Packet Loss Resilience Lighting Control for Wireless Sensor Networks

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Abstract—The use of wireless sensor networks in offices for the purpose of conserving power has been attracting attention. At the same time, we are conducting research and development of an Intelligent Lighting System that targets offices and realizes the illuminance required by the workers. By using a wireless sensor network in the Intelligent Lighting System, we are able to improve the ease of installing illuminance meters. However, in wireless network sensors that use many low power wireless signals, the potential for packet loss due to radio wave conditions exists. In this study, multiple lighting control algorithms that enable convergence on the required illuminance, even if packet loss occurs, are proposed. Moreover, the proposed algorithm was evaluated under multiple environments in which packet loss was generated. By using the Estimation Algorithm, illuminance convergence equivalent to cases involving no packet loss was realized even in environments with a high packet loss rate.

Keywords: Wireless Sensor Network, Lighting Control, Office Environment

1. Introduction

The use of wireless sensor networks where multiple sensors work together to collect information is expected in a variety of fields. The range of application of wireless sensor networks is extensive and covers a broad array of areas, such as outdoor environment monitoring, and control in buildings and factories [1], [2]. In particular, in recent years the introduction of wireless sensor networks in office buildings has increased due to the increase in awareness regarding security and energy conservation. In contrast, measures to improve the intellectual productivity, creativity, and comfort of employees in offices are attracting attention [3], [4]. According to research by Boyce and his team, it has become clear that the intellectual productivity and creativity of employees in an office are improved by improving the lighting environment [5]. Moreover, power consumed by lighting in an office accounts for a significant percentage of the overall power consumption, and thus methods to reduce power consumption by controlling the brightness of lights are proposed [6], [7], [8]. In the midst of this, we are researching and developing the Intelligent Lighting System [9]. The Intelligent Lighting System uses illuminance meters to realize the illuminance level required by individual office employees and thereby improve the lighting environment of offices. Moreover, with the Intelligent Lighting System, energy savings can be improved by minimizing the brightness of unnecessary lights.

A drawback of wired illuminance sensors is the need for wiring work. In contrast, the advantages of wireless sensor networks include an improved ease of installing the illuminance meters and the ability to flexibly support changes in an office layout. However, with wireless sensor networks that use a lot of low power wireless signals, the potential for severing communications or data loss due to radio wave conditions exists. Offices in particular contain a varied layout of office equipment and obstacles, and often times, the status of radio waves can unexpectedly worsen dramatically due to the movement of office employees and the use of electronic devices. The Intelligent Lighting System changes the brightness of lighting and implements feedback control based on illuminance information transmitted from the illuminance meters. However, in some cases, the feedback control becomes unstable due to severed communication or data loss, and as a result, convergence to the illuminance required by the office employees cannot be achieved.

In this study, Periodic Algorithm that uses an illuminance value prior to a packet loss occurrence, Wait Algorithm that waits until a packet arrives, and Estimation Algorithm that estimates the illuminance value are proposed as lighting control algorithms that enable convergence on the required illuminance even if packet loss occurs. These three algorithms differ in control timing and the illuminance used in the lighting control. Construction of a system that is resistant to packet loss is possible by changing the control timing and the illuminance used in the lighting control.

Our contributions in this paper are as follows.
- Presenting a "Packet Loss Resilience Scheme for Lighting Control" that does not place a load on the network or wireless sensor nodes when packet loss is generated.
- Using 15 light controllable ceiling lights and wireless sensor nodes to build the "Packet Loss Resilience Scheme for Lighting Control" in real space.
- Evaluated the stability and speed of illuminance convergence for the "Packet Loss Resilience Scheme for
Lighting Control” in multiple environments that generate packet loss.

This paper is configured as follows. First, in the following section, a lighting control algorithm for the Intelligent Lighting System is presented. In Section III, a lighting control algorithm that takes into consideration packet loss and for which a proposal is given in this paper is presented, and the evaluation thereof is given in section IV. In Section V, we discuss related research, and the conclusion is presented in Section VI.

2. Intelligent Lighting System

2.1 Overview of an Intelligent Lighting System

An Intelligent Lighting System achieve each user’s required illuminance, and aim to improve the level of intellectual productivity. Using the Intelligent Lighting System, energy consumption will be improved by minimizing the brightness of unnecessary lights.

The Intelligent Lighting System, as indicated in Fig. 1, is composed of dimmable lights, illuminance sensors, control PC, and power meter, with each elements connected via a network. The illuminance sensor is provided for each user, and the illuminance in front of the user is measured by the sensor. In the control device installed for each lightings, illuminance information is collected from each illuminance sensor together with information about the power consumption from the power meter. Based on these datas, the control device will adjust the illuminance according to an optimization technique to achieve the illuminance requested by each user while also striving to keep the power consumption to a minimum.

2.2 Lighting Control Algorithm

The Intelligent Lighting System used an algorithm based on the general purpose optimization method called Hill Climbing. Furthermore, with this algorithm, the factor of influence on lighting for each illuminance sensor was estimated and to efficiently bring about changes in luminance, depending on circumstances.

Control Algorithm using Stochastic Hill Climbing

The Intelligent Lighting System uses Stochastic Hill Climbing method (SHC) for lighting control purposes. The Intelligent Lighting System aims to adjust the illuminance to equal or greater than the target illuminance for the location where the sensors are installed, and autonomously finds the lighting intensity to minimize the amount of electrical power used for lighting. This illuminance is formulated as an objective function. The objective function is shown in Equation 1.

\[ f = P + w \sum_{j=1}^{n} g_i \] (1)

\[ P = \sum_{i=1}^{m} C d_i \] (2)

\[ g_i = \begin{cases} 0 & (I_t - I_c) \leq 0 \\ (I_t - I_c)^2 & (I_t - I_c) > 0 \end{cases} \] (3)

\( n \) : Number of illuminance sensors
\( m \) : Number of lightings, \( w \) : Weight
\( P \) : Amount of consumed electrical power
\( I_c \) : Current illuminance, \( I_t \) : Target illuminance
\( C d_i \) : Current luminance

Making the brightness of the lamps the design variable, we aim to minimize the \( f \) in Equation 1. \( f \) is formed from the amount of consumed electrical power \( P \) (Equation 2) and \( g_i \) (Equation 3), which represents the difference in the illuminance between the current illuminance \( I_c \) and the target illuminance \( I_t \). \( g_i \) is added only if the current illuminance lower than the target illuminance. Also, \( g_i \) is multiplied by a weight \( w \), and the value of this weight \( w \) determines whether priority is given to minimizing, either the constraint conditions on the target illuminance, or the amount of consumed power.

Control Algorithm using Regression Analysis

In SHC, the distance of the lightings and the illuminance sensor is not excluded. Therefore, we have developed an Adaptive Neighborhood Algorithm using Regression Coefficient (ANA/RC)[10], which was developed by adapting the Stochastic Hill Climbing method (SHC) specifically for lighting control purposes. It enables the control system to learn the influence of each lighting on each illuminance sensor by regression analysis. By changing the luminous intensity in response, it enables a quick transition to the optimum intensity. However, the level of influence tends to be inaccurate at the start because the amount of change in light intensity and illumination is small. Therefore, the control system use SHC at the start. Then, the control system shifts to ANA/RC after a specified period of time.
3. Packet Loss Resilience Scheme for Lighting Control

We propose a lighting control algorithm that takes into consideration packet loss. The Periodic Algorithm that uses the illuminance value prior to the generation of a packet loss implements control using the last acquired illuminance when packet loss is generated as the present illuminance. The Wait Algorithm that waits until the packet arrives places control on standby when packet loss occurs until the next packet arrives. The Estimation Algorithm estimates the illuminance value when a packet loss is generated and compensates for the lost illuminance.

3.1 Periodic Algorithm

With the Periodic Algorithm that uses the illuminance value prior to the generation of packet loss, when packet loss is generated, calculation of the objective function is performed using the last acquired illuminance as the present illuminance. This algorithm is a technique that is used in existing Intelligent Lighting Systems. Next, the Periodic Algorithm flow is presented. First, the occurrence of packet loss is confirmed when illuminance is acquired. Namely, the presence of packet loss is confirmed by determining whether or not the illuminance data has been updated. Normally, if transmission and reception of an illuminance value has been implemented, the obtained illuminance value is used in the calculation of the objective function as is. If packet loss has occurred, calculation of the objective function is performed using the last acquired illuminance value as the current illuminance value. Therefore, the generation of the next illuminance and the determination of the objective function value are performed in the same manner as when packet loss has not occurred. With Periodic Algorithm, if packet losses are continuously generated, the same illuminance value is continued in the system. As a result, there is the possibility that a difference could occur between the actual illuminance value and the illuminance value in the system.

3.2 Wait Algorithm

With the Wait Algorithm that waits until a packet arrives, when packet loss occurs, control is placed on standby until the next packet arrives. The Wait Algorithm flow is presented next. First, the presence of packet loss occurrence is confirmed when illuminance is acquired. Namely, the presence of packet loss is confirmed by determining whether or not the illuminance data has been updated. Normally, if transmission and reception of an illuminance value has been implemented, the obtained illuminance value is used as is in the calculation of the objective function. If packet loss has occurred, the present luminance is maintained as is, and lighting control is placed on standby. After illuminance information is received, the system shifts to calculating the objective function, and lighting control is implemented. If packet losses are continuously generated, the same illuminance value is continued in the system, but no difference is generated between the actual illuminance value and the illuminance value in the system. With Wait Algorithm, control is not implemented during the occurrence of packet loss, and thus there is the possibility of an occurrence of delay in illuminance convergence.

3.3 Estimation Algorithm

With the Estimation Algorithm, the illuminance value is estimated when packet loss is generated, and compensation is implemented for the lost illuminance. Next, the Estimation Algorithm flow is presented. First, the presence of packet loss occurrence is confirmed when illuminance is acquired. Namely, the presence of packet loss is confirmed by determining whether or not the illuminance data has been updated. Normally, if transmission and reception of an illuminance value has been implemented, the obtained illuminance value is used as is in the calculation of the objective function. If packet loss has occurred, the illuminance is estimated, and the objective function is calculated.

\[ I_c = \sum_{i=1}^{m} L_i \times R_i \]  \hspace{1cm} (4)
\[ x = I_c \times \frac{I}{I_c'} \]  \hspace{1cm} (5)

\( I_c \) : Estimated illuminance value
\( m \) : Number of lightings
\( L \) : Luminance, \( R \) : Level of influence
\( x \) : Corrected illuminance value
\( I \) : Last acquired illuminance value
\( I_c' \) : Estimated illuminance value when the last illuminance was acquired

The estimated illuminance value is determined from Equation 4. The estimated value for illuminance is obtained from a summation of the luminance of each light multiplied by the level of influence. Because this Periodic Algorithm uses the level of influence, it can only be applied during ANA/RC. Moreover, when compared to the influence obtained by turning on the lights one at a time, the influence dynamically obtained with SHC is inaccurate, and as the lights become further separated from the illuminance meter, the influence tends to become more inaccurate [11]. This is thought to be due to lighting being more easily influenced by the changes in the luminance of other lights as lights become further separated from the illuminance meter.

Therefore, the calculation results of the illuminance value estimation are corrected by Equation 5. The correction is implemented using a ratio of the last acquired illuminance value and the estimated illuminance value when the last illuminance was acquired. The corrected illuminance value is used to calculate the objective function. For example, if
the current estimated value for illuminance is 900 lx, the illuminance when the last illuminance was acquired is 400 lx, and the estimated value for illuminance when the last illuminance was acquired is 800 lx, then the illuminance compensation is performed as 450 lx.

4. Evaluation

4.1 Evaluation Overview

In order to evaluate the effectiveness of Periodic Algorithm, Wait Algorithm, and Estimation Algorithm, illuminance convergence was verified in environments in which packet loss occurs. Testing was performed at the Intelligent System Creation Environment Laboratory in the Kochikan Building of Doshisha University, and in the test, 15 white fluorescent lamps and 4 wireless sensor nodes were used. Of the wireless sensor nodes, 3 were used as illuminance meters, and 1 was used as a sync node.

A scene of the testing site is shown in Fig. 2, and the testing environment is shown in Fig. 3. The wireless sensor nodes were installed in three locations, including directly beneath one light, between two lights, and between four lights. Fig. 3 shows the positional relationship between the fluorescent lamps and the wireless sensor nodes. The number to the side of each fluorescent lamp indicates the number of the each fluorescent lamp, and the letter to the side of each wireless sensor node indicates the symbol used to identify each sensor. For the wireless sensor nodes, MOTE MICAz [12] from Crossbow were used. An MDA088 general purpose exterior sensor base plate was installed on the MOTE MICAz, and a lead type Napica illuminance meter was embedded to enable acquisition of the illuminance value.

Moreover, for the first 200 seconds, illuminance convergence was conducted with SHC for regression analysis, and after 200 seconds, the system shifted to ANA/RC. When Wait Algorithm was used, the shift to ANA/RC was delayed only for the number of times that packet loss was generated, and because Periodic Algorithm cannot be used during SHC, Wait Algorithm was used.

In order to simulate multiple environments in which packet loss occurs, packet losses were generated by the sync node. Three patterns were used for packet loss generation including a case with random generation 10% of the time, a case with generation 50% of the time, and a case that assumed packet loss with burst properties (loss rate of 58.3%). Ordinarily, packet loss of 50% or higher is thought to not easily occur, but a pattern with this type of high packet loss rate was used in order to verify to what extent the proposed algorithm can function properly. The testing applied Periodic Algorithm, Wait Algorithm and Estimation Algorithm to each of the three types of packet loss patterns described above.

4.2 Testing Results for a Case in which the Illuminance Value was Properly Transmitted and Received

Fig. 4 shows a history of illuminance for a case in which the illuminance value is properly transmitted and received. From Fig. 4, we can see that all of the illuminance meters entered the convergence range for the target illuminance in about 240 seconds. During the next 200 seconds as well, the illuminance remained in the convergence range, and thus one could argue that convergence was achieved. Moreover, sensor node C entered the convergence range about 80 seconds after the target illuminance was changed, and for the next 200 seconds as well, the illuminance remained in the convergence range, and thus we found that convergence was achieved.
4.3 Testing Results for a Case in which Packet Loss was Generated with 10% Probability

Fig. 5 shows the illuminance convergence results for the sensor node C for a case in which Periodic Algorithm, Wait Algorithm, and Estimation Algorithm were used when packet loss was generated with a probability of 10%. In addition, Fig. 6 shows an expanded view of the graph of Fig. 5 from 900 seconds to 1,200 seconds. From Fig. 5, a significant difference between the three algorithms was not observed for a case in which packet loss occurred with a probability of 10%. However, from Fig. 6, we can see that with Periodic Algorithm, it took approximately 100 seconds to enter the illuminance convergence range after the target illuminance was changed, and that there was a delay of about 20 seconds in reaching convergence compared to the case in which transmission and reception of the illuminance value were performed normally. With Wait Algorithm and Estimation Algorithm, we found that the convergence range is entered at about the same time as the case in which transmission and reception of the illuminance value were performed normally even after the target illuminance was changed.

4.4 Testing Results for a Case in which Packet Loss was Generated with 50% Probability

Fig. 7 shows the illuminance convergence results for the sensor node C for a case in which Periodic Algorithm, Wait Algorithm, and Estimation Algorithm were used when packet loss was generated with a probability of 50%. In addition, Fig. 8 shows an expanded view of the graph of Fig. 7 from 900 seconds to 1,200 seconds.

From Fig. 7, it is clear that the convergence range was entered with Periodic Algorithm at about 500 seconds for the case in which packet loss was generated with 50% probability. In contrast, with Wait Algorithm and Estimation Algorithm, the convergence range was entered at about 620 seconds. With Wait Algorithm, this was because a delay in illuminance convergence was generated in order to return the luminance each time that packet loss occurred. With Periodic Algorithm as well, it is thought that a similar delay occurred because Wait Algorithm is used at the time of SHC.

From Fig. 8, we can see that with Wait Algorithm and Periodic Algorithm, the convergence range was entered and convergence occurred at about 80 seconds after the target illuminance was changed. In contrast, we can see that with Periodic Algorithm, the convergence range was entered and convergence occurred at about 180 seconds after the target illuminance was changed. The reason for the delay occurring in illuminance convergence with Periodic Algorithm after the target illuminance was changed is thought to be that the current illuminance value was not used in the objective function calculation when packet loss occurred, and thus accurate control could not be implemented. However, because no deviation from the convergence range occurred...
4.5 Testing Results for a Case that Assumed Packet Loss with Burst Properties

The pattern for the actually measured packet loss was used as the burst loss pattern. With a loss rate of 58.3%, packet loss like that shown in Fig. 9 was generated. This uses the loss pattern obtained through actual measurements.

The illuminance convergence loss results for the sensor node C for a case that used Periodic Algorithm, Wait Algorithm, and Estimation Algorithm when packet loss with burst properties occurred is shown in Fig. 10. In addition, Fig. 11 shows an expanded view of the graph of Fig. 10 from 900 seconds to 1,600 seconds.

From Fig. 10, it is clear that all algorithms entered the convergence range at about 480 seconds, and from Fig. 11, we can see that with Periodic Algorithm, about 300 seconds were necessary until the convergence range was entered after the target illuminance was changed. Furthermore, even after entering the convergence range, at about 1,400 second, the illuminance deviated by about 50 lx from the illuminance convergence range. Therefore, convergence to the target illuminance was not completed until about the 1,600 second after the target illuminance was changed. The cause for control not converging is thought to be a problem with the calculation of the objective function. For the case in which Periodic Algorithm was used, when packet loss was continuously generated, the previous illuminance was used repeatedly, and thus, the illuminance became uniform, and the illuminance penalty term became a constant. As a result, it is believed that the objective function became a function that considered only power consumption, and thus, the illuminance fell below the target illuminance. Moreover, when Wait Algorithm was used, a time of about 260 seconds was required until the illuminance convergence range was entered after the target illuminance was changed. With Wait Algorithm, it is thought that time was required to reach convergence because illumination control was not implemented during the time in which packet loss was continuously generated. However, because no deviation from the convergence range occurred for a period of 200 seconds after the convergence range was entered, one could argue that convergence was achieved. On the other hand, when Periodic Algorithm was used, convergence occurred at about 80 seconds after the target illuminance was changed, and for the next 200 seconds, control remained stably within the convergence range. Thus, one could argue that convergence was achieved. This is the same convergence speed as the case in which the illuminance value is normally transmitted and received, and it is believed that this result was achieved because control was implemented by estimating the illuminance even during the time that packet loss was continuously generated.
generated. This result also indicates that Periodic Algorithm is effective in an environment that assumes continuous packet loss.

5. Related Work

A significant amount of research that takes into consideration the occurrence of packet loss in wireless sensor networks is being conducted, and research is being conducted on a technique that retransmits the transport layer as a technique that considers packet loss[14], [15]. However, techniques that retransmit packets place a load on the network. Research is also being implemented on a technique that temporally and spatially brings redundancy, installs sensor nodes, and takes packet loss into consideration[16], [17]. With this technique as well, the number of times for packet transmission and the number of transmitters both increase, thereby placing a load on the network. In contrast, with the proposed algorithm, the number of times for packet transmission is not increased, and thus network load can be reduced, and the algorithm is useful.

6. Conclusion and Future Work

In this study, we proposed a lighting control algorithm that takes into consideration packet loss in a wireless sensor network. We were able to confirm illuminance convergence with Periodic Algorithm for three cases including a case in which packet loss is generated with 10% probability, a case in which packet loss is generated with 50% probability, and a case in which packet loss was generated with burst properties occurred. Moreover, even after the target illuminance was changed, we were able to obtain an illuminance convergence speed that was equivalent to a case in which the illuminance value was normally transmitted and received. Hence, Periodic Algorithm is useful in environments in which packet loss is generated. Based on the above, the effectiveness of the illuminance value estimation algorithm in environments such as offices where radio wave conditions are poor and bursty packet loss occurs was demonstrated.

In the future, a higher speed influence examination technique will be considered. With the technique used in this testing, delays are generated in lighting control only for the number of times that packet loss is generated during SHC. However, by using a higher speed influence examination technique, we anticipate that the shift from SHC to ANA/RC will be accelerated, and that the illuminance convergence speed will be improved. Moreover, when use of wireless sensor nodes in an actual environment is considered, battery operation time must also be considered. A conceivable technique to increase battery operation time is to reduce the number of times that the illuminance value is transmitted. It is also conceivable that the proposed illuminance value estimation algorithm can be used to compensate for illuminance values that are not transmitted due to reducing the number of transmission times.

References