Abstract—Wireless sensor networks use a large number of collaborating sensors with a built-in wireless device to enable the collection of information in real space. Their wireless sensor nodes require time-synchronization in order to achieve a high degree of sensing accuracy, which is imposed upon them by wireless sensor network applications. A number of researchers have proposed time-synchronization protocols, since these protocols require packet transmissions, they consume excessive energy and impose additional traffic load on the network. Therefore, it is important to implement a time-synchronization technique that does not require packet transmission or reception. This paper proposes a time synchronization protocol based lighting control, which is a time synchronization technique that uses light-controllable lighting fixtures and wireless sensor nodes equipped with an illuminance sensor without packet transmission or reception. This paper also examines synchronization errors with the proposed method and verifies time-synchronization wireless sensor nodes.

Keywords: Time Synchronization, Lighting Control, Wireless Sensor Network, Energy Conservation

1. Introduction

Wireless sensor networks use a large number of collaborating sensors with a built-in wireless device to enable the collection of information in real space. Compared with wired networks, such wireless networks significantly reduce the cost of implementation. In addition, such networks enable detailed observation of events that were impossible to observe in the past. Wireless sensor networks require their network components to time-synchronize in order to maintain the time integrity of data and to implement power-saving protocols. Their wireless sensor nodes also require time-synchronization in order to achieve a high degree of sensing accuracy, which is imposed upon them by wireless sensor network applications. A number of researchers have proposed time-synchronization protocols, including approaches using satellite-based GPS and Network Time Protocol [9] to time-synchronize nodes on the Internet. However, these protocols are not necessarily optimal in wireless sensor networks with a diversity of node characteristics and strict power constraints. Time synchronization protocols that take advantage of small propagation delays in wireless sensor networks have been proposed. They include Timing-sync Protocol for Sensor Networks (TSN) [2], Reference Broadcast Synchronization (RBS) [1], and Flooding Time Synchronization Protocol (FTSP) [5]. However, since these protocols require packet transmissions, they consume excessive energy and impose additional traffic load on the network.

The authors of this paper are currently developing an Intelligent Lighting System, i.e., a lighting control system that takes power-saving into account [4],[8]. The Intelligent Lighting System consists of lighting fixtures whose light levels are controllable, wireless sensor nodes, a sink node, a control PC, and a power meter [7]. This system enables lighting fixtures to autonomously adjust their light levels and provides each location within an office the level of lighting that the office worker at that particular location desires. By introducing this Intelligent Lighting System, light conditions in an office will improve and power consumption will reduce. The Intelligent Lighting System uses wireless sensor nodes equipped with an illuminance sensor to obtain illuminance at fixed intervals. The Intelligent Lighting System uses the collected illuminance data for control and to estimate geo-locations and disturbances. However, since wireless sensor nodes are not time-synchronized, different wireless sensor nodes may exhibit different times. Thus, it is also necessary to time-synchronize wireless sensor nodes in the Intelligent Lighting System.

In addition, challenges in using wireless sensor nodes in an office include the cost of replacing batteries in these nodes and instability in the wireless communication environment due to a person or an obstacle in the wireless communication pathways. In particular, when multiple packets are lost consecutively due to an increased level of network traffic caused by an unstable wireless communication environment, existing time-synchronization approaches may not only fail to time-synchronize wireless sensor nodes but also increase the number of packet transmissions and create an even larger network traffic load. Therefore, it is important to implement a time-synchronization technique that does not require packet transmission or reception. This paper proposes Time synchronization Protocol based Lighting Control (TPLC), which is a time synchronization technique that does not require packet transmission or reception. TPLC uses light-controllable lighting fixtures and wireless sensor nodes...
equipped with an illuminance sensor. This paper also examines synchronization errors with the proposed TPLC and verifies TPLC time-synchronization wireless sensor nodes.

2. Time Synchronization Protocol for Wireless Sensor Networks

2.1 An importance of time synchronization protocol

Wireless sensor networks require time-synchronization to maintain the time integrity of data and to implement power-saving protocols. Due to this, there exists a large body of research on time synchronization in wireless sensor networks. Examples of such research include TPSN, RBS and FTSP. These are time-synchronization protocols specifically designed for wireless sensor networks that also achieve a high degree of accuracy in time-synchronization with relatively simple mechanisms.

2.2 Flooding Time Synchronization Protocol

FTSP is a technique that extracts all time synchronization errors occurring in a single hop and minimizes such time synchronization errors to achieve a high degree of time synchronization accuracy [5]. In order to minimize time synchronization errors in a single hop, i.e., propagation errors, and errors due to computation, the MAC layer at both the sender and the receiver uses a timestamp. Using a timestamp with both the sender (during transmission) and the receiver (during reception) enables time synchronization errors to be minimized between the sender’s and the receiver’s timestamps and to be ignored at the time of send, access and receive as shown in Figure 1. In addition, since FTSP only requires packet transmission in one direction, FTSP may time-synchronize an entire network by broadcasting a packet to the entire network.

By implementing FTSP on Mica2 [3], it is confirmed that FTSP achieves time synchronization with an average time synchronization error of 1.4 us and with a max time synchronization error of 4.2 us. FTSP does not, however, consider the instability in a wireless communication environment such as packet loss. In addition, FTSP requires packet transmission and reception, resulting in a possible increase in power consumption at wireless sensor nodes.

3. TPLC: Time Synchronization Protocol based Lighting Control

3.1 Overview

This paper proposes TPLC, a time-synchronization technique based on lighting control that does not require the transmission or reception of packets.

With TPLC, lighting fixtures autonomously adjust their luminance to cause changes in the illuminance level measured by illuminance sensors. TPLC then uses the changes in the measured illuminance to determine when to initiate time synchronization and achieves time synchronization. When adjusting the luminance of lighting fixtures, the luminance adjustment needs to be within a range that is not noticeable by office workers to maintain a comfortable work environment. Existing research indicates that, if the change in illuminance due to luminance adjustment is within 7% of the current illuminance level, one may not detect such luminance adjustments [11]. TPLC performs time synchronization using this small change in illuminance. Therefore, in order to design an algorithm for TPLC, it is necessary to examine how the illuminance changes in time when the luminance is adjusted.

3.2 The measurement of illuminance on a wireless sensor node

We examine changes in illuminance measured by an illuminance sensor on a wireless sensor node for a given illuminance change within approximately 7% of the current illuminance. In these experiments, a MOTE MICAz made by Company C serves as a sensor node [6]. MDA088, a general-purpose external sensor board, is installed onto the MOTE MICAz, and a lead-type NaPiCa illuminance sensor [10] is embedded in the external sensor board to measure illuminance. In these experiments, an illuminance sensor is configured to measure illuminance every 100 ms.

Experiments were conducted in a lab at Doshisha University. The lab used in the experiments simulates an actual office environment and used 15 Panasonic white fluorescent lamps (FHP45EN) and one wireless sensor node. Figure 2 shows a bird’s-eye view of the experimental set up. White color partitions were placed by the windows to prevent outside light from entering the lab. The vertical distance between a fluorescent lamp and a wireless sensor node was 1.9 m when the wireless sensor node was placed vertically under the fluorescent lamp. A wireless sensor node was placed vertically under fluorescent lamp 7, and only fluorescent lamp 7 was light-controlled.

A NaPiCa illuminance sensor has a low resolution. Therefore, in these experiments we used a highly precise ANAF11 illuminance sensor and adjusted the illuminance measurements obtained through the NaPiCa illuminance sensor using equation 1.
With the initial condition where illuminance on a desk surface measured by ANA-F11 is 500 lx, we increased illuminance by 15 lx (i.e., 3% of 500 lx), kept illuminance at the increased level for six seconds, and then restored the original illuminance, and obtained how the measured illuminance changed. Figure 3 uses 100 ms intervals to measure illuminance and shows how illuminance changed at a given time.

Figure 3 shows that a NaPiCa illuminance sensor successfully detects a change in lighting illuminance even for a small illuminance change within 7% of the current illuminance. Based on these findings, this paper proposes a time synchronization algorithm for TPLC.

3.3 Algorithms

This section explains the time synchronization algorithm for TPLC. Illuminance data does not contain time information such as a timestamp in a packet. Due to this, it is necessary to implicitly convey time information to an illuminance sensor so that time synchronization is initiated based on illuminance measurements obtained by the illuminance sensor. TPLC initiates time synchronization by varying the illuminance of a lighting fixture to cause fluctuations in illuminance and having an illuminance sensor detect the illuminance fluctuations. However, as seen in Figure 3, even when the lighting stays at the same luminance level, errors occur in the illuminance measurements, and fluctuations occur in the measured illuminance. When varying illuminance, changes in illuminance need to be larger than errors yet still small enough to not cause discomfort for office workers. Therefore, in performing time synchronization, TPLC applies a small luminance change and initiates time synchronization only when the increase in the measured illuminance caused by the luminance change is at the predetermined ratio.

The following describes a set flow to perform to initiate time synchronization. Assume that all lighting fixtures are initially on and that all wireless sensor nodes are placed within a distance to measure illuminance and are powered on at the same time within a single illuminance measurement time interval. First, periodically measures the current illuminance at every illuminance measurement interval; Calculate the change in illuminance from the measured current illuminance and the previously measured illuminance using the equation; Initiate time synchronization when the illuminance change is equal to the predetermined value. The following set flow constitutes one step.

(1) An illuminance sensor measures the current illuminance.

(2) A lighting fixture increases its luminance by \(x\% \), where \(x < 7\%\).

(3) If an illuminance sensor detects a change in illuminance, calculate the amount of illuminance change.

(4) If the change in illuminance is equal to the predetermined value, store the measured illuminance value obtained in (1) and the illuminance value after the illuminance change.

(5) If the measured illuminance values before and after the illuminance change in the current step and in the previous step are equal within a margin of error, time-synchronize wireless sensor nodes.

(6) A lighting fixture returns its luminance to what it was before the luminance change. Perform the above operation (1).

This is the time synchronization algorithm for TPLC. Flow (4) is necessary because of the following reasons. Without flow (4), TPLC recognizes an illuminance increase of larger than the predetermined value and may falsely
initiate time synchronization. Referring to the measured illuminance value after time synchronization in the previous step prevents false initialization of time synchronization.

4. Evaluation

4.1 Overview

We implemented TPLC on a wireless sensor node and examined synchronization errors. Experiments were conducted under the same conditions as those seen in Figure 2 and used two wireless sensor nodes. In order to examine synchronization errors in TPLC, wireless sensor nodes were placed in three different patterns. These patterns were: (A) Both wireless sensor nodes were placed directly under one lighting fixture. (B) One wireless sensor node was placed directly under each of two lighting fixtures that were located at a distance from each other. (C) Both wireless sensor nodes were placed at the midpoint between two adjacent lighting fixtures.

First, in placement that both wireless sensor nodes were placed directly under one lighting fixture, only one lighting fixture was used. Thus, it was a placement that did not require wireless sensor nodes to consider the distance between the lighting fixture and wireless sensor nodes, nor the luminance changes at adjacent lighting fixtures. Figure 4 shows this placement.

Second, in placement that one wireless sensor node was placed directly under each of two lighting fixtures that were located at a distance from each other, one wireless sensor node was placed directly under each of two lighting fixtures that were located at a distance from each other. Figure 5 shows this placement.

Third, in placement that both wireless sensor nodes were placed at the midpoint between two adjacent lighting fixture, wireless sensor nodes were placed at the midpoint in the horizontal direction between two adjacent lighting fixtures. Figure 6 shows this placement.

Experiments were conducted with the aforementioned placement patterns to examine synchronization errors. In the experiments, time synchronization was performed through increasing and decreasing the illuminance of a lighting fixture (or lighting fixtures) by 15 lx every two seconds. For all three placement patterns, luminance was first increased and then decreased, and this increase/decrease in luminance was repeated a total of 1,000 times. The experiments used the FTSP’s global time as the correct time. TPLC’s synchronization error is defined as the time synchronization error of the global time obtained through comparing global times between sensor nodes when a wireless sensor node initiates time synchronization. Since the average synchronization error of FTSP was within 1 ms, the experiments did not consider synchronization errors that occurred in FTSP.

4.2 Evaluation in TPLC when both wireless sensor nodes were placed directly under one lighting fixture

In the following, we examine synchronization errors in TPLC for wireless sensor node placement pattern that both wireless sensor nodes were placed directly under one lighting fixture. In placement that one wireless sensor node was placed directly under one lighting fixture, wireless sensor nodes A and B were placed directly under lighting fixture 7 and only lighting fixture 7 was light controlled.

Figure 7 shows a distribution of synchronization errors. The horizontal axis shows the synchronization error [ms], and the vertical axis shows the probability of the error occurring. Table 1 summarizes the synchronization errors. Synchronization errors depend on the length of the time intervals measuring illuminance. Time synchronization with TPLC becomes more precise as the length of the illuminance measurement time intervals decreases. However, the
shorter the illuminance measurement time intervals are, the more power wireless sensor nodes consume. It is therefore necessary to design an algorithm that does not depend on the length of illuminance measurement time intervals.

4.3 Evaluation in TPLC when one wireless sensor node was placed directly under each of two lighting fixtures that were located at a distance from each other

In the following, we examine synchronization errors in TPLC for wireless sensor node placement pattern that one wireless sensor node was placed directly under each of two lighting fixtures that were located at a distance from each other. Wireless sensor node A was placed directly under lighting fixture 4, and wireless sensor node B was placed directly under lighting fixture 10. For this experiment, only lighting fixtures 4 and 10 were light controlled. Figure 8 shows a distribution of synchronization errors. Table 2 summarizes the synchronization errors.

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<th>synchronization error value [ms]</th>
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<td>average</td>
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<td>minimum</td>
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Table 2: The values of synchronization errors in TPLC when one wireless sensor node was placed directly under each of two lighting fixtures that were located at a distance from each other.
Table 3: The values of synchronization errors in TPLC when both wireless sensor nodes were placed at the midpoint between two adjacent lighting fixture.

<table>
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<tr>
<th>Synchronization Error Value [ms]</th>
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<tbody>
<tr>
<td>Average</td>
<td>88</td>
</tr>
<tr>
<td>Maximum</td>
<td>277</td>
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<tr>
<td>Minimum</td>
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was placed directly under each of two lighting fixtures that were located at a distance from each other is almost identical to in placement pattern that both wireless sensor nodes were placed directly under one lighting fixture.

The spatial relation between the two lighting fixtures in the experiments was such that they did not affect each other. Thus, each of the two illuminance sensors independently initiated time synchronization based on the illuminance from its respective lighting fixture. The lighting fixtures used in placement that one wireless sensor node was placed directly under each of two lighting fixtures that were located at a distance from each other differed from the lighting fixture used in placement that one wireless sensor nodes were placed directly under one lighting fixture. To perform light control on lighting fixtures, a light control signal was sent to each and every lighting fixture. The signal reached different lighting fixtures with different propagation delays.

In the experiments, the propagation delay of the light control signal could have introduced synchronization errors. However, the propagation delay of the light control signal for the laboratory used in the experiments was significantly smaller than the length of illuminance measurement time intervals, and thus, it did not impact synchronization errors. This explains how the experimental results for synchronization errors for the placement that one wireless sensor node was placed directly under each of two lighting fixtures that were located at a distance from each other are similar to those for placement pattern that both wireless sensor nodes were placed directly under one lighting fixture.

4.4 Evaluation in TPLC when both wireless sensor nodes were placed at the midpoint between two adjacent lighting fixtures

In the following, we examine synchronization errors in TPLC for wireless sensor node placement pattern than both wireless sensor nodes were placed at the midpoint between two adjacent lighting fixture. Wireless sensor nodes A and B were placed at the midpoint in the horizontal direction between lighting fixtures 7 and 12. For these experiments, only lighting fixtures 7 and 12 were light controlled. Figure 9 shows a distribution of the synchronization errors. Figure 10 shows a cumulative error distribution for 3 placement patterns. Table 3 summarizes the synchronization errors.

Figure 9: The distribution of synchronization errors in TPLC when both wireless sensor nodes were placed at the midpoint between two adjacent lighting fixture.

Figure 10: The cumulative error distributions for TPLC.

Figure 10 shows that the experiments for the placement than both wireless sensor nodes were placed at the midpoint between two adjacent lighting fixture resulted in a cumulative error distribution that differs from those seen in placement that both wireless sensor fixture resulted in a cumulative error distribution that differs from those seen in placement that both wireless sensor nodes were placed directly under one lighting fixture and in placement that one wireless sensor node was placed directly under each of two lighting fixtures that were located at a distance from each other. With the placement than both wireless sensor nodes were placed at the midpoint between two adjacent lighting fixture, there are less synchronization errors within 100 ms, and the average synchronization error is larger.

In the experiments, illuminance sensors were placed at the midpoint between two adjacent lighting fixtures that were close to each other. A luminance change of one lighting fixture affected the illuminance sensor placed directly under the other lighting fixture. As a luminance change at either lighting fixture affects the illuminance measured by illuminance sensors, it is possible that an increase in illuminance in the current step becomes different from that in the previous step, depending on when luminance changes occur at lighting fixtures. When a change in illuminance differs in each step, it significantly affects synchronization errors. For
example, assume that 500 lx was referred to in the previous step. In the current step, whether time synchronization is initiated or not is determined when the measured illuminance approaches the referred value of 500 lx. Different lengths of time required for illuminance to reach 500 lx after the initial change in luminance clearly result in different times to initiate time synchronization. When each sensor node experiences different changes in measured illuminance in every step, it necessarily results in large synchronization errors. Due to this, we sure that synchronization errors are larger with the placement than both wireless sensor nodes were placed at the midpoint between two adjacent lighting fixture than with the placement that both wireless sensor nodes were placed directly under one lighting fixture and the placement that one wireless sensor node was placed directly under each of two lighting fixtures that were located at a distance from each other.

5. Conclusion and Future Improvements

This paper proposes Time synchronization Protocol based Lighting Control (TPLC), a time synchronization technique that does not require packet transmission or reception. TPLC varies luminance of a lighting fixture (or lighting fixtures) to cause changes in measured illuminance and uses the resulting illuminance changes to initiate time synchronization. By implementing TPLC on MOTE MICAz, we examined synchronization errors. When two wireless sensor nodes were placed directly under a single lighting fixture, TPLC achieved time synchronization with an average error of 62 ms, a maximum error of 172 ms and a minimum error of 4 ms. Experiments were also conducted for wireless sensor node placements where a wireless sensor node was placed directly under two lighting fixtures and where wireless sensor nodes were placed at the midpoint between two adjacent lighting fixtures. Experimental results for these placements show that TPLC achieved time synchronization, although it resulted in larger synchronization errors when compared to the placement where wireless sensor nodes were placed directly under a single lighting fixture.

Future research includes improving time synchronization to be more precise. Time synchronization becomes more precise as the length of illuminance measurement time intervals decreases. However, the shorter the illuminance measurement time intervals are, the more power wireless sensor nodes consume. One may explore an algorithm with varying illuminance measurement time intervals to search for the time when a luminance change completes. Such an algorithm may use shorter illuminance measurement time intervals near the time to initiate time synchronization, but longer intervals otherwise.

References