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Exploring a Mesh-Hub-Based Wireless Sensor Network for Smart Home Electrical Monitoring

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Abstract
The method of indeterminate monitoring of household appliances involves analyzing voltage and current signals detected at the power supply. Each electrical appliance exhibits a distinct consumption pattern (e.g., vacuum cleaners, ovens, etc.), including their switch-on and switch-off timings. The monitoring system determines these consumption patterns of electric appliances. This study introduces a wireless sensor network designed for subtle monitoring of household appliance consumption. This study addresses the challenges and issues concerning wireless sensor networks, alongside the notable advantages and capabilities in the areas mentioned above, such as network structure, performance methods, monitoring types, and energy consumption factor analysis. Through empirical investigation and scientific discourse, the study's findings indicate that a higher number of nodes and windows in a building correlates with a reduced rate of energy transfer. Conversely, employing fewer nodes and windows increases the speed at which energy is transferred.

Keywords Indeterminate monitoring · Household appliances · Wireless sensor networks · Power supply · Consumption patterns

1 Introduction

Indeterminate monitoring of household appliances is a method that analyzes the voltage and current signals at the power supply [1]. The nodes get various environmental information in a wireless sensor network and perform local processing, including compression and quantification. Eventually, the network sends messages directly to the main central station or other nodes [2, 4]. The ability of wireless networking to communicate directly with natural phenomena has led to the widespread use of this network in observing specific areas and unique places that are hard to reach, such as battlefields. Similarly, the wireless sensor network is helpful for firefighters and fire detection systems, either in buildings or forests, to measure the temperature and humidity in particular areas [5, 6]. Most sensor nodes use unrecoverable batteries; therefore, it is essential to conserve energy as much as possible [7]. One of the methods to save energy is data aggregation. Other solutions, such as radio

Extended author information available on the last page of the article

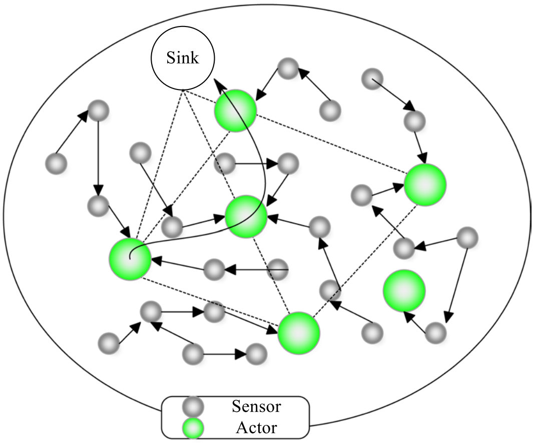

Fig. 1 The design of a wireless sensor network [11]

scheduling, limiting packets control, and topology control, are also used to perform this action efficiently [8]. Figure 1 shows the design of wireless sensor networks. A significant barrier in implementing this system is connecting the sensor to household electrical appliances and computer systems [8]. In addition, when deploying this system, changes should be made in the home wiring utilities of the building, which is also a deterrent factor [9]. Another requirement is monitoring household appliances' energy consumption, which involves processing the voltage and current signals at the power supply location. Then analyzing these signals relative to the type of electrical equipment, exploring the start-up and the switch-off time, and dealing with the pattern of consumption of the electric appliances [9, 10].

This study aims to introduce and design an Open–source wireless sensor network that works through the subtle monitoring of the consumption of electrical household appliances. This research develops a digital signal processor (DSP) design, which can detect electric-powered devices using conventional signal processing techniques and intelligent classification protocols. A diagnostic method for detecting the type of electric vehicle based on pattern recognition and done by machine vectors are used in this research. Moreover, the current issues and problems about wireless sensor networks and their relative advantages and abilities regarding the network structure, method of performance, type of monitoring, and factor analysis of energy consumption, have been empirically identified and then scientifically are discussed.

1.1 Objectives and Motivations

This study aims to introduce and design an open-source wireless sensor network that enables inconspicuous monitoring of electrical household appliance consumption. The research aims to develop a digital signal processor (DSP) design capable of detecting various electric-powered devices using conventional signal processing techniques and intelligent classification protocols. Additionally, the study seeks to address current challenges and issues within wireless sensor networks while exploring their relative advantages and capabilities, particularly in terms of network structure, performance methods, monitoring types, and energy consumption factor analysis. The ultimate goal is to empirically identify and scientifically discuss these aspects, contributing to a comprehensive understanding of efficient energy management in the context of household appliances. In summary, the motivations for this study encompass energy efficiency, technological advancements, user convenience, safety, and the potential for positive societal and environmental contributions. Several motivations drive this study:

1. Energy Efficiency and Conservation: With growing concerns about energy consumption and environmental sustainability, there's a pressing need to develop innovative solutions for effectively managing household appliance energy usage. The study addresses the imperative to conserve energy and reduce wastage by designing a wireless sensor network that monitors appliance consumption.
2. Advancements in Sensor Technology: Rapid advancements in sensor technology have made it feasible to gather precise data from various environments. This study leverages these advancements to create a wireless sensor network that can collect accurate information about household appliance consumption patterns.
3. Automation and Convenience: Automated monitoring of household appliances provides convenience to users, allowing them to track and manage their energy usage effortlessly. This motivates the development of a system that can seamlessly integrate with everyday life and enhance users' control over their energy consumption.
4. Remote Monitoring and Management: Remotely monitoring and managing household appliances through wireless networks adds a layer of convenience for users. This could be particularly beneficial for individuals who travel frequently or need to control their appliances from a distance.
5. Real-time Data Insights: By analyzing real-time data from appliances, users can gain valuable insights into their usage habits. This can lead to informed decisions about optimizing energy consumption and reducing costs.
6. Technological Innovation: Designing a wireless sensor network for household appliances represents a novel application of technology. The study contributes to technological innovation by exploring ways to integrate sensors, communication protocols, and data processing techniques for practical energy management.
7. Addressing Technical Challenges: The study aims to tackle challenges such as data aggregation, energy conservation, and efficient wireless communication within the context of a sensor network. Overcoming these challenges can have broader implications for sensor network applications beyond household appliances.
8. Societal and Environmental Impact: A successful implementation of this technology could have positive societal and environmental impacts by promoting energy-conscious behaviors and reducing overall energy consumption, contributing to a more sustainable future.
9. Interdisciplinary Collaboration: The study involves collaboration between fields like signal processing, wireless communication, energy management, and appliance engineering. Such multidisciplinary work fosters cross-pollination of ideas and expertise, potentially leading to breakthroughs and innovative solutions.

2 Research Methodology

The research methodology employed in this study encompassed a systematic and structured approach to investigate various aspects of wireless power monitoring, energy transfer, and data transmission to household appliances. The methodology was divided into distinct phases to address the research objectives comprehensively. The initial phase involved designing the wireless power monitoring system. This encompassed integrating components such as batteries, ground connections, and motion sensors into a functional configuration. The setup was designed to facilitate energy consumption analysis and data collection from household appliances. The next step focused on creating a meshed building layout. This involved strategically placing 14 wireless sensor nodes throughout the building. The placement aimed to cover various areas and gather data from different locations to assess energy transfer efficiency. The research methodology comprised several interlinked phases, from preliminary design and energy transfer assessment to appliance data transmission and future recommendations. The mixed-methods approach enabled a comprehensive exploration of wireless power monitoring and data transmission in the context of household appliances. Based on the explanations provided, the process involves aggregating and analyzing data. This process begins with examining the design of a wireless sensor network within a building. The investigation then delves into the probability of achieving successful energy transfer across one to three windows. Subsequently, the transfer of information and commands is elucidated, showcasing the role of wireless sensor nodes and Bluetooth devices as the ultimate conduits for transmitting instructions to household appliances.

2.1 Nodding of the Wireless Monitoring System of Building Energy Consumption

The first step to designing a wireless sensor network is to examine the energy performance of the wireless monitoring system, through which an electrical system calculates the amount of energy transmitted. The electrical system applied to the building includes the ground, the battery, and the motion sensor. Figure 2 shows the wireless system monitoring node design.

At each node, a sensor sends pulses to the center. As shown in Fig. 3, each pulse analyzes a node in 60 s, which provides repetition periods in 60 s. Indeterminate monitoring of home appliances was devised by Fred, Ed Kern, George Hart at MIT and funded by the Power Research Institute in the early 1980s. This idea was first proposed by Dr. George

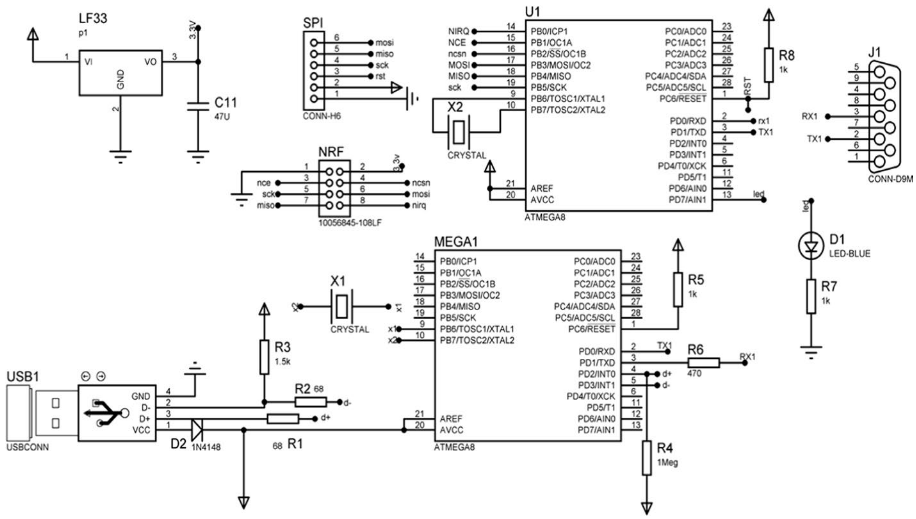

Fig. 2 Wireless system monitoring node design

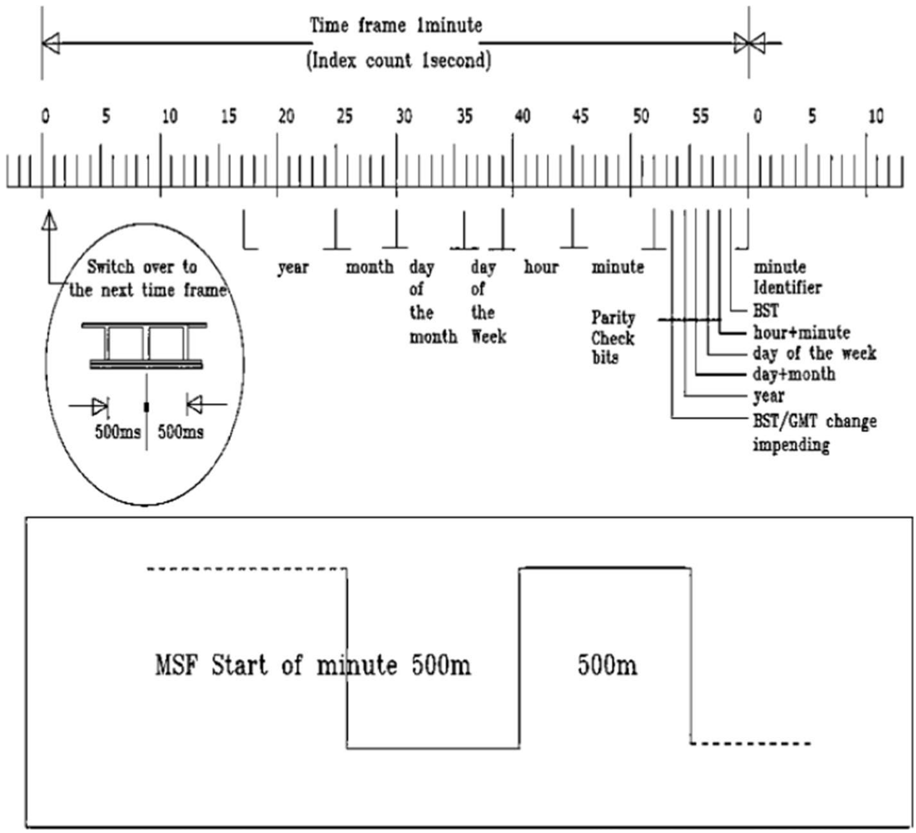

Fig. 3 The details and properties of 60 s MSF pulse

W. Hart while collecting and analyzing data for a home-based photovoltaic system. Dr. W. Hart captured the energy consumption of several homes in 5-s intervals and found that it was possible to detect the type of power device that was turned on or off by the curve [12, 13]. Two prototypes of this system were consequently designed from 1982 to 1988. In the following years, France and Finland also implemented examples of this system [13, 14]. For instance, in pursuit of understanding household energy consumption patterns, saving energy, and developing specific policies to reduce energy consumption, France and 11 other European countries launched large-scale monitoring operations. By doing so, they aimed to raise awareness of household energy consumption for various types of equipment and different consumer's lifestyles [15]. Consequently, a review of the energy consumption of household appliances was revealed, which led to significant changes that have taken place over the past ten years in French households, especially in electronic equipment (home entertainment and office equipment) [15]. Two critical aspects of these changes are as follows:

1) Deep changes in audiovisual equipment due to the advent of new technologies.
2) The availability of computer equipment and accessories provides new services and, as a result, the introduction of new technologies.

The package provided by the monitor is convenient and allows the user to access the system through the interfaces provided by the manufacturer on the web. In this category of implementations, users are restricted to the features provided by the manufacturer and generally cannot adapt to other systems or even develop the design [16]. With the presence of smartphones, the provision of the Android operating system offers excellent opportunities for developing automation and intelligent control systems. Hence, by developing an Android-based system, users can access wireless components using the nRF24L01 modules via Bluetooth and the Web. Such an Android-based system is not for data collection and is further equipped with alerts and remote access [17]. To implement and monitor the intangible devices of the wireless device remotely, using a wireless sensor network is considered necessary. Therefore, high-performance and low-power devices become essential in implementing and assessing the energy consumption issue. Moreover, wireless sensors such as NRF24L01 can be used with low-cost and low-power chips to create a topology suitable for covering vast spaces [18].

2.2 Mesh Structure

Mesh network is widely used due to its simple structure and unique topology properties in many networks, including traditional and interconnection networks [19]. As shown in Fig. 4, in a wireless sensor network using the mesh structure, a sensor divides the distance between the two adjacent nodes (or aligns the size of the meshes in the Mesh network); we aimed to send information and commands to wireless signals in each range. Of course, it is necessary to remember that the distance between all the edges in the mesh network is the

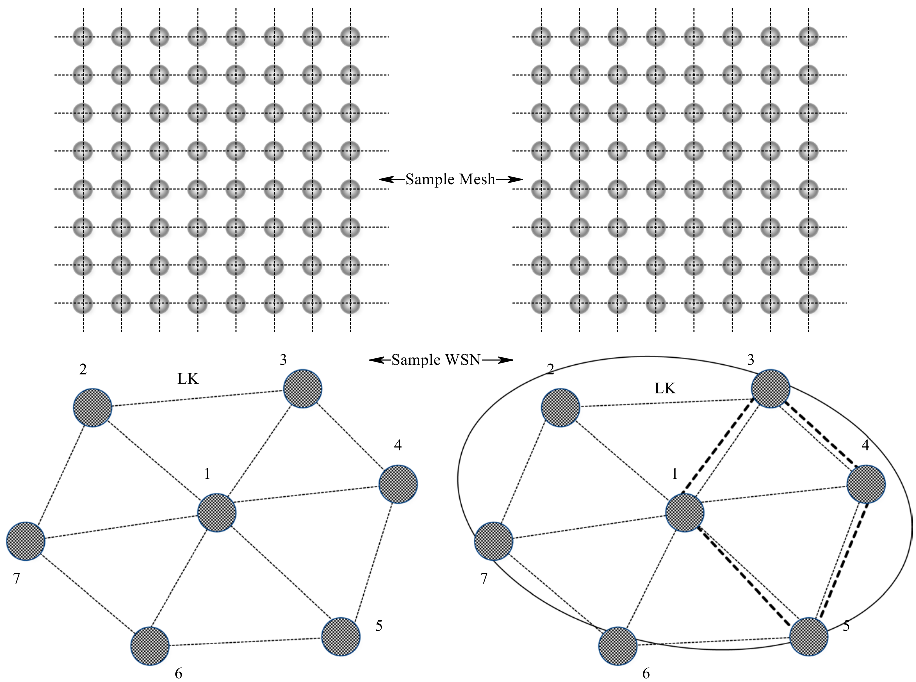

Fig. 4 The structure of traditional mesh network

same. However, sending information on this network is like a traditional mesh network; each sensor node can only send data to its neighbors in the conventional mesh network [20].

2.3 Multi-Sensor Integration in a Package

An independent processor on each sensor board makes integrating multiple analog and digital sensors in a single node possible. In this way, when the data is sent, instead of transmitting data from a sensor, the data is sent from several sensors that save power in the system. Besides, the presence of an independent processor in each sensor allows for pre-processing, and as a result, we will have a set of smart sensors [21]. Consequently, Wireless Smart Sensor receives data from sensors connected to the node by the processor in the node and sends it after coding the gateway [22]. Figure 5 demonstrates the wireless smart sensor structure. This system should measure the current and voltage of the typical electricity supply and calculate and process these two quantities. It should include the following sections [23]:

1) Measurement section
2) Signaling section

The measurement and signaling section are responsible for instantaneous voltage and current measurement, signal amplification, and reliable data transfer to the processor. The necessary hardware in this section is a DSP with two channels for measuring the voltage

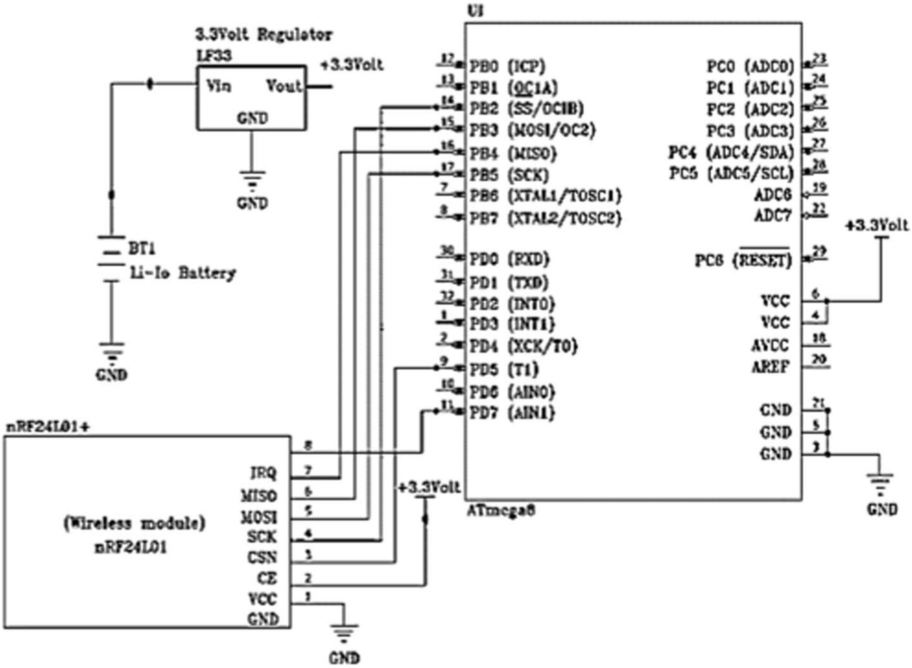

Fig. 5 The details of the wireless smart sensor structure

and converting it to digital data. By placing a resistance in the path of the null wire where the total returning circuit passes through, the voltage is generated at the two ends of the resistance; this voltage is measured with channel DSP number one. The amount of current consumed by the electric appliance is obtained by dividing this voltage by the value of resistance [24]. Also, the city voltage is measured by connecting another DSP channel to the secondary side. The electric instrument's reactive and active power consumption will be obtained using the measured city voltage [25–40].

2.4 Math Building Meshing

As shown in Fig. 6, the meshed map of the building, which has 14 wireless sensor nodes, is considered the default, while the wireless sensor nodes are embedded in the entire building and located next to the window. Such wireless sensor nodes transmit energy and information; in other words, they send data to the nearest sensor nodes. Mathematical optimization techniques, such as linear or integer programming, can optimize energy consumption patterns based on appliance usage and energy costs. In assessing network resilience, you might employ reliability and availability calculations to quantify how robust your network

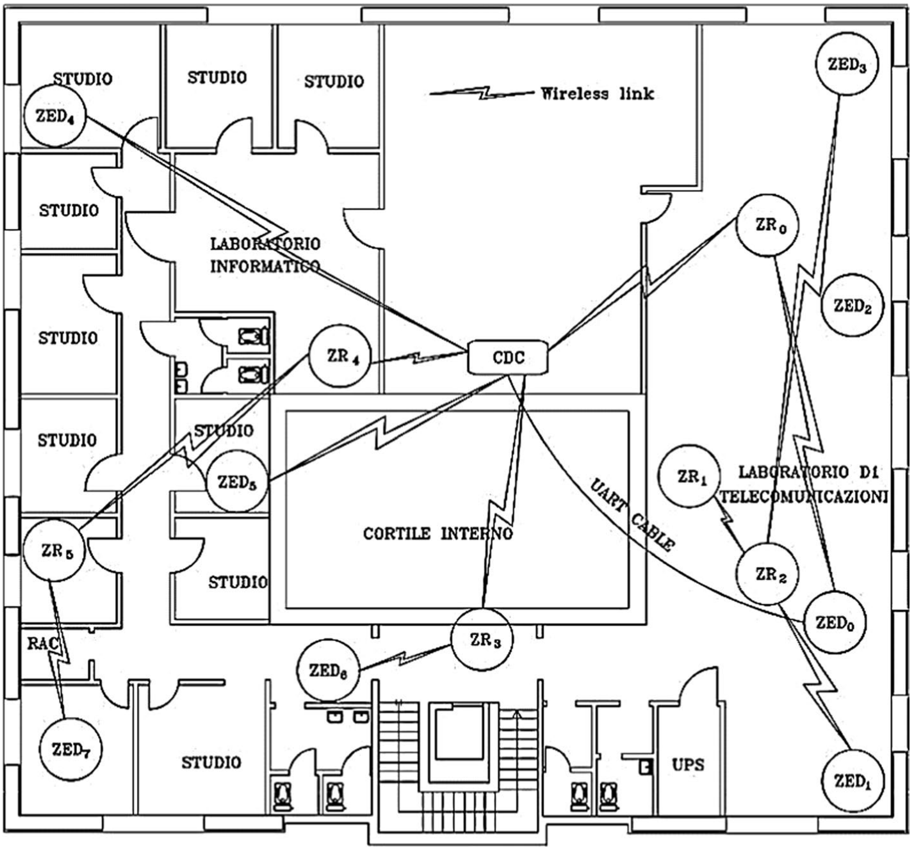

Fig. 6 Map of the evaluated building

is against node failures or unauthorized access. Here are some mathematical concepts and techniques that can be applied to various aspects of your research on wireless power monitoring, energy transfer, and data transmission to household appliances:

- Energy Consumption Analysis: Mathematical formulas are crucial in understanding energy consumption patterns. The relationship between power (P), voltage (V), and current (I) is described by the equation $P = VI$. This equation enables you to calculate the power consumed by each household appliance based on its voltage and current values. Additionally, to determine the total energy consumed over a specific time period, the formula $E = Pt$ can be employed, where E represents energy, P is power, and t is time. This equation allows you to quantify the energy consumed by appliances in relation to their power usage and operating duration.
- Energy Transfer Efficiency: Evaluating the efficiency of energy transfer involves mathematical calculations. By employing the formula Efficiency = (Useful Output Energy / Input Energy) * 100, you can quantify the effectiveness of energy transmission between nodes or devices. This efficiency measurement provides insights into how effectively energy is being transferred and utilized within your wireless sensor network.

3 Method and Result

At first, the research sample, including a building nodding, doors, windows, and all sections of the building with the possibility of energy dissipation, has been studied. The sensors were also considered as the research sample. The results of the current applied study can be used to develop the applied knowledge in this particular context. In this research, since the information is generated and sent to the system instantly, we used the observation method to process the data. Due to the simulated structure, there is no reallocation, and a map of a building has been investigated for system verification and simulation of the sensors. In the current project, a qualitative analysis method was used. In this type of research, our data is transmitted through sensors to the electronic system. The electronic system program detects the most amount of energy waste at different parts of the home. Hence, reducing its consumption would also reduce the amount of waste. In this research, MATLAB R2015b software has been used to transfer energy successfully, and the B4A software has been used to transfer data to home appliances. By reviewing previous studies possibility of successful transmission of one, two, and three windows in 10 s was investigated in the current research to understand the possible association between the number of windows and heat transmission. here's a high-level algorithmic outline for this research on wireless power monitoring, energy transfer, and data transmission to household appliances (Algorithm 1).

Algorithm 1

1. Initialize Wireless Power Monitoring System:
   - Configure batteries, ground connections, and motion sensors.
   - Initialize wireless sensor nodes and communication protocols.
2. Design Building Mesh:
   - Determine optimal locations for wireless sensor nodes.
   - Distribute nodes near windows and key energy consumption points.
   - Create a building mesh layout.
3. Assess Energy Transfer Efficiency:
   - Collect data on energy transfer rates using wireless sensor nodes.
   - Measure energy transfer efficiency with varying window counts.
   - Analyze collected data to identify correlations.
4. Simulate Appliance Data Transmission:
   - Set up a simulation environment for appliance data transmission.
   - Define command sets for each appliance's responses.
   - Establish Bluetooth communication channels between devices.
5. Send Commands to Appliances:
   - Transmit predefined commands to appliances via Bluetooth.
   - Monitor and record appliance responses and response times.
6. Analyze Appliance Responses:
   - Calculate response time for each appliance.
   - Analyze energy consumption changes following commands.
   - Assess the proportionality between issued commands and responses.
7. Address Challenges and Recommendations:
   - Identify network interruption challenges and unauthorized access risks.
   - Suggest solutions and recommendations for future research directions.
8. Conclude and Discuss Implications:
   - Summarize findings related to energy transfer, data transmission, and responses.
   - Discuss implications for energy efficiency and smart appliance control.
   - Train machine learning models for appliance recognition based on energy patterns.
   - Evaluate model accuracy and effectiveness in classifying appliances.
9. Optimization and Energy Management (If applicable):
   - Apply optimization techniques to manage energy consumption patterns.
   - Assess the impact of optimized energy usage on efficiency and costs.

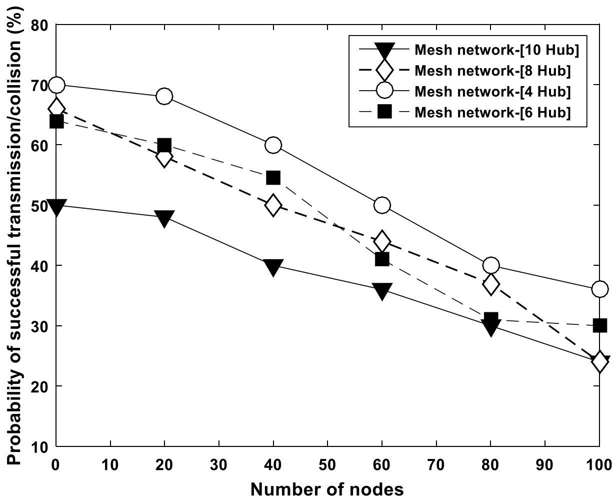

Fig. 7 The success rate of energy transfer in 100 wireless sensors nodes in different hubs

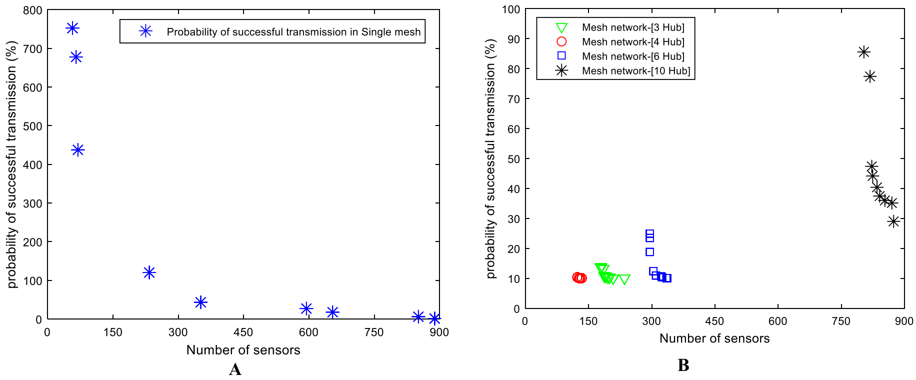

Fig. 8 The probability of successful transmission from 1 window during 10 s, **a**: with single mesh, and **b**: for different hubs

Figure 7 shows the probability of a successful energy transfer of 100 nodes; if the number of nodes increases, the likelihood of failure and lack of energy increase. Meanwhile, the following formula is used to achieve success:

$$D_{succ}(n) = \sum_{i=1}^{n} ip_{succi} \times 100 \tag{1}$$

A loop is designed to illustrate the ratio of the number of nodes to the energy transfer rate. During the experiment, the amount of energy transmitted was minimized because the more the sensor nodes, the lower the rate of effective energy transfer. Moreover, the more the windows, the less successful the optimization process of energy transfer.

It is vital to reduce the number of windows in the room or build and replace them with more ventilation and lighting to prevent energy loss. The probability of successful transmission from 3 windows during 10 s, shown in Fig. 8 (a), is related to the single mesh. And Fig. 8 (b) is related to single mesh with different hubs.

3.1 Measuring Different Antenna

Different sensors have different pulse ranges, and the energy consumption quality depends on the distance between the sensor antennas. The optimization of energy consumption depends on the electrical features of the systems, including the sensors antennas. Tab. 1 represents the distance between antennas:

Table 1 Measurement intervals for different antenna

Antenna type	Output power setting (dBm)[1]	Indoor distance (m)	Outdoor distance (m)
PCB	9	5–10	30–35
Chip	9	15–20	60–70
1/4 Wavelength wire	9	30–35	90–100

The output power can be set from −70 to 9 dBm in five steps

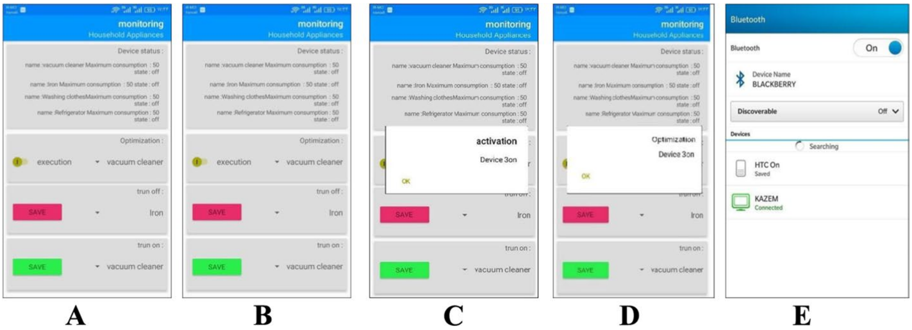

Fig. 9 **a**: Data submission and Sending Data to Home Appliances, **b**:Turning on the device 3, **c**: Turning the device1 off, **d**: Turning the optimizer on and **e**: Choosing the Bluetooth device

3.2 Sending Data to Home Appliances

To cast light on information transmission to home appliances and their operation, the process of observations and examinations involved in this study is explained here. By default, four home appliances were used as a sample, including dishwasher, iron, laundry, and refrigerator. During the observations, optimal consumption of each device was documented, and then its maximum consumption, in both power-off and power-on status, was recorded. For example, we expected default of 50 watts per hour for the maximum power consumption and considered an optimum consumption of 40 watts. Figure 9 below shows the actual status of the equipment. As noted in Fig. 9, the optimization is not applied by default, and turning the device on/off was selected manually. Immediately after touching the OK button, the device would be connected to Bluetooth and ready to submit commands to target devices. (Fig. 9 part A-E) demonstrates the way to activate the Bluetooth connection. Finally, the device also has Bluetooth, which receives and applies the desired command. The results reflect that the more the number of nodes and windows in a building, the less the rate of energy transfer. In other words, the less the number of nodes and windows, the more the rate of energy transmission.

3.3 Detecting Events in a Signal

A step-wise change in the active power signal, which is greater than the threshold value, represents a change in the state of the event as one of the electrical appliances. Therefore, the better the detection, the better the diagnosis's quality, accuracy, and accuracy. Hence developing an appropriate algorithm for this task is vital.

4 Conclusion and Future Work

This research initially focused on detailing the wireless power monitoring system's configuration, encompassing batteries, ground connections, and motion sensors. Subsequently, the study delved into the creation of a meshed building layout, strategically placing 14 wireless sensor nodes throughout the structure. The obtained results indicated an inverse relationship: an increase in the number of windows correlated with a decrease in the effectiveness of energy transfer. In the subsequent phase of the study, data was transmitted to four household appliances within a simulated setting. Necessary commands were then dispatched via Bluetooth to the designated devices, with the outcomes reflecting a proportionate response to the issued commands. Within Wireless Sensor Networks (WSNs), a significant challenge is network interruption caused by node failures or node discovery by unauthorized entities. To further explore this field, several avenues for future research could be considered. Ventilation and lighting systems could be explored as alternatives to traditional windows to mitigate the observed impact on energy transfer. Additionally, utilizing email as a medium for transmitting commands to appliances could be explored. Furthermore, in the context of information transmission to appliances, a hybrid approach combining WiFi and Bluetooth might be more efficient than using Bluetooth alone. In conclusion, this research contributes to understanding wireless power monitoring and data transmission within the context of household appliances. The study paves the way for enhanced energy efficiency and smarter appliance control systems by addressing challenges and proposing future research directions.

Appendix:

We can provide a simplified algorithmic outline for the process of wireless power monitoring and data transmission to household appliances.

1. Initialize Wireless Power Monitoring System:

- Configure batteries, ground connections, and motion sensors.
- Set up sensor nodes and establish communication protocols.

2. Design Building Mesh:

- Determine optimal placements for wireless sensor nodes throughout the building.
- Distribute nodes near windows and critical energy consumption points.

3. Energy Transfer Assessment:

- Collect data from wireless sensor nodes on energy transfer rates.
- Measure energy transfer success based on the number of windows.
- Analyze collected data to establish a correlation between windows and efficiency.

4. Simulate Appliance Data Transmission:

- Create a simulated environment for data transmission to household appliances.
- Define command sets for different appliances and their optimal energy consumption.
- Establish a Bluetooth communication channel between devices.

5. Send Commands to Appliances:

- Transmit predefined commands via Bluetooth to designated appliances.
- Monitor appliances' response times and behaviors.
- Record data on command-response interactions.

6. Analyze Command-Response Proportionality:

- Process collected data to determine the proportionality between issued commands and appliance responses.
- Calculate response time, energy consumption changes, and compliance with predefined behaviors.

7. Address Challenges and Propose Future Directions:

- Identify challenges related to network interruption and unauthorized node access.
- Recommend future research directions, such as exploring alternative window options, email-based command transmission, and hybrid WiFi-Bluetooth approaches.

8. Conclude and Discuss Implications:

- Summarize research findings related to wireless power monitoring and appliance data transmission.
- Discuss implications for energy efficiency, smart appliance control, and potential applications.

Please note that this outline provides a general flow of the research process, implementing the actual algorithms for data transmission, command processing, and energy monitoring will require programming languages and platforms suitable for your research context.

Here's a pseudo code representation of the research process for wireless power monitoring and data transmission to household appliances.

```
FUNCTION initializeWirelessPowerMonitoringSystem():
 ConfigureBatteries().
 SetupGroundConnections().
 InitializeMotionSensors().
 InitializeSensorNodes().
 EstablishCommunicationProtocols().
FUNCTION designBuildingMesh():
 DetermineOptimalNodePlacements().
 DistributeNodesNearWindows().
 CreateBuildingMeshLayout().
FUNCTION assessEnergyTransfer():
 FOR each wireless sensor node in building:
 MeasureEnergyTransferRate(node).
 AnalyzeEnergyTransferData().
FUNCTION simulateApplianceDataTransmission():
 FOR each appliance in simulated environment:
 DefineCommandSets(appliance).
 EstablishBluetoothConnection(appliance).
FUNCTION sendCommandsToAppliances():
 FOR each appliance in simulated environment:
 TransmitCommandsViaBluetooth(appliance).
 MonitorApplianceResponses(appliance).
 RecordCommandResponseData(appliance).
FUNCTION analyzeCommandResponseProportionality():
```

```
 FOR each recorded data point:
 CalculateResponseTime(dataPoint).
 AnalyzeEnergyConsumptionChanges(dataPoint).
 DetermineComplianceWithBehaviors(dataPoint).
FUNCTION addressChallengesAndRecommendations():
 IdentifyNetworkInterruptionChallenges().
 SuggestSolutionsForUnauthorizedNodeAccess().
 ProposeFutureResearchDirections().
FUNCTION main():
 initializeWirelessPowerMonitoringSystem().
 designBuildingMesh().
 assessEnergyTransfer().
 simulateApplianceDataTransmission().
 sendCommandsToAppliances().
 analyzeCommandResponseProportionality().
 addressChallengesAndRecommendations().
 ConcludeResearch().
 main().
```

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Authors' contributions PP: supervision, KR: writing draft, JAA: Revision, MG: Project manager, AJ: revision, SMHB: conceptualization, CFC: software, YL: supervision.

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Availability of data and material The leveraged data has been declared in the body of the article.

Declarations

Conflict of interest Authors declare that they do not have any conflict of interest.

Ethics Approval and Consent to Participate Not applicable.

Consent for Publication All authors agree for this submission.

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