5^{th} node is involved in 2 groups. As shown in this figure, the offset table size of the 5^{th} node is double when compared to sensor nodes included in a group.

In the RIP method, since all sensor nodes have updated their local time based on the global time sent from a base station, only the space for the time offset of itself is needed, instead of the large offset table. Thus, the RIP needs only K bytes space for handling the time synchronization. The use of a small amount of memory could manage a large number of sensor nodes simultaneously. Therefore, the RIP method has an advantage that the more accurate detections to various events are possible through deploying many sensor nodes in fields.

4. Performance Evaluation

4.1. Experimental Environment

To evaluate our RIP and the RBS method, the NS2 2.26 combined with the NRLSensorSim Extension function with all other parameters is plugged into the tested methods to obtain quantitative information on the behavior on the different schemes. Our experiments are performed with varying the number of sensor nodes and the size of Grid.

4.2. Performance in the Single Hop

To measure the performance of the RIP and RBS method in the single hop model, firstly we make 500 x 500 Grid map. Base on this Grid map, a reference packet sender node is deployed into the center position and the other sensor nodes are spread across the entire Grid map randomly. As the performance metrics, the number of messages and the convergence time for all sensor nodes are considered. The Fig. 6 shows the number of messages according to the increase in the number of sensor nodes. As shown in this figure, the RBS scheme exchanges 17677 messages between sensor nodes. Otherwise, the RIP scheme just represents 427 message exchanging. When the number of sensor nodes is 30, the RIP method results in 98% less messages than the RBS method.

In the case of where applications and communication protocols are developed in the basis of wireless sensor networks, the low power consumption is an important requirement to prolong sensors' lifetime. According to the previous researches such as the Mica series [5], the wireless communication operation via the RF took a great amount of power consumption. From our experiments to the RIP and the RBS methods, the RIP method takes not only the small number of messages to synchronize all sensor nodes but also it reduces the amount of overheads introduced by wireless communication. These advantages let the wireless sensor nodes perform their originally required functions well, without the burden of the time synchronization.

The Fig. 7 shows the convergence time until all sensor nodes completed the time synchronization. As shown in this figure, compared to the convergence time of the RBS method, the RBS method rises up abruptly according to the

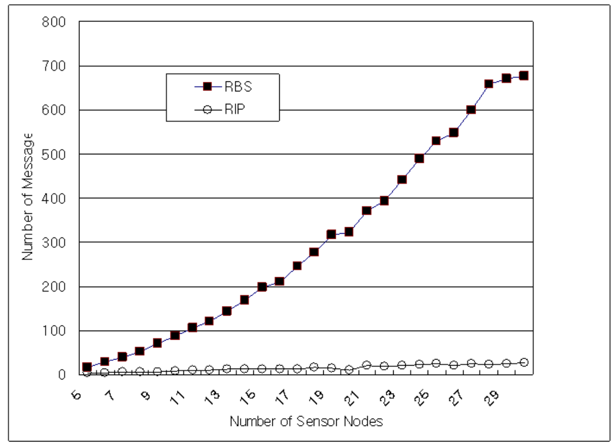


Figure 6. Number of Messages in Single Hop RIP

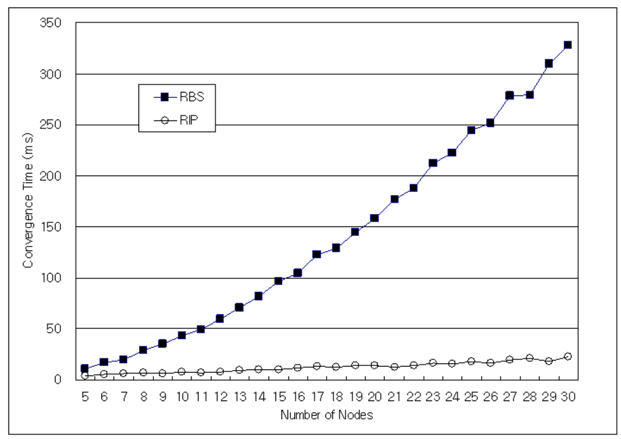


Figure 7. Convergence Time in Single Hop RIP

number of sensor nodes. However, the RIP method represents a small quantity in the increment. As described in the Section 3, in the RIP method, the time synchronization is started by a message from a reference sender node and is finished by interpolating the relative time difference to the time of a base station. This method completes the time synchronization by exchanging two messages. Due to the step by step synchronization activities in the RIP method, it appears to need the more time for completing the time synchronization. Contrary to our thinking, since the RIP method requires only two message exchanges to complete the synchronization of one group, the total convergence time is too shortening as shown in this figure.

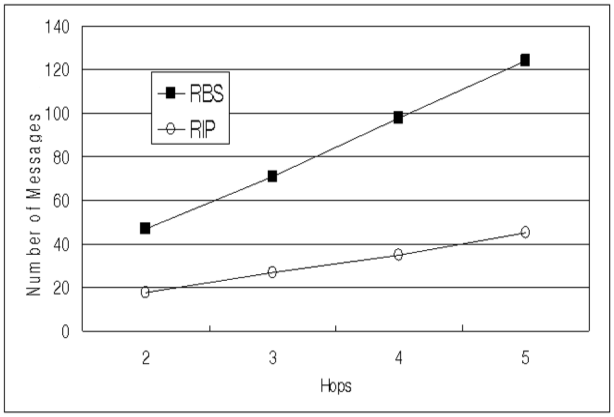


Figure 8. Number of Messages in Multiple Hops RIP

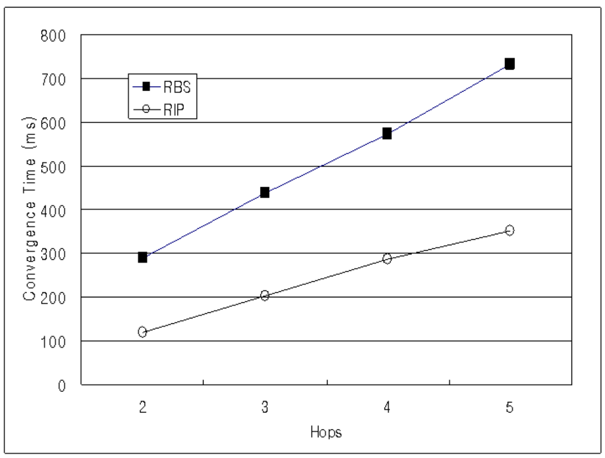


Figure 9. Convergence Time in Multiple Hops RIP

However, since the RBS method begins to synchronize all sensor nodes simultaneously included in each group, this operational characteristic causes the conflicted messages across all wireless sensor nodes. From the message conflictions, the RBS results in the relative long convergence time. As shown the Fig. 7, under 30 sensor nodes, the RIP method produces 91% less convergence time than the RBS.

4.3. Performance in the Multiple Hops

For the performance in multiple hops environment, the number of messages and the convergence time are measured across from 2 hops to 5 hops. In our experiment, one group is composed of a base station, a reference packet sender node, general sensor nodes and a gateway node that communicates with the other group. The Fig. 8 shows the number of messages according to increased hop sizes. As calculated in the Section 3, if the number of sensor nodes is n, the RIP method generates 2 messages and the RBS takes n x (n-1) messages. Since the synchronization activities in each hop have not impact upon the other hops, it is natural that the amount of messages in the both is increased linearly as the number of nodes is added. However, as shown in the Fig. 8, the speedup of the RBS scales quite steeply when compared to the RIP method.

The Fig. 9 shows the convergence time in the multiple hop environments. As shown in this figure, the result is similar to that of the number of messages induced in single hop environment. In the RIP method, after the upper groups near to a base station are synchronized firstly, the proceeding of synchronization spreads over the lower groups successively. Otherwise, the RBS method performs the time synchronization at once in all groups after a reference packet sender establishes the random time for synchronizations. However, since the RIP completes the synchronization within short limits in each group, the convergence time is more than two times as fast as that generated in the RBS.

4.4. The Amount of Power Consumption

The reduced messages are helpful to decrease the amount of power consumption. Based on the experiments of the previous Section, we will attempt to compute the impact of our RIP method in the aspect of power consumption. In the Mica2 Mote, the RF receipt requires 29 mW and the transmission needs 42 mW. On the sleep state of micro processors, the small amount of power is exhausted such as the ranges of uW. Thus, by controlling the state of micro processor between the sleep and the active state, the energy of sensor nodes can be saved. However, as shown in this Table, the transmission and the receipt of a message take a great part of energy consumption compared to the amount of power exhausted by doing the data processing in the micro processor. Based on these observations, the energy saving in data communications is more efficient than the controlling of the micro processor's state. In the case of RF communication, the power of antenna can be cut off for non working situation, which is similar to the way with controlling of micro processors' state [6].

In RIP method, each sensor node uses only the two messages for its own time synchronization. The number of message is very smaller than that of RBS method. Since small number of messages let the RF communication use less, the amount of battery energy consumed is also saved. The Table 1 shows the amount of power consumed by message

Table 1. Power Consumption Rate in the RIP and RBS

Num. of Nodes	Num. of Messages		Consumed Power (Tx)		Convergence Time(ms)		Power consumption Rate (W/s)	
	RIP	RBS	RIP	RBS	RIP	RBS	RIP	RBS
5	4	17	0.17	0.71	0.04	0.11	1.56	6.65
10	8	88	0.34	3.7	0.08	0.43	0.78	8.55
15	13	198	0.55	8.32	0.1	0.97	0.57	8.61
20	11	323	0.46	13.57	0.14	1.58	0.29	8.59
25	24	529	1.01	22.22	0.18	2.44	0.41	9.09
30	27	677	1.13	28.43	0.23	3.28	0.35	8.67
Average							0.66	8.36

exchanges in both the RIP and the RBS method. They are based on both the amount of power consumed by the Tx functions described in the Table **??** and the number of messages generated by two methods in single hop environment. As shown in this Table, the RIP results in the 0.66 W/s and the RBS consumes 8.36 W/s. Due to the use of less messages, the RIP method consumes 12.7 times less power than the RBS method.

5. Conclusion

In this paper, we proposed a new time synchronization method designated by RIP. The RIP method reduced the number of messages for the time synchronization in wireless sensor network. This effect resulted in the decrease in the amount of power consumption so that the lifetime of sensor nodes could be prolonged. To synchronize all wireless sensor nodes, the RIP method used two messages broadcasted from both the reference packet sender and the base station. Each sensor node has synchronized its local time by interpolating with the time difference achieved from two messages. Instead of synchronizing with the timestamp values of all sensor nodes, since the RIP performed the synchronization based on the reference packets such as doing the RBS method, it eliminated the access time and transmission time that were regarded as the sources of inaccurate time synchronization. In addition, since each sensor node received only the two messages for its own time synchronization, the number of message exchanges fell down tremendously. Since the decrease in the number of messages caused the diminishing the energy consumption, the lifetime of wireless sensor nodes could be extended.

Throughout the detailed experiments for the RIP and the RBS method, we confirmed that the RIP method has greatly decreased the number of messages for synchronizing. In addition, the reduced messages might shorten the convergence time for total time synchronization. When applying these results to the real wireless sensor motes, the RIP method showed the 12.7 times less power consumption than the RBS method. As a result, the saved energy has contributed to the extension of the lifetime of the wireless sensor nodes and the shorten convergence time has guaranteed the quick response to events inadvertently happened. These effects by the RIP method could facilitate the deployment of wireless sensor nodes in isolated working areas.

References

[1] M. Lemmon, J. Ganguly and L. Xia: Model-based Clock Synchronization in Networks with Drifting Clocks. In Proceedings. 2000 Pacific Rim International Symposium on Dependable Computing, pp.177–184, December 2000.

[2] J. Berthaud: Time synchronization over networks using convex closures. IEEE/ACM Transactions on Networking, vol.8 no.2, pp.265–277, April 2000.

[3] K. Romer: Time Synchronization in Ad Hoc Networks. In ACM Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc 01), pp.173–182, October 2001.

[4] K. Romer, P. Blum and L. Meier: Time Synchronization and Calibration in Wireless Sensor Networks. Handbook of Sensor Networks: Algorithms and Architectures, pp. 199–237, Wiley and Sons, October 2005.

[5] J. Hill, R. Szewczyk, A. Woo, S. Hollar, D. Culler and K. Pister: System architecture directions for network sensors. In Proceedings of the 0th International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS-IX), November 2000.

[6] J. Polastre, R. Szewczyk, C. Sharp and D. Culler: The Mote Revolution: Low Power Wireless Sensor Network Devices. in Proceedings of Hot Chips 16: A Symposium on High Performance Chips, August 2004.