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Article

Intelligent Sensor Network Construction and Real-time Monitoring System Development for Light Environment of Sports Buildings

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Abstract: Sports buildings are an important part of public service facilities, with the significant characteristics of large space and high frequency use, while sports buildings are generally exposed to the lack of light environment sensing network and poor real-time monitoring effect and other problems. In this regard, the article proposes a method of constructing an intelligent sensing network and real-time monitoring system for the light environment of sports buildings based on ZigBee technology, which utilizes ZigBee technology to build an intelligent sensing system, combines with an intelligent control system to realize the real-time monitoring of the light environment data of the sports buildings and evaluates the comfort of the environment. It is found that the transmission rate of the intelligent sensing network is 3.77MB/s, and the packet loss rate and bit error rate of the network node communication with or without interference are lower than 1.5%. The comfort of the light environment of the sports building performs well when the light level is between 172lx and 325lx. The development of intelligent sensing network and real-time monitoring system for the light environment of sports buildings can provide reliable support for optimizing the design strategy of light environment and improving the efficiency of light environment monitoring in sports buildings.

Keywords: ZigBee technology; intelligent sensing network; real-time monitoring system; environmental comfort

1. Introduction

As an important place for organizing all kinds of sports events, cultural performances and mass fitness activities, the indoor light environment is directly related to the quality of the activities and the experience of the participants. A good light environment can provide clear visual conditions for athletes, reduce visual fatigue, and improve game performance; create a comfortable atmosphere for spectators to watch the game, and enhance the immersion and pleasure of watching the game; for activities such as gymnastics, figure skating, etc., the skillful use of natural light can create a unique stage effect, and enhance the artistic infectious force of the performance [1-5]. In addition, sufficient natural light can also improve indoor air quality, inhibit bacterial growth, which is conducive to the health of users [6]. However, sports buildings face many challenges in the management of the light environment of sports buildings due to their own special nature, as well as factors such as optical standards for sports lighting and the specificity of different sports programs. For example, soccer stadiums require high brightness, strong uniformity, and anti-glare; basketball/badminton indoor stadiums require anti-flicker, avoiding light spillage or over-concentration, and restoring the true color of the venue; indoor swimming stadiums require the avoidance of glare and direct light to prevent water reflections from interfering with the athletes' line of sight [7-9]. While the light environment of sports buildings rely on manual inspection, it is difficult to dynamically perceive the changes in the light environment, and the lighting fault detection and monitoring is inefficient, slow response, high cost, and easy to affect the normal conduct of sports events [10-12].

With the development of the building towards energy saving and environmental protection, safety and professionalism, the light environment management has become the design focus of the sports building, and it is necessary to optimize the light environment management of the building in conjunction with other energy consumption and security systems [13-15]. The continuous maturation of the Internet of Things, artificial intelligence, wireless communication technology, big data, edge computing and other technologies has led to the development of intelligent sensor networks, and any sensors can coordinate with each other to achieve data communication, complete real-time monitoring of environmental changes, fault warning and dynamic adjustment of parameters based on the environmental parameters, equipment operating status and environmental needs, and realize energy-saving, safe, professional and low-cost environmental design [16-20]. And the intelligent sensing network becomes an effective measure to assist the management of the light environment of sports buildings.

In the light environment management of sports buildings, scholars have proposed their own intelligent real-time methods for monitoring and adjusting the light environment of buildings. Shengmin [21] developed an intelligent lighting control system through proportional-integral-differential incremental control, Caratab multiplication model, and multilevel fuzzy comprehensive evaluation model, which can accurately satisfy the lighting needs of different sports events in a large-scale stadium. Dong [22] applied a grayscale modulation model to analyze the lighting needs of different competition events in stadiums, and combined with a neural network algorithm to design an intelligent lighting control algorithm, which can be used for adaptive lighting regulation and control for different events in the same stadium. Qi [23] designed an automatic lighting control model for ice skating events in large stadiums, which controlled the circuit activities through microgrids to improve the lighting system's coordination and synchronization, and guarantee the normal lighting of the competition species. Fan [24] optimized the sports lighting system from the perspective of point, line, and surface light sources by using building information modeling and Internet of Things (IoT) technology to achieve real-time light information monitoring, which promotes energy-saving design of sports buildings. Pavlov et al [25] proposed an intelligent lighting control system for skiing slopes, in which the system self-adaptively adjusts the spotlight under a variety of weather conditions. Under various weather conditions, the system adaptively adjusts the light output of the spotlight and changes the spectrum to reduce the occurrence of safety accidents and ensure the safety of the skiers. Kim et al [26] used 14 types of environmental monitoring sensors and object recognition technology to collect environmental data, and introduced intelligent edge computing to construct an indoor multi-environmental sensor system.Edge computing technology can process the collected data and improve the efficiency of effective information transmission. Yi et al. et al [27] combined light sensors and infrared sensors to identify the light intensity and the number of people in the stadium, real-time monitoring of the relevant equipment, and realized the intelligent adjustment of area lighting in accordance with the requirements of energy saving and lighting effect.

Herglotz et al. [28] pointed out that current smart sensor networks, supported by sensing, artificial intelligence, 5G+ and other technologies, can rely on the data collected by the sensors to be automatically sensed and processed, and develop into intelligent and cognitive sensor networks to realize intelligent adjustment and control. Zhou et al. [29] proposed a wireless sensor network for mobile target tracking based on edge intelligence technology and designed a dynamic resource allocation algorithm for dynamic continuous tracking for intelligent sensing scheduling. Cheng et al. [30] integrated sensor technology, distributed wireless sensor network based on ZigBee protocol, and lighting control rules to design a building intelligent lighting system with energy-saving efficacy, which can be intelligently controlled based on the usage data of individual fixtures in the building and natural lighting rules to realize energy saving. Wang and Wang [31] constructed a smart lighting sensor network using sensor network technology, introduced an adaptive weighting algorithm to fuse the data in the sensing network, optimized the data information, constructed the mapping relationship, and realized the distributed control of smart lighting based on the area, human physiological parameters, and environmental parameters. Jia et al. [32] assembled a light sensor, a distance sensor, a wireless communication network and a power supply on a UAV, which was used to collect the light data in the stadium, and processed the data through a local outlier factor algorithm, which could obtain the light parameters at different height positions in the stadium, which helped to monitor the light environment in the stadium in real time. Sahoo et al [33] used reinforcement learning algorithms to integrate sensors for light environment monitoring and collect environmental data, based on which the lighting demand is dynamically adjusted in real time, thus reducing light pollution and improving the efficiency of light environment management. Vashishtha et al. [34] proposed an intelligent adaptive lighting algorithm with the help of reinforcement learning and fuzzy logic, which can achieve personalized indoor lighting needs based on data such as environmental parameters, number of people, compared to light intensity, and personality preferences.

The article builds an intelligent sensing network and real-time monitoring system based on ZigBee technology. In this system, the tree topology of ZigBee technology is utilized to establish a sensing network, and the monitoring leaf nodes are utilized to acquire environmental parameters. And the performance of the monitoring system was explored by evaluating and analyzing the collected data to unfold the illuminance, thermal environment comfort and light environment comfort. This study provides a reliable data source for the establishment of optimal design strategies for the light environment of sports buildings, and also further satisfies the physiological comfort needs of the public.

2. Intelligent sensor networks and real-time monitoring systems

The development of healthy buildings is the key to improving national physical fitness and realizing a healthy China. A suitable physical environment is an important means to ensure the physical and mental health of users. The light environment design of sports buildings can significantly save energy and improve the users' sports environment. Sports buildings have special design challenges in terms of light environment monitoring and environmental comfort due to their large scale, high capacity and high lighting requirements. The establishment of an intelligent sensing network is imperative to effectively improve the real-time monitoring of the light environment in sports buildings.

2.1. Sensor Network Architecture

2.1.1. ZigBee technology

ZigBee is a proximity bi-directional wireless communication technology oriented to low power consumption, low cost, low complexity and low data rate.The overall power consumption of ZigBee modules is very low due to its lower data rate, lower operating frequency band and smaller capacity protocol stack.The basic members of a ZigBee network are called devices.The full-featured devices (FFDs) can communicate with each other and also can communicate with half-functional devices (RFDs), and RFDs can only communicate with FFDs in one direction. ZigBee networks with different topologies can be formed by setting the devices as different device types (RFD or FFD) through software [35].

The ZigBee network layer supports three topologies, i.e., star structure, mesh structure, and tree structure. The star structure topology consists of a coordination point, one or more end nodes. The coordination point must be a full-featured device, located at the center of the network, responsible for establishing and maintaining the entire network. A number of FFDs in a mesh structure communicate with each other in a fully peer-to-peer fashion, and each node can communicate with other nodes within its communication range; one will be recommended as the coordination point. Tree structure nodes can use Cluster-Tree routing to transmit data and control information, the end leaf nodes are generally RFDs, and the FFDs in the coverage area acting as coordination points provide synchronization services to the connected nodes.

The ZigBee protocol architecture is based on the Open Systems Interconnection (OSI) model, but only the protocol layers related to LR-WPAN applications are defined. It consists of the physical layer, the medium control layer, the network layer (NWK), the application support layer (APS), and the application layer (APL) from the bottom up, where the standards for the APL, APS, and NWK layers are developed by the ZigBee Alliance.

2.1.2. Sensor network construction

For the establishment and configuration of intelligent sensing network for the light environment of sports buildings, it is not only necessary to design the node hardware equipment, but also necessary to have the corresponding software to support. The ZigBee sensing network for the light environment of sports buildings needs to be set up with the help of Z-Stack protocol stack as the communication protocol so that the terminals and coordinators in the network can communicate effectively with each other and realize the information interaction with the intelligent gateway, thus completing the orderly formation of the ZigBee network. Based on the ZigBee network topology, combined with the realization function of the light environment sensing network of sports buildings, a tree topology is used to build the ZigBee network.

The ZigBee network coordinator plays an important role in data transmission, device management and control command sending among nodes in the network, and at the same time, it can establish a connection with the gateway through the serial port, transmit the data of each node to the gateway and receive the control commands sent by the gateway, so as to complete the establishment of the network, and realize the orderly management of each node's equipment by the gateway. In ZigBee network, the node devices, coordinator and gateway communicate with each other by sending communication data, so the frame structure of sending communication commands should be defined accordingly. According to the type of data sent by each node in the ZigBee network, the communication data can be divided into uploading node information data and uploading node sensor data.

Figure 1 shows the process of building a sensor network. After entering the event, first reset the settings of each layer in the network, the system enters the open state and uses the polling listening mechanism to wait for the event access. When a response is received, the number, type and priority of the response event is judged, and then according to the judgment results, the event is processed by calling the corresponding function in the event table. In the process of network operation, there may be a change or reorganization of the network state, with the end of the event access, the network state tends to stabilize and realize the construction of ZigBee network, when there is a new event access the network will be re-adjusted on the basis of this, such as joining new node devices or coordinators and so on. The terminal nodes in the ZigBee network set up in this paper mainly include temperature sensor and lightness sensor nodes, which are able to collect information about the light environment of the sports building and upload it to the gateway through the coordinator.

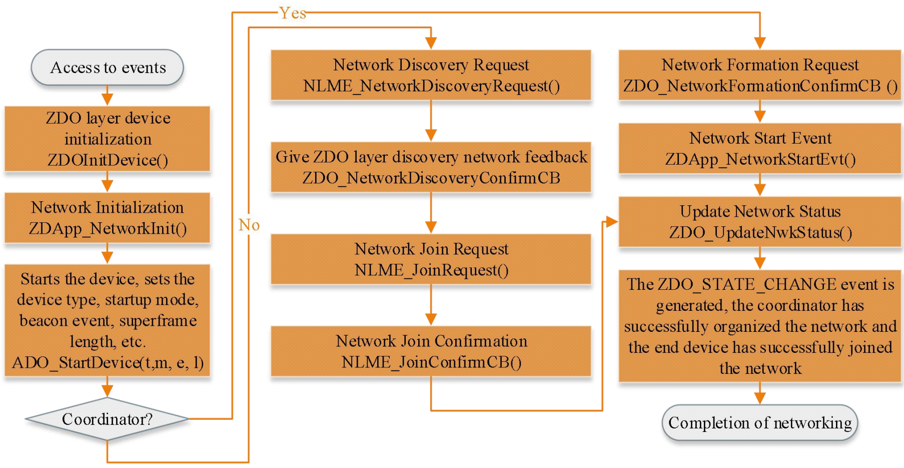


Figure 1. Sensor network setup process.

2.2. Real-time monitoring system

2.2.1. Monitoring system framework

In order to realize the real-time monitoring of the light environment of the sports building, this paper designs a system that combines the sensing network and real-time monitoring, and its specific structure is shown in Figure 2. The system consists of a central control node, a monitoring node, and a dimming node. The monitoring node completes the collection of temperature and PAR value of light environment radiation, the central control node completes the calculation of dimming amount based on real-time environment factor and target value, and the dimming node completes the execution of dimming command. ZigBee is used to realize self-organized network and wireless information interaction between nodes [36].

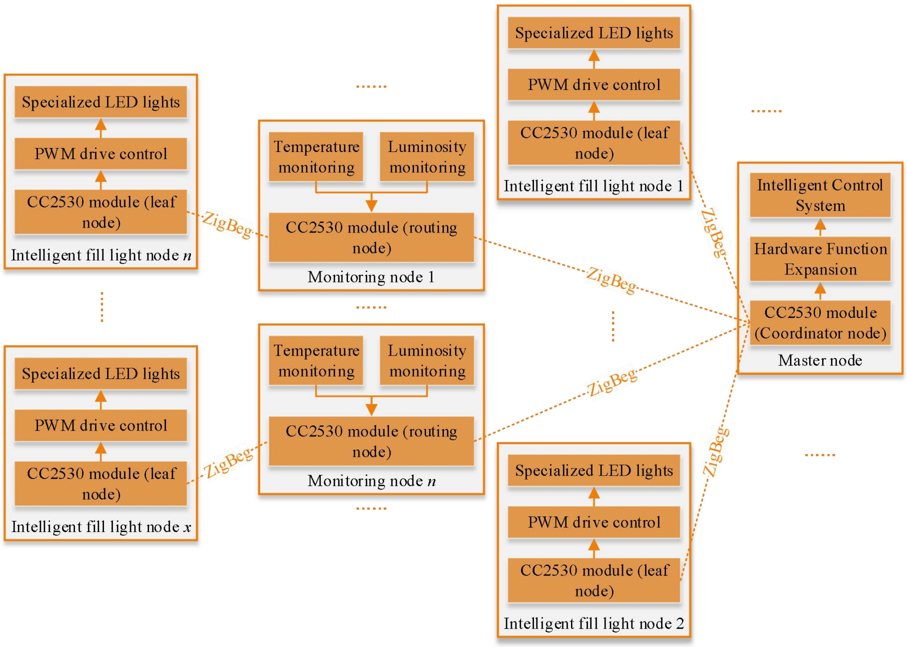


Figure 2. Schematic diagram of system structure.

Comprehensive wireless signal transmission in the sports building, light environment monitoring mode and the influence of external environmental factors, the system adopts a tree topology. The central control node acts as the ZigBee root node with network coordination and intelligent control functions. The monitoring node acts as a ZigBee routing node to complete the light environment monitoring and control information routing in the sports building. The light environment control node, as a ZigBee leaf node, receives dimming control parameters based on pulse width modulation (PWM) and completes the quantitative control of dimming lights in the light environment of the sports building.

2.2.2. Information collection module

In the intelligent sensing and real-time monitoring system for the light environment of sports buildings, the light and heat environment information acquisition module is responsible for the acquisition of heat exposure experience and light exposure experience, and the program integrates the temperature, humidity, illuminance acquisition function and the wireless data transmission function. In the design structure of the photothermal environment information acquisition module, it mainly includes a transparent plastic shell and the main control circuit board of the microcontroller placed in the shell, the illumination sensor module, the temperature and humidity sensor module, the wireless data communication module and the battery.

The temperature and humidity sensor module includes a temperature and humidity sensor and a digital-to-analog conversion circuit, and the output of the temperature and humidity sensor is connected to the input of the digital-to-analog conversion circuit. The illumination sensor module includes an illumination sensor and a digital-to-analog conversion circuit, and the output end of the illumination sensor is connected to the input end of the digital-to-analog conversion circuit. The output of the digital-to-analog conversion circuit is connected to the input of the main control circuit board of the microcontroller of the photothermal environment acquisition module, and the output signal of the main control circuit board of the microcontroller of the photothermal environment acquisition module is connected to the local data storage card for information storage, and the local information storage is uploaded to the real-time monitoring platform of the photoelectric environment of the sports building through the wireless data communication module on a regular basis. Photothermal environment acquisition module microcontroller main control circuit board is equipped with a charging interface, through the battery on the environmental experience collection photothermal environment acquisition module of the entire circuit for power supply.

2.3. *Evaluation of environmental comfort*

2.3.1. Illumination of sports buildings

Illumination is the luminous flux per unit area falling on the illuminated surface, that is, the luminous flux density on the illuminated surface, that is, the illuminance of a point being illuminated is equal to the luminous flux on the point surface element and the ratio of the area of the surface element. That is:

$$X_{LU} = \frac{d\Phi}{dA} \tag{1}$$

In this paper, the illuminance of sports building refers to the natural light illuminance, i.e., under the diffuse light irradiation in the sky, the illuminance of a given point on the plane indoor of the sports building, which can be measured by illuminance meter. Illuminance is a basic indicator for evaluating the quality of lighting, in different types of buildings have different illuminance requirements, the Chinese specification for visual work is divided into I ~ V lighting levels, and provides for the corresponding indoor illuminance values at all levels, sports buildings belong to the III class of lighting levels.

2.3.2. Thermal comfort

In the light environment comfort analysis of sports buildings, the audience and the environment for hot and cold exchange, hot and cold feeling is the audience of the environment hot and cold subjective feeling. The environmental parameters that play a role in the comfort of the audience's thermal environment are indoor air temperature, indoor air relative humidity, respectively, indoor air temperature, indoor air relative humidity to establish an environmental parameter comfort evaluation model, and use the comprehensive indicators to give the thermal environment of the sports building for comfort evaluation [37].

(1) Air temperature comfort evaluation model PMV_{TMP}

PMV_{TMP} is defined as when the air temperature is 19~24°C, the public feels comfortable, i.e., $PMV_{TMP} = 0$, and when the indoor air temperature is lower than 11°C or higher than 32°C, the indoor occupants feel uncomfortable, i.e., $PMV_{TMP} = 2$, so the key points are taken as $11°C, 24°C, 32°C$, the environmental parameter of the thermal environment, the independent variable of indoor air temperature X_{TMP}, defines the air temperature comfort evaluation model PMV_{TMP} as follows:

$$PMV_{TMP} = 16.01 \log \frac{X_{TMP}}{24} \left(X_{TMP} > 24 \right) \tag{2}$$

$$PMV_{TMP} = 10.64 \log \frac{24 + 24 - X_{TMP}}{24} \left(X_{TMP} \le 24 \right) \tag{3}$$

(2) Relative humidity comfort evaluation model PMV_{RH}

PMV_{RH} is defined as when the relative humidity of indoor air is 45%~65%, the indoor occupants feel comfortable, i.e., $PMV_{RH} = 0$, and when the relative humidity of indoor air is lower than 45% or higher than 85%, the indoor occupants feel uncomfortable, i.e., $PMV_{RH} = 2$. When the indoor air relative humidity is greater than 45%, the environmental parameter of the thermal environment, indoor air relative humidity independent variable X_{RH}, defines the indoor air relative humidity comfort evaluation model PMV_{RH} as follows:

$$PMV_{RH} = 9.80 \log \frac{X_{RH}}{50} \left(X_{RH} > 50 \right) \tag{4}$$

When the air relative humidity is not greater than 50%, the environmental parameter air relative humidity independent variable X_{RH} of the thermal environment, define the air relative humidity comfort evaluation model PMV_{RH} as follows:

$$PMV_{RH} = 13.69 \log \frac{50 + 50 - X_{RH}}{50} \left(X_{RH} \le 50 \right) \tag{5}$$

(3) Thermal environment comfort evaluation model PMV_{TE}

PMV_{TE} is defined as, respectively, air temperature, air relative humidity to establish the air temperature comfort evaluation model, air relative humidity comfort evaluation model, and the use of comprehensive indicators to the thermal environment comfort to establish an evaluation model. Therefore, based on PMV_{TMP} and PMV_{RH} models, the thermal environment comfort evaluation model PMV_{TE} is defined as:

$$PMV_{TE} = MAX\left(PMV_{TMP}, PMV_{RH}\right) \tag{6}$$

2.3.3. Light environment comfort

The design of intelligent sensing network and real-time monitoring system for the light environment of sports buildings is aimed at better realizing the analysis of the light environment of sports buildings, and this paper introduces the evaluation model of light environment comfort, combined with the data obtained from real-time monitoring, to carry out a comprehensive evaluation of the comfort of the light environment of sports buildings.

For the evaluation of light environment comfort has the following definition, in general, the indoor illuminance value of the sports building is 400lx, when the illuminance increases to 700lx, the indoor personnel will have a relatively uncomfortable feeling. For this reason, for the indoor light environment illuminance environmental parameters selected by the key point is 700lx as well as 400lx. Illuminance if is greater than 400lx, define the light environment comfort evaluation model as follows:

$$PMV_{LU} = 4.11\log\frac{X_{LU}}{400}\left(X_{LU} \geq 400lx\right) \tag{7}$$

When the illumination is below 4001x, define the comfort evaluation model PMV_{LU} as follows:

$$PMV_{LU} = 5.159\log\frac{400+400-X_{LU}}{400}\left(X_{LU} < 400lx\right) \tag{8}$$

where X_{LU} is the independent variable of the environmental parameter illuminance of the light environment.

3. Validation of sensing networks and monitoring systems for the light environment

With the rapid development of the national economy and the continuous improvement of the living standard of the residents, people participate in national fitness activities through various sports. In response to the national call and concept of “Healthy China” and “Fitness for All”, the number of sports buildings is also increasing, which not only provide a place for the public's daily activities, but also provide venues for some sports events. However, in the process of practical application, the poor effect of light environment monitoring may lead to poor quality of natural lighting, serious indoor glare, and low comfort of indoor thermal environment and other problems. Therefore, it is important to actively explore the effectiveness of the application of real-time light environment monitoring system to lay a solid foundation for further promoting the effect of real-time monitoring of light environment in sports buildings and improving the comfort of light environment.

3.1. Evaluation of environmental comfort

3.1.1. Analysis of Illumination in Sports Buildings

Based on the intelligent sensing and real-time monitoring system for the light environment of sports buildings established in this paper, it is applied to the analysis of light environment illumination of sports buildings. Three university gymnasiums (GYM1~GYM3) with open-window design are selected to build the sensing network and monitoring system, so as to obtain the indoor and outdoor illuminance data of the three gymnasiums (the time is 07:00~17:00). Based on the illuminance calculation formula, the indoor and outdoor illuminance values of the gymnasiums were calculated respectively.

Figure 3 shows the outdoor illuminance trends of different stadiums at different times. From the figure, we can see that the outdoor illuminance of these three stadiums fluctuates in a parabolic trend regardless of the time of day. Their maximum illuminance usually occurs in the interval of 10:30 a.m.

and 12:30 p.m., and their illuminance values range from 2.66*10^{4}lx to 2.92*10^{4}lx, showing that there is sufficient natural light. However, the outdoor luminance of these stadiums only exceeded the standard values designed for natural light outside the urban area during this period. Then, after 16:00 p.m., this rate of decline increased dramatically, resulting in a decrease in their minimum illuminance to a level of approximately 0.38*10^{4}lx. In addition, when the sun began to sink in the fall and winter, that is, at 5 p.m., the outdoor illuminance in this area was already below 0.09*10^{4}lx. It can be seen that the natural light environment in this area in the fall and winter has a great deal of uncertainty and unpredictability, and the data obtained by the monitoring system is not far from that obtained by the actual illuminance meter, which to a certain extent illustrates the real-time monitoring system's efficiency and accuracy. In general, the outdoor brightness of Gymnasium 1 (GYM1) is generally better than that of the other two sports buildings (GYM2 and GYM3), while the outdoor brightness of Gymnasiums 2 and 3 is similar.

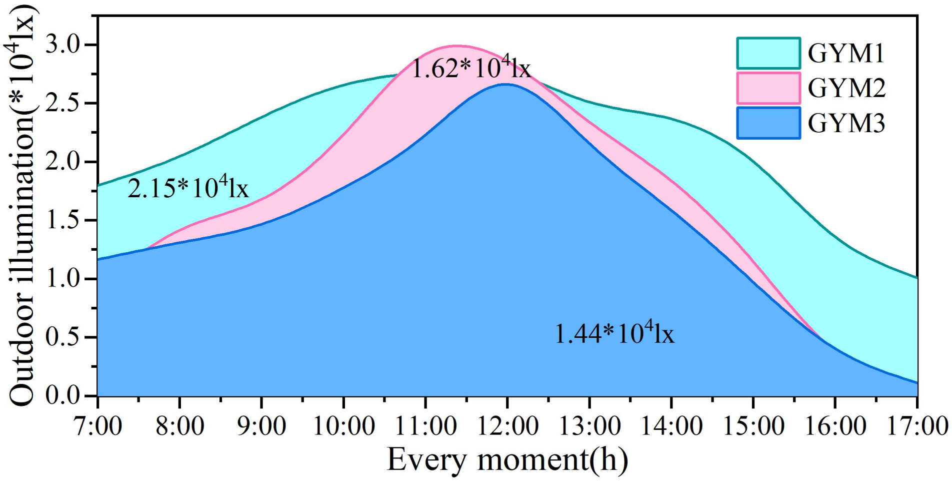


Figure 3. External illumination varies with day time.

In addition, for the interiors of the three stadiums, we averaged the lighting illuminance values obtained for each specific time period to obtain their average illuminance values. This approach helps to comprehensively assess the natural daylighting of the three stadiums during the daytime. Figure 4 shows the changes in the mean illuminance values of the sports areas of the three stadiums over time.

As can be seen from the figure, the illumination mean value of Stadium 1 is relatively stable and maintained at a relatively low level, fluctuating only around 9~10 and 16 o'clock, while the illumination mean value of the rest of the time period is in the range of 50lx, which is much lower than the requirement of the stadium building regarding the lighting illuminance of 200lx. After evaluation, the average illuminance at each measurement point of the stadium3 is only 166.38lx, which is far below the minimum requirement for the lighting design of the stadium. The lack of natural light results in a very dark interior environment in the stadium, and hence the need to rely on artificial lighting to make up for this, thus increasing energy consumption. Of the three stadium buildings, it can be seen that the mean illuminance values in Stadium 2 show a similar pattern of increase and decrease over time as the exterior. From 7:00 a.m. to 12:00 p.m., its average illuminance gradually increases and reaches its highest value of the day, 321.48 lx, at around 12:15 p.m. However, after this moment, its illuminance begins to diminish. During the time period from 8:00 to 15:00, the average luminance at all the measurement points of the Gymnasium 2 is higher than 170lx, which means that the lighting regulations of the Gymnasium can be met for about 66.67% of the day (12 hours of daylight).

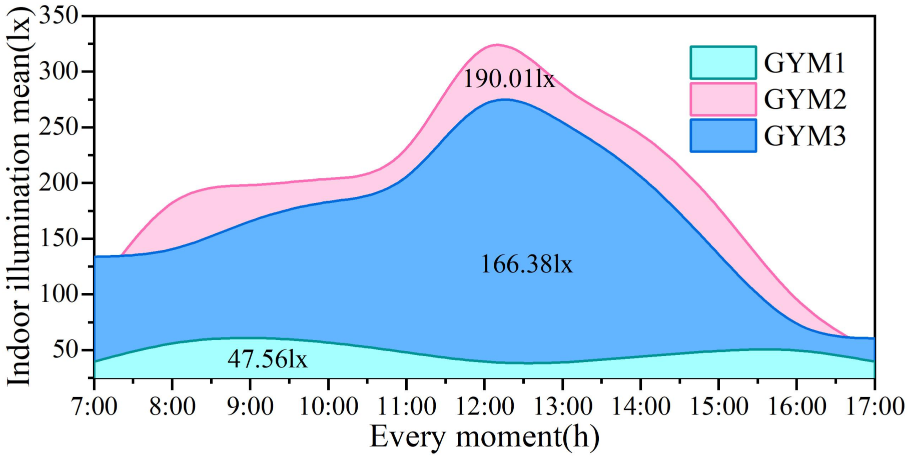


Figure 4. Changes in the mean of illumination.

3.1.2. Evaluation of thermal environment comfort

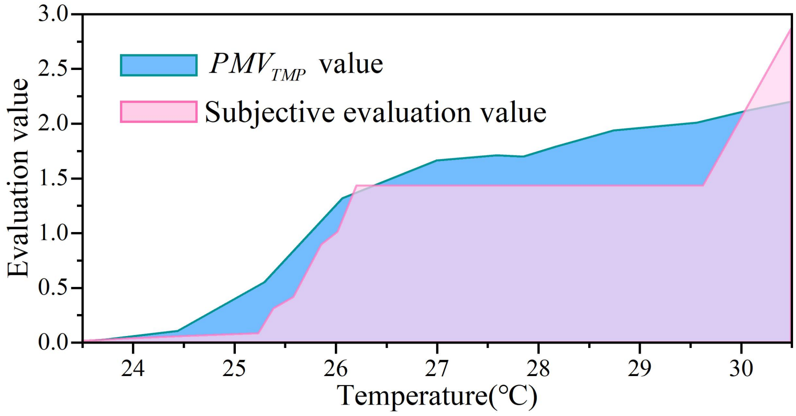
For the real-time monitoring system of the light environment of sports buildings, relying on the light data obtained from the monitoring, it can help the operating personnel to clarify the comfort situation of the thermal environment inside the sports building, so as to better optimize the light environment of the sports building, and to ensure that the public can obtain physiological comfort and psychological comfort in the process of sports special requirements.

At low and medium temperatures, the comfort evaluation model of air temperature and air relative humidity of indoor thermal environment parameters of sports buildings PMV_{TMP} is shown in Table 1 in relation to the subjective evaluation of indoor public comfort.

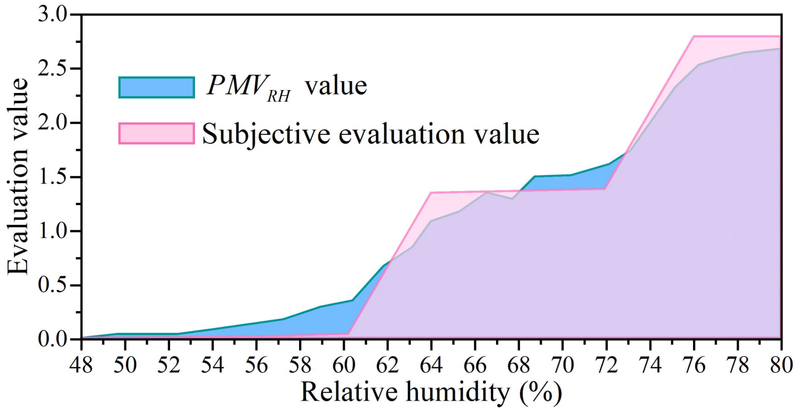
Table 1. The relationship between PMV_{TMP} and public comfort.

Temperature (°C)	Relative humidity (%)	PMV_{TMP}	PMV_{RH}	Comfort evaluation
11.5	25	2	2	Uncomfortable
24.5	45	0	0	Comfort
28.5	65	1	1	A little uncomfortable
32.5	85	2	2	Uncomfortable
33.5	95	3	3	Extremely uncomfortable
34.5	95	3	3	Extremely uncomfortable

Figure 5 shows the comparative relationship between the comfort evaluation model of air temperature and relative humidity of indoor thermal environment parameters and the subjective evaluation value of comfort of the public, where Fig. 5(a)~(b) shows air humidity and relative humidity, respectively. As can be seen from the figure, the comfort model of air temperature corresponds basically with the subjective comfort evaluation value of the indoor public. In order to create an indoor environment of sports buildings with a high public comfort rating, the temperature should be controlled below 26°C and the relative humidity below 65%, so as to ensure that indoor athletes feel physiologically comfortable in sports buildings.



(a) PMV_{TMP}



(b) PMV_{RH}

Figure 5. The comparison between model and comfort subjective evaluation.

According to the information of air temperature and air relative humidity environmental parameter indexes collected by the light environment sensing network and real-time monitoring system of the sports building, the thermal environment comfort evaluation model is established by using the comprehensive indexes of air relative humidity and air temperature, and the comparative relationship between the thermal environment comfort evaluation model and the public comfort subjective evaluation value is verified, and the data of the air temperature and air relative humidity environmental parameter indexes of the thermal environment are shown in Table 2. The data of air temperature and air relative humidity of the thermal environment are shown in Table 2.

Table 2. Evaluation model of thermal environment comfort.

Scene	PMV_{TMP}	PMV_{RH}	PMV_{TE}
S1	2.83	2.32	2.83
S2	1.65	1.91	1.91
S3	2.74	2.28	2.74
S4	1.09	1.56	1.56
S5	1.65	1.83	1.83
S6	2.77	2.34	2.77
S7	1.35	1.64	1.64
S8	1.72	1.77	1.77

Based on the data in the above table, the comparative relationship between the comfort evaluation model of the indoor thermal environment of sports buildings and the subjective evaluation value of indoor public comfort is obtained as shown in Figure 6. As seen from the figure, the correspondence between the comfort evaluation model of the indoor thermal environment of sports buildings and the subjective evaluation value of public comfort is basically consistent. In order to create an indoor thermal environment of sports buildings with high subjective public comfort ratings, the air temperature should be controlled below 26 ℃ and the relative humidity below 65%, and the corresponding values of the air temperature and relative humidity comfort evaluation model are both 1, which means that the comfort evaluation result of the audience in the sports buildings is "slightly uncomfortable".

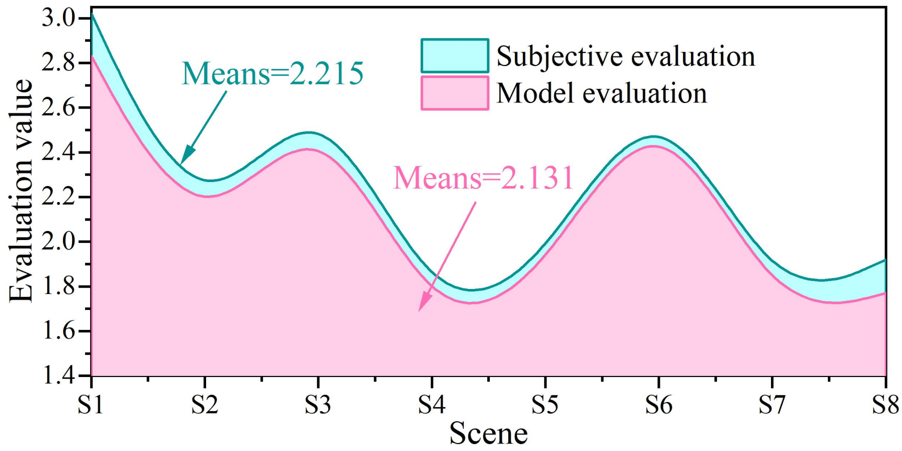


Figure 6. Comparison of thermal environment comfort evaluation.

3.1.3. Evaluation of light environment comfort

Light environment is a particularly important part of the indoor environment of sports buildings. A good light environment is good for people's physical and mental stretching, and helps to improve the efficiency of the personnel's movement, on the contrary, staying in the dark environment for a long time will make people depressed, cause physiological rhythm disorder, and bring health risks to people. Based on the data obtained from the light environment sensing network and real-time monitoring system of the sports building, combined with the previous method to calculate the light environment comfort evaluation value of the sports building, and then compare it with the audience subjective voting results (-3,3), to obtain the results of the comparison between the two as shown in Figure 7.

The data distribution on the graph shows that the sports building light environment evaluation index PMV_E is basically consistent with the results of the subjective voting value of the comfort of the light environment. Especially in the range of PMV_E is 0 to 1, it can better reflect the human evaluation of the comfort of the light environment. When $172lx \le E_{LU} \le 325lx$, the corresponding evaluation index PMV_E ranges from [-1,1], at which time the indoor illuminance can satisfy the vast majority of people and the light environment is more comfortable. Architectural lighting design standards require sports building illuminance to reach 300lx, at this time, the light environment is in a higher requirement, almost no one will be dissatisfied with the light environment. When $E_{LU} < 172lx$, it means that people feel uncomfortable with the current indoor light environment because it is slightly dark, and when $E_{LU} > 325lx$, it means that people feel uncomfortable with the current indoor light environment because it is slightly bright.

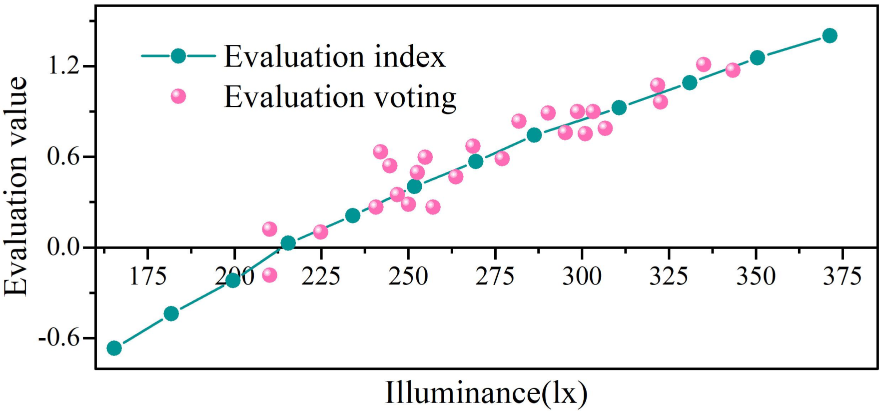


Figure 7. Model evaluation and subjective voting results.

3.2. Monitoring system performance validation

3.2.1. Network transmission efficiency

The test environment is a cloud storage platform built based on three devices, with device numbers Computer01~03. To ensure the smooth operation of the system, the corresponding server and client of the intelligent sensing network and real-time monitoring system for the light environment of sports buildings are built based on the Hadoop cloud environment. In order to verify the network transmission efficiency of the system in this paper, the paper is tested for star, tree and mesh tray structures respectively, so as to clarify the transmission efficiency of different topologies. In this paper, the transmission time and transmission rate are taken as the indexes respectively, and the system operation effect under different network topologies is counted, and its comparison results are shown in Table 3.

As can be seen from the table, as the test file increases from 64MB to 5000MB, the file transfer time as well as the transfer rate under the three network topologies of star, tree and mesh are gradually reduced. The average value of transmission rate of the intelligent sensor network established based on tree topology in this paper is 3.77MB/s, while the average values of transmission rate under star and mesh topologies are 3.01MB/s and 3.29MB/s, respectively.In the star network, the test terminal-to-terminal communication, the transmission efficiency of the star network is a little bit poorer than that of the tree network under the condition of the same packet and the same distance and the The more terminal nodes joined by the coordinator the worse the transmission efficiency. The reason for the above phenomenon is that in the star network, the communication between terminal nodes must be relayed through the coordinator, and there is also channel interference between terminals. In the tree structure test, the communication quality of the tree network is better than the mesh network in the same situation. Because the ZigBee Pro protocol stack in the tree network uses a more optimized routing mechanism, which makes the information transit faster and reduces the loss in the propagation process. So the communication quality is higher. The above results fully demonstrate that the intelligent sensing network designed in this paper has better transmission efficiency and can better realize the real-time transmission of light environment data in sports buildings.

Table 3. System operation effect statistics result.

Size /MB	Star structure		Tree structure		Network structure	
	Time/s	Rate/(MB/s)	Time/s	Rate/(MB/s)	Time/s	Rate/(MB/s)
64	20.12	3.18	16.38	3.91	19.46	3.29
128	32.65	3.92	28.21	4.54	30.18	4.24
256	63.18	4.05	50.69	5.05	55.96	4.58
512	175.43	2.92	132.57	3.86	162.83	3.14
1024	396.27	2.58	304.95	3.36	358.92	2.85
2048	816.51	2.51	634.26	3.23	765.46	2.68
5000	2628.35	1.90	2027.49	2.47	2248.35	2.22
Means	-	3.01	-	3.77	-	3.29

3.2.2. Node Communication Tests

In order to ensure that the collected sensor data can be transmitted effectively, the communication performance between ZigBee nodes needs to be tested. In the testing process, the main consideration is the packet loss rate and BER. Since the nodes mainly collect indoor environmental data of sports buildings, the nodes should be considered to be arranged at a reasonable height in practical application, so as to enhance the practicality of the measurement data.

A gymnasium with an area of about 60 square meters is chosen to simulate the application scenario of the system, 10 terminal nodes are randomly arranged at a height of 3m from the ground, 5 router nodes are arranged near the coordinator, and finally the coordinator is arranged in the relative center of the room. The terminal nodes send data packets to the coordinator at the same time, each packet contains 32 bytes of data, and the interval between two data packets is 0.5 s. The router nodes are only responsible for data routing and forwarding. The test is divided into five groups, each group sends a different total number of packets, in order to test the network's anti-jamming, the total number of packets in the same case of adding interference nodes for comparison experiments. The jamming nodes are acted by additional terminal nodes that send packets to the coordinator uninterruptedly. The test results are shown in Table 4.

From the test results, it can be seen that the packet loss rate and BER of the network node communication with and without interference are lower than 1.5%, which can ensure the normal communication of sensor data. Combined with the results of the analysis of network transmission efficiency, it shows that the intelligent sensing network and real-time monitoring system for the light environment of sports buildings designed in this paper has the characteristics of high efficiency and high accuracy, which can ensure the efficiency and safety of data transmission.

Table 4. Node communication performance test results.

Packet number	Interference-free node			Have interfering nodes.		
	Receive	Packet loss rate	Bit error rate	Receive	Packet loss rate	Bit error rate
500	500	0.00%	0.00%	500	0.00%	0.00%
1000	1000	0.00%	0.00%	998	0.20%	0.12%
2000	1998	0.10%	0.08%	1983	0.85%	0.57%
4000	3992	0.20%	0.15%	3951	1.23%	0.96%
8000	7981	0.24%	0.23%	7886	1.43%	1.15%

3.2.3. Real-time monitoring errors

In order to make the monitoring results more accurate in the future, this system uses the least squares method for data regression analysis based on the collection results of the light environment parameters of the sports buildings for one consecutive week. Regression analysis is a common method to statistically analyze two variables with correlation. In this system, the measured and actual series of data of light environment parameters with correlation can be plotted in a right-angle coordinate system, and the regression linear equation can be derived by the least squares method (least square method) to get the best fitting curve of the light environment factor of the sports building, in order to reduce the error between the measured value and the actual value of the system. Following this, the system is able to predict the monitoring data based on the overall trend, so that the monitoring results develop towards an ideal and balanced trend.

In the specific environment of sports buildings, the measured values will be affected by many uncontrollable factors, while the linear regression model approximation itself will cause errors, the result of this effect is called random error, the smaller the error value, the better the regression model fit. In order to reduce the measurement error of the light environment factor of the real-time monitoring system, the measured light level and the actual light level are fitted, according to the fitting curve equation of the least squares method and the linear regression model can be obtained as shown in Fig. 8 of the daylight light level fitting curve.

The fitting results show that the correlation index R^2 between the measured and actual values of the light environment of the sports building reaches 0.985, which indicates that the system in this paper has a high accuracy in the collection of data related to the light environment, and it can fully reflect the changes in the light environment of the sports building, and it can provide a reliable data support for the enhancement of the public's physiological comfort as well as the optimization of the design of the light environment.

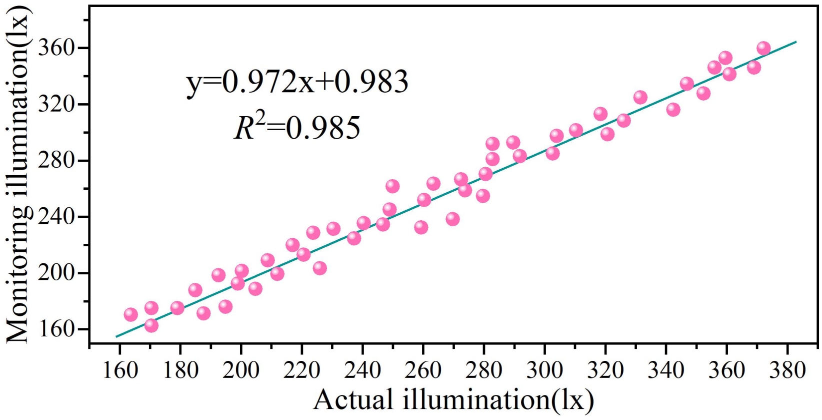


Figure 8. Daylight illumination curve.

4. Conclusion

Considering the current sports building light environment design lack of reliable data support based on this paper, this paper proposes a sports building light environment intelligent sensing network and real-time monitoring system based on ZigBee technology, and proposes an environmental comfort evaluation to analyze the comfort situation of the sports building light environment. It is found that the average value of the transmission rate of the intelligent sensing network is 3.77MB/s, and the packet loss rate and BER of the network nodes' communication are lower than 1.5% with and without interference. When the illuminance is between 172lx and 325lx, the comfort of the light environment of the sports building performs well and can meet the public's physiological comfort needs.

This paper still has some limitations. One is that only ZigBee technology is considered when building the sensing network, and the combination of big data and cloud platform may further enhance the network building effect nowadays. The second is that when monitoring the performance verification of the system, there is no impact experiment of large-scale data volume, which may lead to poor concurrent performance of the system and fail to meet the efficient application in large-scale scenarios.

Therefore, the feasibility of the application of big data cloud platform and IoT technology in the construction of the sensing network will be further explored in the subsequent research. On the basis of ensuring the stable operation of the system, the concurrency capacity of the system is improved so that it can better meet the demands of large-scale application scenarios.

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