Design and Application of Intelligent Building Environment Monitoring System Based on Wireless Sensor Network

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With the development of intelligent building technology, environmental monitoring systems are playing an increasingly important role in the field of construction. However, the current existing systems still have shortcomings in terms of data transmission efficiency and energy consumption management. To effectively promote the technological upgrading and application promotion of building environment monitoring, wireless sensor networks are applied to environmental monitoring systems to improve the informatization level of intelligent buildings. Based on the low-power adaptive clustering routing algorithm, an improved algorithm is proposed to solve the high energy consumption and uneven distribution of cluster heads. According to the results, the monitoring area was 300×300m, the cluster heads of the improved algorithm were relatively evenly distributed in various regions. At 261 rounds, the surviving nodes in the improved algorithm decreased. As time increased, the surviving nodes in the improved algorithm increased. The energy use speed of the improved algorithm was the slowest. Because it changed the conditions for the low-power adaptive clustering routing algorithm to re-select cluster heads and clustering methods, it reduced the energy consumption during cluster formation. The improved algorithm could better reduce energy use and extend network lifespan. The actual and predicted values of the building environment detected by the improved system almost overlapped, indicating that the temperature monitoring accuracy of the system was high, reaching 98.6%. The robustness is significantly enhanced. This system can monitor the internal environment of buildings in real time, optimize energy allocation and rational utilization, monitor equipment energy consumption, ensure the reliability of electrical equipment operation, and improve energy utilization efficiency. This provides a new reference direction for environmental monitoring work.

Povzetek: Predstavljen je sistem za inteligentno spremljanje okolja v stavbah, ki temelji na brezžičnih senzorskih omrežjih in izboljšanem LEACH algoritmu. Prispevek izboljšuje kvaliteto spremljanja temperature, zmanjšuje energijsko porabo in podaljšuje življenjsko dobo omrežja, kar optimira učinkovitost okolij v pametnih stavbah.

1 Introduction

The demand for safe and convenient information exchange in building structures is gradually increasing. Intelligent building has become one of the primary development areas. The Intelligent Building Environmental Monitoring System (IBEMS) not only improves the energy efficiency and building comfort, but also provides new solutions to ensure the health and safety of residents. Wireless Sensor Network (WSN), as the core technology in this field, can achieve real-time data collection and transmission in different building environments through its distributed sensor nodes [1]. Bacanin et al. focused on the application of intelligent wireless medical systems. WSN and Graph Long Short-Term Memory neural network were used to reduce the backup of sensing environments and predict air quality, while reducing equipment cost. The results showed that the system was practical [2]. Although the application of WSN in intelligent buildings has brought many advantages, existing monitoring systems still face challenges such as data processing and network optimization. The Low Energy Adaptive Clustering Hierarchy (LEACH) protocol, as a classic WSN routing protocol, has been widely used in energy limited network environments. However, the LEACH algorithm is not suitable for large-scale WSN applications and requires more efficient algorithms to handle large amounts of data and nodes [3]. To avoid high energy consumption and uneven distribution of Cluster Heads (CH), an improved LEACH routing algorithm is designed. The ZigBee technology is adopted as the data transmission communication mode of IBEMS to achieve low power consumption, real-time monitoring, abnormal alarm, and remote viewing functions. The main contributions are as follows. 1. Based on the LEACH routing algorithm, this study ensures network communication efficiency, reduces energy consumption, and increases network lifespan, improving the informatization level of intelligent buildings. 2. This study proposes an improved algorithm that combines cell clustering and CH selection to address the high energy consumption and uneven CH distribution in traditional algorithms. The improved algorithm makes the application of WSN in environmental monitoring systems more efficient and reliable. The application of ZigBee technology in IBEMS provides a more convenient and efficient solution for the operation and management of intelligent building. The comprehensive application of WSN in IBEMS promotes the informatization level of intelligent building. This helps to achieve intelligent monitoring and management of building environments, and improve building operational efficiency and user experience.

The research mainly includes four parts. The first part reviews research on WSN and environmental monitoring. The second part introduces the WSN intelligent building environment monitoring system. The first section covers the LEACH routing algorithm and its improved algorithm for WSN. The second section builds an improved routing algorithm for IBEMS. The third part focuses on IBEMS testing and performance analysis for the improved routing algorithm. The first section introduces the test results of the improved routing algorithm. The second section is the performance analysis of IBEMS. The fourth part is the conclusion. The schematic diagram of this study is shown in Figure 1.

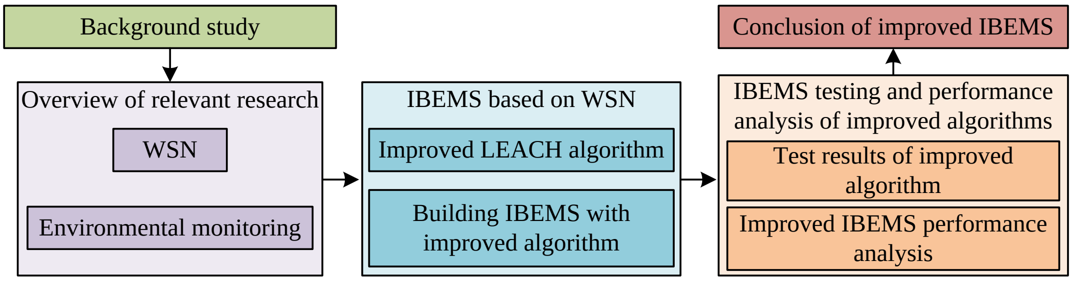


Figure 1: Schematic diagram of research structure

2 Related works

In recent years, the research focus of WSN has gradually extended to applications, such as logistics management and smart home. Many scholars have conducted in-depth research on it. Pang et al. designed an improved lion swarm sensor management scheme. This scheme combined logistic chaotic sequences to solve the energy-saving problem of WSN used for target tracking in defense operations. An energy-saving objective function and constraints were constructed. The results showed that the method was effective and applicable [4]. In order to improve energy efficiency, Prakash et al. conceived a meta-heuristic energy-saving clustering algorithm that combined particle swarm optimization and WSN, thereby extending the lifespan of sensor nodes. The results showed that this method had good stability [5]. Saemi et al. used local and global search algorithms to improve the quality of path search for ocean data mobile phones. WSN energy-saving routing protocol is used to collect data and improve efficiency. The results showed that this method was feasible [6]. To improve network lifespan and effectively alleviate energy holes, Amaran et al. used WSN routing algorithm to form a chain execution greedy algorithm to select chain neighbors. The aggregated data was sent to its subsequent HN until it reached the Base Station (BS). The results indicated that this method had certain advantages [7]. To enhance the energy balance among all sensor nodes within the cluster, Abderrahmane and Hajraoui developed a fuzzy LEACH algorithm that improved network lifespan, energy consumption, and the packets transmitted to BS. The results indicated that the method was effective, reducing WSN energy consumption by approximately 0.99% to 5.64% [8]. To extend the lifespan of WSN in IoT applications, Tawfeeq and Abdullah extracted the correlation values of each node through CH. The consistency algorithm significantly could improve network throughput, prolong network life-cycle, and enhance network stability. The results indicated that the method had good effectiveness [9].

To comprehensively reflect the development and changes of environmental quality and optimize its management methods, many scholars have conducted extensive research on environmental monitoring methods. Huang and Kieffer developed an intelligent IoT sensor system to collect more building environmental parameters to improve the accuracy of building environmental monitoring. This method could accurately calculate the occupancy rate of energy-saving buildings and improve the accuracy of building occupancy statistics. The results indicated that the system had good functionality and performance [10]. Yu et al. designed an intelligent method to automatically extract features from raw signals to identify building structural damage, meeting any damage identification target. The results indicated that this method had high recognition accuracy and generalization ability [11]. Fan et al. proposed a portable noise time-frequency characteristic monitoring system to analyze the noise patterns in power transformer rooms for the transformer noise pollution in residential buildings. This could improve the living environment and ensure the reliable operation of the power system. The results indicated that the system had good practicality [12]. For environmental dose measurement, Alshehri et al. obtained signal attenuation by measuring environmental temperature, storage time, and irradiation dose using MCP-N and TLD-100H to avoid high loss rates. The results indicated that the method had good stability [13]. Ho and Wang developed a sensing system that combined the wireless functionality of the Internet of Things to enhance the portability of environmental monitoring devices. It was used to measure particulate matter, temperature, humidity, and ultraviolet radiation in the air. The data was uploaded to a remote server. The results indicated that this method had good practicality [14]. To provide secure routing for environmental monitoring, Thangaiyan conceived a reliable wormhole detection system to estimate the energy during the route maintenance phase, which was used to balance the energy and detect attackers. The results indicated that the system had certain feasibility [15].

In summary, current WSN and environmental monitoring are mainly focused on traditional application fields such as industry and agriculture. However, there are shortcomings in handling complexity and data processing in the IBEMS field, and the existing LEACH routing algorithm has insufficient performance in handling uneven CH distribution. Therefore, based on the LEACH routing algorithm in WSN, the IBEMS is optimized. The research aims to avoid issues such as high energy consumption during cluster formation, optimize energy consumption, and enhance the lifespan and stability of the network. At the same time, ZigBee technology is adopted as the data transmission communication method for IBEMS, in order to achieve low power consumption, real-time monitoring, abnormal alarm, and remote viewing functions.

The main contributions and performance indicators of the relevant methods are shown in Table 1.

Table 1: Summary of related works

Research scholar	Main contributions	Performance index	Result
Pang et al.	Improved Lion Swarm Sensor Management Combined with Logistic Chaotic Sequence	Energy consumption and target tracking effectiveness	Effective and applicable
Prakash et al.	Meta-heuristic energy-saving clustering algorithm combining particle swarm optimization and WSN	Stability and node lifespan	Stability
Saemi et al.	Local and global search algorithms	Path search quality, data collection efficiency	Feasible
Amaran et al.	Chain execution greedy algorithm	Network lifespan and energy balance	Having certain advantages
Abderrahmane et al.	Fuzzy LEACH algorithm	Energy consumption, data transmission volume	Energy consumption reduced by 0.99% to 5.64%
Tawfeeq et al.	Consistency algorithm	Network throughput, network life-cycle, and stability	effective
Yu et al.	Automatic feature extraction algorithm	Recognition accuracy and generalization ability	High recognition accuracy
Thangaiyan	Wormhole detection system	Energy balance, attack detection	Feasible

3 Intelligent building environment monitoring system based on WSN

This chapter introduces the LEACH routing algorithm in WSN, which is improved by cell clustering and CH selection. ZigBee technology is used as the data transmission communication method for IBEMS.

3.1 WSN and LEACH routing algorithm

WSN is a distributed sensing network that can perceive the external world. WSN considers the lifespan of each node. The distance of single hop transmission cannot be too far, and multi-hop relays are required. Traditional routing protocols cannot use WSN as they lack infrastructure. Therefore, in order to extend the lifespan of the network, it is necessary to reduce energy consumption. However, traditional routing protocols focus on Quality of Service (QoS) [16]. Mostly, WSN is used in harsh environments, such as unstable wireless channels, node movement and failure, which can cause its topology to change at any time. The schematic diagram of WSN structure is shown in Figure 2.

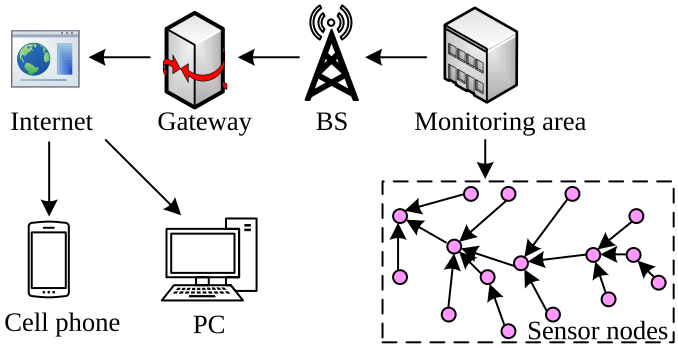


Figure 2: Schematic diagram of WSN architecture

From Figure 2, in WSN, the network settings are flexible. The device location can be adjusted. It can also be connected to the internet through various means. WSN routing protocols are of great importance in extending the lifespan of WSN. Therefore, it is necessary to set the WSN routing protocol. LEACH randomly selects CH nodes in a cyclic manner. The energy load is evenly distributed to each node, reducing the energy use required for creating and maintaining clusters to extend the service life of WSN. However, it has some limitations. In LEACH, it is assumed that all nodes can communicate directly with the aggregation node. Each node can support different protocols. Therefore, it is unsuited to large-scale WSN. The protocol does not specify how to allocate the number of CH nodes to cover the entire network. Therefore, the selected CH nodes are concentrated in a certain area. This makes some nodes without any CH nodes around them. During the cluster establishment phase, sensor nodes randomly generate in (0,1]. Compared with the threshold $T(n)$, if it is below the value, the node will be selected as the CH. In order to ensure that each node has an equal chance of becoming the CH, the range is set between (0,1] to ensure that the generated random number is within a continuous range without bias towards any specific value. This can effectively achieve fair competition between nodes, ensuring that the selected CH has randomness and uniformity. After selecting the CH node, it sends the message that it becomes the CH. The node decides which cluster to join based on the received message strength. The corresponding CH is informed to finish the cluster construction [17]. During the initialization phase of the LEACH routing algorithm, the $T(n)$ is shown in equation (1).

$$T(n)=\begin{cases}\dfrac{p}{1-p*\left(r \bmod \dfrac{1}{p}\right)} & n\in G\\ 0 & otherwise\end{cases} \quad (1)$$

In equation (1), p is the percentage of nodes that become CH nodes. r is the current round. G is the set of nodes that are not selected as CH in the most recent round $\frac{1}{p}$. Based on $T(n)$, each node will become the CH in a certain round of $\frac{1}{p}$. After $\frac{1}{p}$ round, all nodes will be eligible to become the CH again.

3.2 Improved LEACH routing algorithm

LEACH assumes that in the initial CH selection round, all nodes have the same energy. Each node that becomes a CH consumes approximately the same energy [18]. Therefore, the protocol is unsuited to networks with imbalanced energy. There are problems in the LEACH routing algorithm, such as uneven distribution of CH and high energy consumption during cluster formation [19]. An improved LEACH algorithm is proposed, which combines cell clustering and CH selection (CC-LEACH). CC-LEACH can help achieve effective energy management by grouping nodes into different cells and constructing a hierarchical structure, which can reduce energy consumption and extend network lifespan. The CC-LEACH algorithm process is shown in Figure 3.

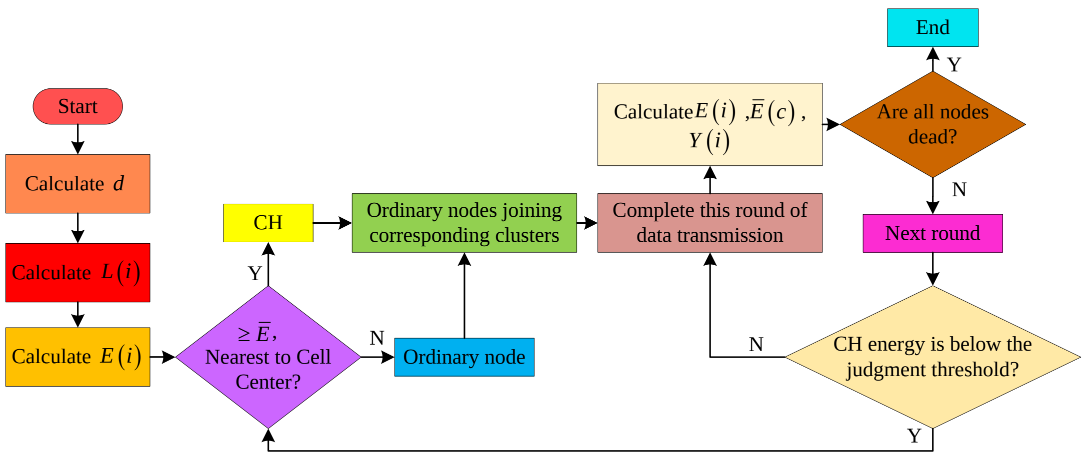


Figure 3: CC-LEACH algorithm process

In Figure 3, the CC-LEACH algorithm changes the clustering method of the LEACH. Based on cell division, the monitoring area is divided into several virtual cells d , each cell being a cluster. The cluster division is completed first, and then CH is selected. This can effectively optimize the network structure, reduce communication overhead and conflicts, and improve the stability and reliability of the network. Meanwhile, this method can reduce data transmission delay, achieve faster data transmission and processing, and improve the real-time performance of the system. The number of virtual cells is d , as shown in equation (2).

$$d = p * n \tag{2}$$

In equation (2), n is the total nodes. The edge length of the virtual cell is r . The communication distance between nodes is D. To ensure that each node in a virtual cell can transmit data to any node in another virtual cell, the communication distance between nodes should not exceed a certain range. The maximum side length is shown in equation (3).

$$r^2 + (2r)^2 < D^2 \Leftrightarrow r \leq D/\sqrt{5} \tag{3}$$

In equation (3), r^2 is the area of a virtual cell. $(2r)^2$ is the diagonal length of the virtual cell. D^2 is the maximum allowed distance between two nodes. In the area A , n sensor nodes are evenly distributed. The minimum total number of virtual cells is m , as shown in equation (4).

$$m = A \Big/ \left(\frac{D}{\sqrt{5}}\right)^2 \tag{4}$$

The distance $L(i)$ between the node and the center of the virtual cell is shown in equation (5).

$$L(i) = \sqrt{\left(x(i) - x(c)\right)^2 + \left(y(i) - y(c)\right)^2} \tag{5}$$

In equation (5), $x(i)$ is the abscissa. $y(i)$ is the vertical coordinate. $y(i)$ is the horizontal axis of the virtual cell center where the node is located. $y(i)$ is the vertical coordinate of the virtual cell center where the node is located. The remaining energy of each $E(i)$ is calculated. The average energy is $\bar{E}(c)$. In the CH cell, if $E(i) \geq \bar{E}(c)$, the node with the shortest distance from the center of the cell becomes CH. After completing one round of data transmission, $E(i)$ and $\bar{E}(c)$ are calculated. The threshold $Y(i)$ is determined. The $Y(i)$ is shown in equation (6).

$$Y(i) = a * \bar{E}(c) \tag{6}$$

In equation (6), a is a constant. $a = 0.9$ is set to trigger energy consumption judgment at 90% of the average energy of the node can ensure that the node continues to work with sufficient energy, achieving effective utilization of energy resources. Therefore, when $a = 0.9$ is reached, the energy consumption of the node can be controlled in a timely manner to avoid network interruptions caused by energy depletion. At the same time, nodes do not frequently enter energy-saving mode when their energy level is high, thereby reducing the energy consumption of frequent wake-up and prolonging the overall network lifespan. For cells with CH energy lower than the judgment threshold $Y(i)$, and then proceed to select cells that meet $E(i) \geq \bar{E}(c)$. It is closest to the center of the cell. The rest enters the data transmission. According to the communication method of the LEACH algorithm, CH fuses the data and transmits it to BS, completing the task [20]. After all nodes die, the loop ends. Taking the communication distance d and the transmission of k bit data as an example, the energy required for CH to transmit to BS is shown in equation (7).

$$E_{Tx\to BS}(k,d)=\begin{cases}(E_{Tx}+E_{DA})*k+E_{mp}*k*d^4, d>d_0\\(E_{Tx}+E_{DA})*k+E_{fs}*k*d^2, d\le d_0\end{cases} \quad (7)$$

In equation (7), E_{Tx} is energy loss required to transmit unit data. E_{DA} is the energy required for CH fusion processing of unit data. E_{mp} is power consumption required by the amplifier to transmit unit data signals when using a multi-path propagation model. E_{fs} is the power consumption required for the transmitting unit data signal amplifier when using a free space propagation model. The energy required for cluster members to transfer to the associated CH is shown in equation (8).

$$E_{Tx\to CH}(k,d)=\begin{cases}E_{Tx}*k+E_{mp}*k*d^4, d>d_0\\E_{Tx}*k+E_{fs}*k*d^2, d\le d_0\end{cases} \quad (8)$$

CH receives a data packet from a member within a cluster and fuses the energy required for processing the data, as shown in equation (9).

$$E_{Rx}(k,d)=(E_{Tx}+E_{DA})*k \quad (9)$$

In equation (8), E_{Rx} is the energy loss required to receive unit data. The communication distance threshold d_0 is calculated, as shown in equation (10).

$$d_0=\sqrt{E_{fs}/E_{mp}} \quad (10)$$

3.3 Construction of intelligent building environmental monitoring system

WSN is a multi-hop self-organizing network, which is used for monitoring. In the data transmission, measurement data can be directly transmitted without other media. This reduces the number of damaged parts during monitoring and management, effectively reducing production cost. Moreover, WSN can comprehensively monitor different parts, making work more comprehensive. Intelligent building can optimize building structures, management services based on user needs, providing comfortable, and convenient building environment. Intelligent building is the fusion of advanced technologies, including architecture, computers, communication, and modern control technology. This is a system that uses sensor devices and wireless communication technology to remotely monitor the internal environment of buildings. The detected data can be wirelessly transmitted to the server. Management personnel monitor the internal environmental conditions of buildings in real time through user terminals [21]. The overall architecture of the system is illustrated in Figure 4.

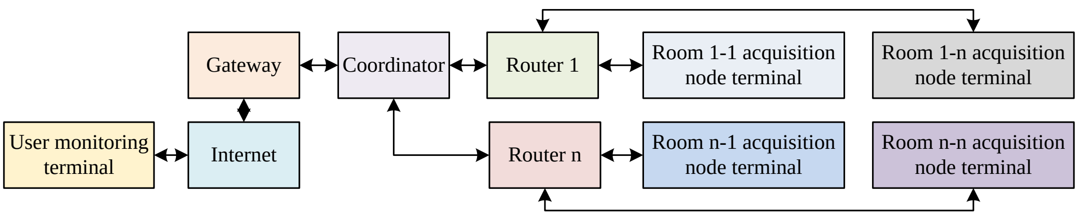


Figure 4: Schematic diagram of the overall system architecture

In Figure 4, the user monitoring terminal is connected to the Internet. Gateway and coordinator control routers 1 to n. Finally, the monitoring connection is completed with the collection node terminals in each room. Router nodes can determine network addresses and IP paths. It can establish flexible connections in a multi-network interconnected environment. Various sub-nets can be connected using different data grouping and media access methods. There are many rooms inside the building, requiring a large number of collection nodes. They are far from the control center. Therefore, multi-hop data forwarding is adopted. Routers are responsible for data transmission. The environmental information monitoring system used inside buildings only transmits environmental information data and concise command information, resulting in a small amount of data transmission [22]. The environmental information collection system has a huge demand for the number of collected nodes. The numerous internal walls of the building require high penetration of communication technology. The node is powered by batteries, which limits energy. In response to the above situation, the study adopts ZigBee technology as the data transmission and communication method of IBEMS to achieve low-power, real-time monitoring, abnormal alarm, and remote viewing functions. Zigbee is a wireless communication method applied to short distances and low rates. The Zigbee system diagram is shown in Figure 5.

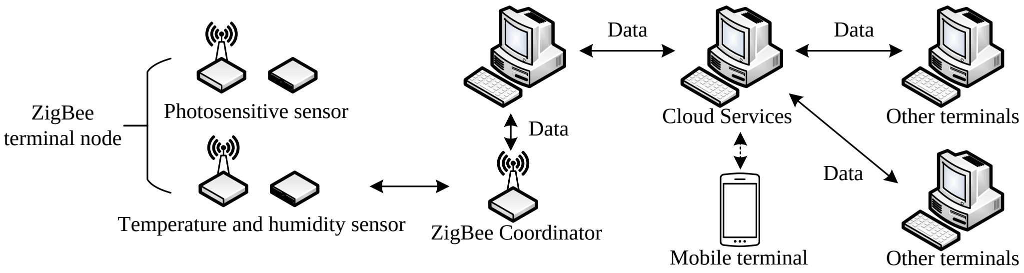


Figure 5: Schematic diagram of Zigbee system

In Figure 5, the ZigBee terminal nodes, such as photosensitive sensors, temperature and humidity sensors, are connected to the ZigBee coordinator. The coordinator transfers data to local or other terminals and uploads it to cloud services for easy viewing on mobile devices. The ZigBee protocol stack consists of the Application Layer (AL), application aggregation layer, Network Layer (NL), data link layer, and Physical Layer (PL). The underlying layer is the media access layer and PL that adopt the IEEE 802.15.4 standard specification. The media access layer is applied to establish, maintain, end, confirm wireless data link data transmission and reception between different devices. The NL ensures the transmission and integrity of data, while also encrypting the data. The AL completes communication between multiple devices based on design purposes [23]. Its main features include low speed, low power consumption, low cost, low complexity, reliability, and security. The main controller of the system terminal node uses the CC2530 chip from Texas Instruments to achieve networking functions with Zigbee communication technology as the core. The normal working voltage required for the chip is 3.3V. To reduce construction cost, a flexible power supply method is designed. The circuit diagram is shown in Figure 6.

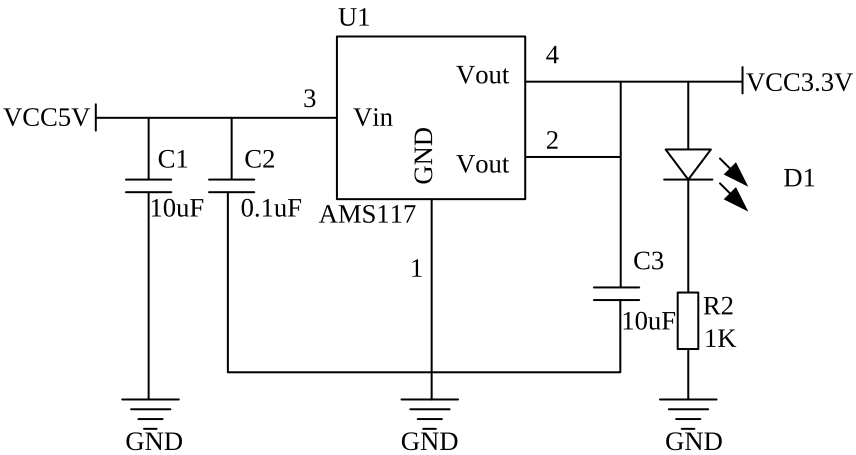


Figure 6: Schematic diagram of the power supply circuit

In Figure 6, rooms 1-4 are powered by a 5V1A power adapter using 220V mains power, or by three No. 5 batteries. The voltage conversion circuit is based on the AMS117 voltage regulator chip. The four types of sensors designed for the system include air quality sensors, human detection sensors, flame sensors, and temperature and humidity sensors to collect internal environmental information of buildings. The system monitoring indicators can be reflected by MAE, RMSE, and R2. The Mean Absolute Error (MAE) is shown in equation (11).

$$MAE = \frac{\sum_{n=1}^{n=b} \left| \left(x_n^t - x_n^p \right) \right|}{b} \quad (11)$$

In equation (11), b represents the total amount of data. x_n^t denotes the true value of the n -th data. x_n^p represents the predicted value of the n -th data. x^p

represents the average value of the predicted data. The Root Mean Square Error (RMSE) is displayed in equation (12).

$$RMSE = \sqrt{\frac{\sum_{n=1}^{n=b}\left(x_n^t - x_n^p\right)^2}{b}} \quad (12)$$

R^2 is shown in Equation (13).

$$R^2 = 1 - \frac{RMSE}{\sqrt{\frac{\sum_{n=1}^{n=b}\left(x_n^t - \bar{x}^p\right)^2}{b}}} \quad (13)$$

MAE and RMSE represent the error between the actual value and the estimated value, with smaller values indicating smaller errors. R^2 reflects the fit degree between the estimated and actual results of the model. The closer its value is to 1, the better the prediction effect.

4 Results analysis of intelligent building environmental monitoring system based on CC-LEACH

This chapter introduces the improved algorithm CC-LEACH in CH distribution and network energy changes in WSN. The accuracy and robustness of the system are tested.

4.1 Performance testing of improved algorithms

The energy model used in the experiment has a transmission and reception energy of 50nJ/bit, an aggregation energy of 5nJ/bit, and a distance threshold of 87m. The simulation comparison experiment uses MATLAB as the experimental platform. The WSN experimental model randomly distributes 180 ordinary nodes in the monitoring area of 300m×300m. Each node is equipped with a positioning device that can determine its own coordinates. Each node has the ability to adjust transmission power. All nodes in the network are isomorphic and have the ability to collect, transmit, and fuse data. Once the node and BS positions are determined, they will no longer change. Table 2 displays the experimental parameters.

Table 2: Experimental parameters

Parameter	Parameter value
Base station location	(150m,150m)
Initial energy	0.5
Sending data energy consumption	50
Accepting data energy consumption	50
Power consumption of free space channel model	10
Multi-path attenuation channel model power consumption	0.0013
Data fusion energy consumption	5
Packet length	4000
Control package length	100

To evaluate the advantages of the CC-LEACH, the CH distribution of the LEACH routing and the improved algorithm were analyzed. The four algorithms are compared. Figure 7 displays the results.

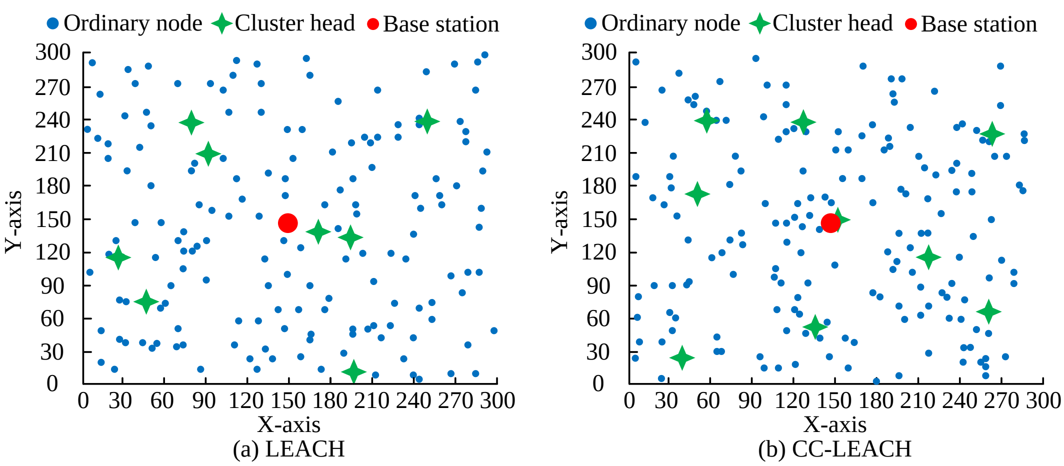
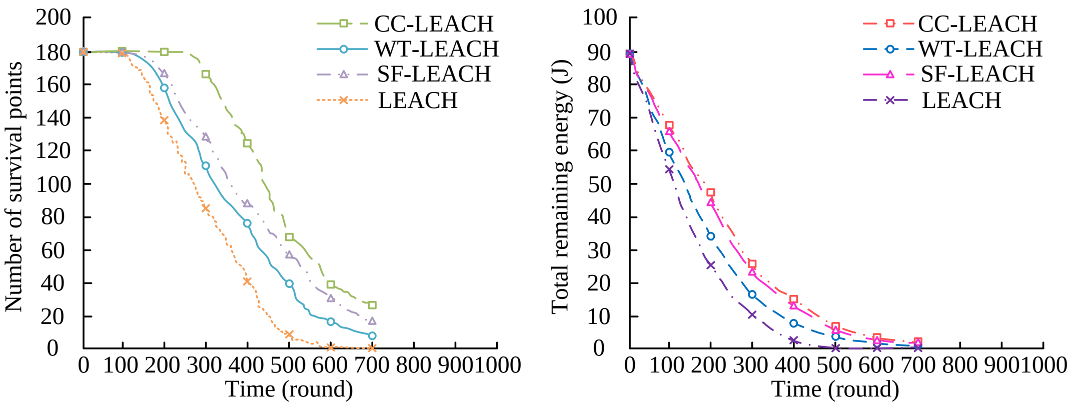


Figure 7: Comparison of CH distribution between LEACH and CC-LEACH in WSN

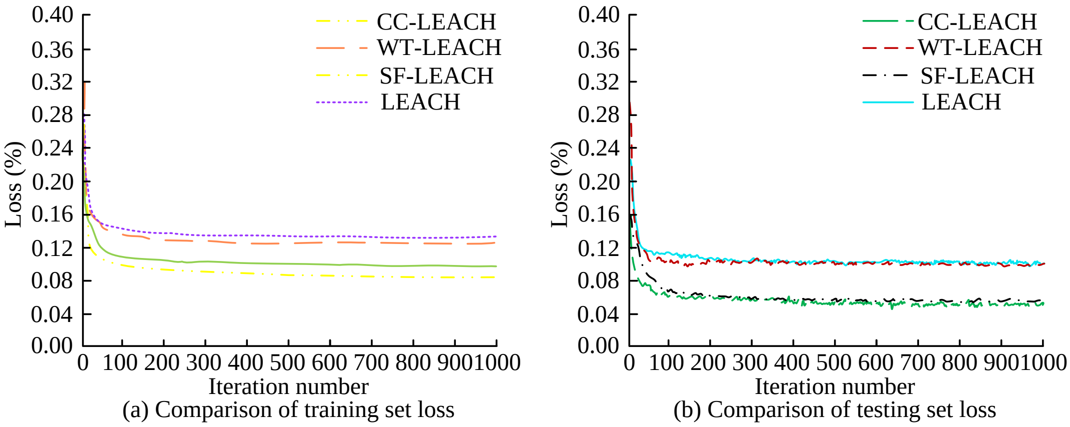
In Figure 7 (a), the monitoring area is 300m×300m. The distribution of the 8 internal CHs is uneven. The LEACH routing algorithm only considered randomness and whether the node had previously served as a CH in previous rounds when running for a CH node. If the CH node was elected in the previous round, the campaign for the CH node in the current round is abandoned. Therefore, CH was concentrated in certain areas while other areas lacked CH. In Figure 7 (b), in the same monitoring area, the CH of the CC-LEACH algorithm was relatively evenly distributed in each area. Because the rows are first clustered, then CH nodes are selected within the cluster based on factors such as node position and energy. For nodes that served as CH, if their current energy was higher than the average energy of their respective cells, they could still participate in the CH node election. Therefore, the CC-LEACH algorithm can compensate for the uneven distribution of CH in the LEACH routing algorithm. WT-LEACH optimizes the LEACH protocol by combining weighted thinking. SF-LEACH is the selection function for optimizing CH nodes in the clustering stage of the LEACH. The LEACH, WT-LEACH, SF-LEACH, and CC-LEACH are compared in experiments. The surviving nodes and remaining energy of different algorithms are compared with the variation of different rounds, as shown in Figure 8.



(a) Comparison of survival points (b) Comparison of residual energy

Figure 8: Comparison of the surviving nodes and remaining energy results in different algorithms

In Figure 8 (a), the surviving nodes for all four algorithms at the initial time were 180. At 261 rounds, the surviving nodes in the CC-LEACH decreased. At 100 rounds, the surviving nodes in the LEACH decreased. As time increased, the surviving nodes in the CC-LEACH always exceeded the other three algorithms. In Figure 8 (b), the remaining total energy of the four algorithms at the initial time was 90J. At 475 rounds, the remaining total energy of the LEACH algorithm was 0. Compared with the other three algorithms, it had the fastest energy consumption speed. The CC-LEACH algorithm had the slowest energy consumption speed, because it changed the clustering method of the LEACH routing protocol algorithm and the conditions for re-selecting CH. This reduced the number of CH elections and energy consumption during cluster formation. The CC-LEACH algorithm can better reduce energy consumption and prolong network lifespan. To analyze the effectiveness, a prediction model is established using the training set. Then this trained model is applied to the testing set for prediction. The loss curves of the four model on training and testing sets vary with iterations, as shown in Figure 9.



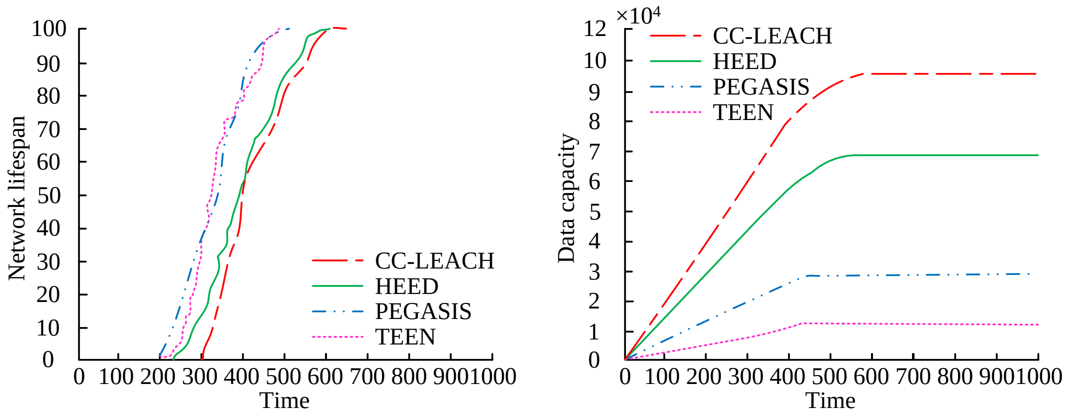
(a) Comparison of training set loss function curves

(b) Comparison of testing set loss function curves

Figure 9: Loss function curve results for different model training and testing sets

In Figure 9 (a), the loss functions of the four model on training the set all decreased with increasing iterations. When the iteration was 170, the loss function of the LEACH algorithm on the training set tended to stabilize, with a loss value of 0.15%. The loss curve of the CC-LEACH algorithm on the training set had the fastest descent speed. The loss value was the smallest, and the final stability was 0.09%. In Figure 8. (b), the loss functions of the four models on testing set all decreased with increasing iterations. The CC-LEACH algorithm had good robustness and monitoring performance.

A comparative experiment is conducted, using a network size of 1000 sensor nodes in a square area of 1000m × 1000m. Comparative algorithms, including Hybrid Energy Efficient Distributed Clustering (HEED) [24], Power Efficient Gathering in Sensor Information Systems (PEGASIS) [25], and Threat sensitive Energy Efficient Sensor Network (TEEN) [26] are selected. The network lifetime and data transmission results of different algorithms are shown in Figure 10.



(a) Comparison of network lifespan

(b) Comparison of Data Transmission

Figure 10: Comparison of network lifetime and data transmission for different algorithms

In Figure 10 (a), the network lifetime of CC-LEACH algorithm was still longer than the other three algorithms. The reason is that it avoids premature death of some nodes and balances the energy consumption of nodes in the network by improving the first round of clustering conditions and clustering methods, thereby extending the overall lifespan of the network. In Figure 10 (b), the overall energy utilization rate of the CC-LEACH network was high, and the data transmission volume gradually increased. Although the TEEN algorithm can reduce unnecessary communication in event driven mode, it performs the worst in terms of network lifespan and data transmission volume.

4.2 Performance testing of the system

To analyze the accuracy of intelligent building environmental monitoring, due to the large amount of test data and for the convenience of graphical display, 100 random data groups are selected for the study. The actual and predicted values of building ambient temperature detected by the CC-LEACH system are compared, as shown in Figure 10.

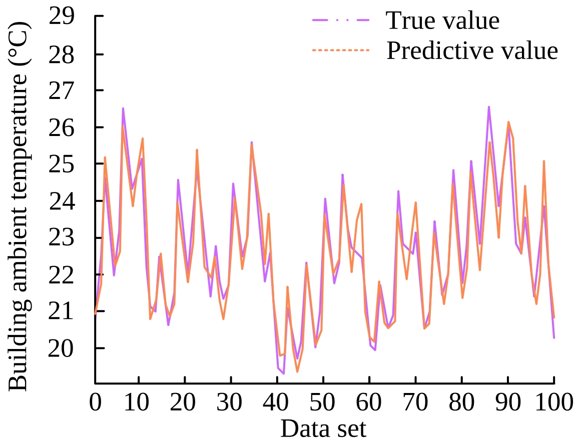


Figure 10: Comparison of real and predicted values of building environment

In Figure 10, the real and predicted values of the building environment detected by the CC-LEACH system almost overlapped, indicating that the temperature monitoring accuracy was high, reaching 98.6%. The temperature standard of a building as determined based on its different usage functions. For example, residential buildings maintained a temperature of 26°C in summer and 20°C in winter. To better evaluate the robustness of the algorithm, a data sample of 5000 is selected for the study. The MAE, RMSE, and R2 of different algorithms are compared. The results are shown in Figure 11.

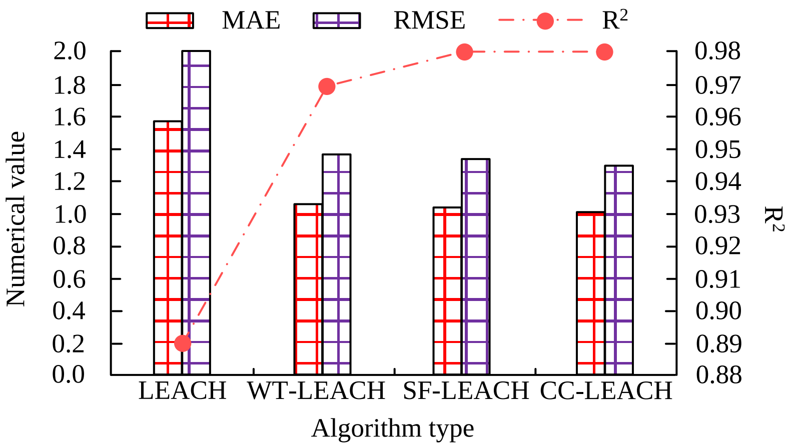


Figure 11: MAE, RMSE, and R2 results of different algorithms

In Figure 11, the LEACH algorithm had the highest MAE, which was 1.57. The prediction error was higher. The MAE values of WT-LEACH, SF-LEACH, and CC-LEACH algorithms were 1.06, 1.04, and 1.01, respectively. The three optimized algorithms all improved performance to varying degrees. The robustness improvement of the CC-LEACH algorithm was more significant. The statistical analysis of building environment data before and after model improvement is shown in Table 3.

Table 3: Statistical analysis results before and after model improvement

Group	1	2	3	4	5	6	7	8
LEACH	2.39	2.11	2.68	2.53	2.85	2.18	2.49	2.45
CC-LEACH	2.60	2.94	2.99	2.94	2.89	2.85	2.94	2.90
Category	Mean value	Variance	df	t Stat	P (Single tailed)	t single tailed criticality	P (two-tailed)	t double tailed critical
Comparison results	2.927	0.243	18	5.713	0.001	1.734	0.002	2.102

In Table 3, the P-value of the single tailed test was 0.001, the P-value of the two- tailed test was 0.002, and the t-value was 5.713, indicating a significant difference between the mean values of the two algorithms. P<0.05 indicates a significant improvement in CC-LEACH compared with LEACH.

The performance testing of the system mainly includes transmission distance testing and data loss rate testing. Based on the sampling period set by the system, different distances between the collection unit terminal node and the coordinator are set. A residential building is selected for the study, with a testing period of 5 days. The building is bustling with people, and various wireless signals are interwoven with each other. These factors have a certain impact on the test results. To improve testing efficiency, the system sampling time is set to 1s. The theoretical value of the amount of data obtained per minute is 60 sets. The system runs for 15 minutes at different distances. To verify the feasibility of the design system, data is obtained through on-site testing of the building, as displayed in Table 4.

Table 4: Performance test data

Set distance (m)	1	5	10	15	17	19	20	21	23	25
Theoretical data volume (group)	900	900	900	900	900	900	900	900	900	900
The amount of test data (group)	898	899	896	893	883	228	176	130	43	36
Data loss rate (%)	0.002	0.001	0.004	0.007	1.8	74.6	80.4	85.5	95.2	96.4

When the coordinator was 17m away from the node, the data loss rate of the system was 1.8%, not exceeding 2%. When the distance from the node was 19m, the data loss rate was 74.6%. At this time, the data loss rate increased significantly. After 25m, the data reached 96.4%. Therefore, the system can complete building environment monitoring tasks with a scale of about 17m.

5 Discussion

At 300 rounds, the network lifetimes of HEED, PEGASIS, and TEED were 1, 14, and 35, respectively. The CC-LEACH algorithm was 43, an increase of 22.86% compared with the TEED algorithm. TEEN controls data transmission through threshold control, extending network lifespan, but there are still shortcomings in energy management. CC-LEACH optimizes CH selection and energy management through an improved low-power adaptive clustering routing algorithm, achieving more balanced energy consumption and significantly extending network lifespan. The data transmission capacities of HEED, PEGASIS, and TEED were 6.9×104, 2.9×104, and 1.2×104, respectively. The CC-LEACH algorithm had a capacity of 9.7×104, which was 40.58% higher than the HEED algorithm. The frequent replacement of CH in HEED algorithm leads to low data transmission efficiency. CC-LEACH has improved data transmission efficiency and significantly increased the total data transmission volume by optimizing the data transmission path. The algorithm complexity of CC-LEACH increases, requiring more computing and communication resources. However, this improvement is to achieve longer network lifespan and higher data transmission capacity, which is effective. In CH selection and path optimization, CC-LEACH consumes more energy in the initial stage, but these initial energy inputs are used for subsequent efficient energy management and data transmission.

6 Conclusion

To effectively promote the technological upgrading and application promotion of building environmental monitoring, WSN is applied to environmental monitoring systems to improve the informatization. The monitoring area was 300m×300m. The CH of the CC-LEACH algorithm was relatively evenly distributed in various regions. At 261 rounds, the surviving nodes in the CC-LEACH decreased. The number of surviving nodes in CC-LEACH increased with time. The CC-LEACH had the slowest energy consumption speed, because it changed the conditions for the LEACH routing protocol algorithm to re-select CH and clustering methods. This reduced the energy use during cluster formation and the CH elections. The CC-LEACH could better reduce energy use and prolong network lifespan. The actual and predicted values of the building environment detected by the CC-LEACH system almost overlapped, indicating that the temperature monitoring accuracy of the system was high, reaching 98.6%. The temperature standard of a building is determined based on its different usage functions, such as residential buildings maintaining 26°C in summer and 20°C in winter. The LEACH algorithm had the highest MAE of 1.57, with a large prediction error. The MAE values of WT-LEACH, SF-LEACH, and CC-LEACH algorithms were 1.06, 1.04, and 1.01, respectively, indicating that the three optimized algorithms improved performance to varying degrees. The robustness improvement of the CC-LEACH algorithm was more significant. However, due to the complexity and uncertainty of the building environment, there are changes in the building structure, materials, and usage, which affect the fluctuation and deviation of sensor data. These all affect the accuracy and real-time performance of the data, thereby affecting the performance of the monitoring system.

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Conflict of interest statement

The author claims no conflict of interest.

Data availability statement

The data will made available on the request.

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