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Secured Encoding-based Realtime Power-saving Approach for AIoT Applications

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Abstract: The convergence of Artificial Intelligence (AI), real-time monitoring, and Internet of Things (IoT) has been targeted for designing intelligent and sustainable power-saving systems for smart cities. This is due to the necessity to decrease wasted energy and distribute the generated power more efficiently. In this paper, a general architecture for an energy management embedded system is developed for smart buildings. Different from the presented approaches in the literature, this study focuses on employing logic encoding and decoding techniques to combine multiple IoT-based sensed signals into a single data packet to facilitate data transmission and accelerate the response time of processing. The encoding-decoding approach gathers four signals (temperature, humidity, light intensity, and motion detection) into a single packet. This data packet is then encrypted using a robust logic-based encryption-decryption scheme developed to assure the integrity of transmitted data packets while maintaining low complexity. Afterward, the encoded and encrypted data packet is sent to a developed AI module for centralized processing located at the main unit. The developed AI module leverages a MIMO fuzzy logic controller to provide multiple intelligent decision-making signals that set the temperature degree, fan speed, and light with the strategy of setting devices in each room into low-power states when not in use. Furthermore, we used the LabVIEW environment to implement the proposed approach due to its user-friendly GUI and reliable connections among different toolkits and applications. To demonstrate the effectiveness of the presented approach, we compared it with the conventional implementation in which each IoT-based sensor' signal is sent through a data packet. Therefore, in this case, the number of transmitted packets depends on the installed appliances in each room. Extensive simulation findings demonstrate that the proposed system architecture delivers an average power-saving of 52.6% for 12 hours of operations compared to conventional system operations. On the other hand, considering speed performance acceleration, a speedup of 37.5% is achieved by processing all IoT-based sensed signals of a room in parallel in one scanning cycle. Meanwhile, our developed encoding-based approach lowers the number of transmitted packets by 3x since a single data packet is sent for each room instead of sending four data packets. In comparison to the conventional (baseline configuration), our proposed encoding-based architecture incurs acceptable register transfer level (RTL) resources required for encoding-decoding, encryption-decryption, and state holding for the sensed data signals of each room. In summary, the obtained results confirm the power-saving validity of the proposed system in terms of low power, speedup, security, and resilience for potential deployment as a dependable system in smart buildings. Hence, it can be generalized for implementation in large buildings, such as hospitals and schools, aiming at reducing electricity costs and achieving intelligent and sustainable power distribution in smart cities.

Keywords: Energy efficiency architecture, Encryption and decryption, fuzzy logic, Internet of Things (IoT), Logic encoding and decoding, Monitoring system, Parallel processing, Smart buildings.

1. Introduction

Smart home automation systems have been gaining significant importance due to the rapid growth and development of electrical and electronic devices [1]. The number of active IoT devices is expected to reach 30.9 billion units by 2025, realizing a significant growth compared to 13.8 billion units in 2021 [2, 3]. As more smart devices are incorporated into buildings, the electricity demand has steadily increased, leading to higher electric bills [4].

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Moreover, the emergence of new smart technologies, such as cloud and edge computing, smart cities, and e-commerce, has led to the widespread use of thousands of electronic devices, including servers, access points, routers, and sensors. These devices operate continuously, resulting in a significant amount of power being dissipated as heat. This excess heat can cause unforeseen consequences, such as the depletion of energy resources and an increase in carbon dioxide (CO2) emissions, both of which contribute to climate change [5].

IoT devices have made daily life more comfortable by enhancing control systems to be smarter and more energy-efficient [6, 7]. This advancement has led to the emergence of intelligent buildings, where numerous sensors, devices, and modules work together as interconnected systems [8, 9]. Among the various applications of IoT, smart homes stand out as the most popular. They feature advanced security systems that help ensure home safety, while also allowing control over household appliances such as lights, alarms, and cooling systems. This enables individuals to monitor and manage their home operations for better energy efficiency [10]. Thus, energy savings are the most significant long-term benefit of smart home technology. It enhances quality of life by providing valuable attributes for clients, such as reducing electricity costs and enabling flexible use of electronics [11]. Consequently, sustainable design and implementation of smart electricity management for power consumption have become top priorities to reduce usage and costs, thereby contributing to a sustainable society [12].

On the other hand, to obtain a clear understanding of the system's operations, it is essential to implement a real-time monitoring framework that can autonomously track power consumption activities, thereby enhancing the system's efficiency and facilitating a comprehensive perception of its operational processes [13]. Thus, LabVIEW has been used as the Integrated Development Environment (IDE) to provide interactive and easy monitoring. It enables an easy-to-understand real-time monitoring front-end (a user-friendly GUI) and offers reliable approaches to connect among various toolkits and applications [14].

In response to these aforementioned challenges, several different hardware and software platforms, such as FPGA, microcontroller chips, System on Chip (SoC), Arduino board, and Raspberry Pi devices, have been the target to implement and deploy automated smart home systems [15-17]. These platforms are mainly designed to improve system efficiency in terms of lowering power consumption, increasing security and safety, and facilitating automated control and monitoring of buildings [18]. Automated systems of smart buildings primarily depend on a collection of distributed IoT-based sensing units connected through wiring or wireless to a centralized processing computer [11, 19]. These embedded systems play a vital role in data sensing, transmission, and processing, aiming for seamless operation of smart buildings to reduce power consumption since it is the most critical aspect.

In the context of Artificial Intelligence of Things (AIoT) for smart buildings, most existing concepts emphasize achieving low power. However, they neglected to investigate multiple desirable outcomes in a general framework, such as response time, the ability to process multiple signals simultaneously, and issues related to network congestion and latency. Moreover, sending each sensed signal individually within a header increases the network traffic and can lead to higher energy consumption for IoT-based units. This is due to several data packets from different IoT sensors being transmitted simultaneously, and as the number of IoT-based units increases, the issue becomes worse. Consequently, there is an increasing demand for developing solutions that can effectively tackle these challenges simultaneously. In this paper, we present an encoding-based approach that combines all sensed signals from IoT-based sensors into a single data packet. The proposed approach effectively addresses the issue of response time when increasing the number of transmitted packets as the number of IoT-based installed appliances increased in smart homes. The presented system collects data from its environment using a cluster of IoT-based sensors, encodes, aggregates, and encrypts the sensed data, and sends them in a single encoded and encrypted vector to an intelligent processing module placed in the main unit to provide centralized processing for all appliances in the building. Furthermore, to allow parallel vector processing at the main unit, an AI module was developed using Multi-Input-Multi-Output (MIMO) fuzzy logic controller. Thus, all sensed environmental and human motion detection signals can be processed simultaneously to expedite the processing of massive data generated from enormous IoT-based sensors. In this context, the synchronization of sending room conditions and receiving control signals is maintained resilient by transmitting and receiving a single packet for each room. It achieves favorable attributes such as accelerating data transmission, increasing the efficiency of processing, and maintaining competitive power-saving.

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The synergy of combining different concepts, including real-time monitoring, Internet of Things (IoT), and Artificial Intelligence (AI) can assist in realizing desirable requirements of smart buildings. Therefore, in this paper, these three technologies are integrated to design and implement an intelligent power-saving system that monitors and manages the power consumption of smart buildings, i.e., cooling systems (Air conditioning) and spotlights (bulbs). The main contributions of this paper can be summarized as follows:

1. We design a secure encoding-based framework architecture to encode, aggregate, and encrypt multiple IoT-based sensed signals of a smart building into a signal data packet.
2. We develop a centralized AI module that receives multiple environmental and motion detection signals from multiple IoT-based sensors, performs per-processing, and makes precise decisions.
3. Develop a low-complexity encryption-decryption approach to maintain resilient data transmission between the rooms and the main unit.
4. Leveraging the time-division multiplexing along with round-robin scheduling to manage and distribute the service of the AI module among eight rooms of a smart building.
5. The simulation outcomes demonstrate the effectiveness of the proposed approach in intelligently lowering power consumption and accurately distributing generated power.

The remainder of the paper is structured as follows. Section 2 reviews some recent prior works. Section 3 presents our proposed secured encoding-based architecture for smart power saving. Besides, the description of the user-friendly GUI based on LabVIEW is covered in Section 3. Simulation and experimental results are discussed and evaluated in Section 4. Section 5 summarizes the contribution presented in this research study.

2. Related work

In this section, several related prior works that have been recently published in the literature are reviewed, aiming to investigate the achieved attributes of leveraging emerging technologies such as artificial intelligence and IoT along with logic encryption designs in terms of energy consumption, monitoring, and control of smart systems [5, 14, 16, 20, 21].

Energy-saving strategies for utilizing IoT sensors distributed throughout a household have garnered significant attention in recent years. For example, the authors in [22] employed a monitoring and control system that manages the operation of home appliances based on mobile applications, achieving a power consumption reduction of 16% compared to the standard operation of these devices. In [21], energy saving is achieved by utilizing the Gurobi optimizer for optimal scheduling of home appliances. On the other hand, integrating AI and IoT was leveraged in several studies for real-time smart home automation systems. In [23], the authors presented an AIoT system for remote control of home features and operations via mobile devices. An IoT-based energy-efficient scalable architecture for a smart classroom was proposed in [24]. The system monitors various environmental parameters, such as temperature, humidity, and CO2 emission levels, to control the lighting and air conditioning of the classroom in real-time. Nevertheless, these techniques fail to protect against external interventions. Besides, when the number of IoT-based devices increases, the network latency becomes higher, which might lead to packet collision.

Fuzzy logic offers roughly a 95% rate of accuracy for scalable computational intelligence problems and is a fast processing approach [25]. Fuzzy logic was used in [26] to design an intelligent controller for smart home automation systems of multiple users. The controller is primarily designed to reduce wasted energy and unnecessary power consumption by integrating embedded systems with the IoT for remote monitoring and control. The presented Smart Energy Control System (SECS) architecture offers precise monitoring and control of massive generated data from multiple residents, achieving a maximum reduction of 87.3% in energy consumption. Likewise, a multivalued fuzzy logic controller was proposed in [16] for centralized control of smart home automation systems. Fuzzy logic with an intelligent load simulator based on Matlab is used in [27] to achieve residential energy demand, offering 52% reduction in energy consumption. However, further protection of the transmitted packets is still demanded for effective IoT-based smart home automation systems.

On the other hand, an embedded system based on Arduino UNO was introduced in [20] to control household appliances. However, since the system was developed using pre-designed software libraries, the implemented modules provide some errors due to the voltage range and ignoring time scheduling to switch the state of appliances automatically when needed. Similarly, an architecture based on Android TV for energy saving was proposed in [5] to reduce power consumption and carbon dioxide emission of video streaming. The system monitors the user's behavior to lower the screen brightness and streaming

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resolution, saving 13% power consumption when reducing the quality of the video from 4k to 1080p. These methods do not provide mature embedded systems, as they rely on limited programming libraries and fail to utilize vector processing to improve response time.

In the context of data security and integrity, a secure data processing framework based on edge computing was proposed in [28] for the Artificial Intelligence of Things (AIoT). This system leverages edge computing to decrease the response time associated with centralized data processing. Data signals are securely transmitted between IoT-based sensors and the edge server through mutual authentication. However, the authors suggested incorporating the hash and XOR operations to improve the security of the proposed system.

Furthermore, in [14], the authors designed an energy management scheme based on LabVIEW for an automated control and monitoring system of smart homes. A framework for optimizing power consumption is proposed to achieve a home energy management system (HEMS). The system utilizes a solar-powered approach to manage the status of installed appliances and reduce power consumption. However, the proposed HEMS cannot provide security for IoT-based transmitted/received signals, and, more importantly, the proposed system sends each sensed signal from an installed IoT-based sensor to an Arduino system for conditions analyzing and then sending back control signals. Consequently, the system is vulnerable to external interventions and can cause network traffic due to individual data packets being sent to monitor and control the conditions of installed home devices.

To summarize, prior studies have primarily concentrated on reducing power consumption, minimizing response time, and maximizing throughput by utilizing approaches that enable real-time sensing of data generated by massive IoT devices. However, they fail to deliver a comprehensive scalable embedded system that offers power-saving while maintaining streamlined architecture with fast response time. In this work, we aim at designing an intelligent scalable energy-saving embedded architecture for smart home automation systems. By using logic design to encode and decode the signals from each room into a single data packet, our system can monitor and control multiple devices simultaneously through a centralized control module, which is mainly developed to ensure real-time precise decision-making of multiple IoT sensors based on vector processing.

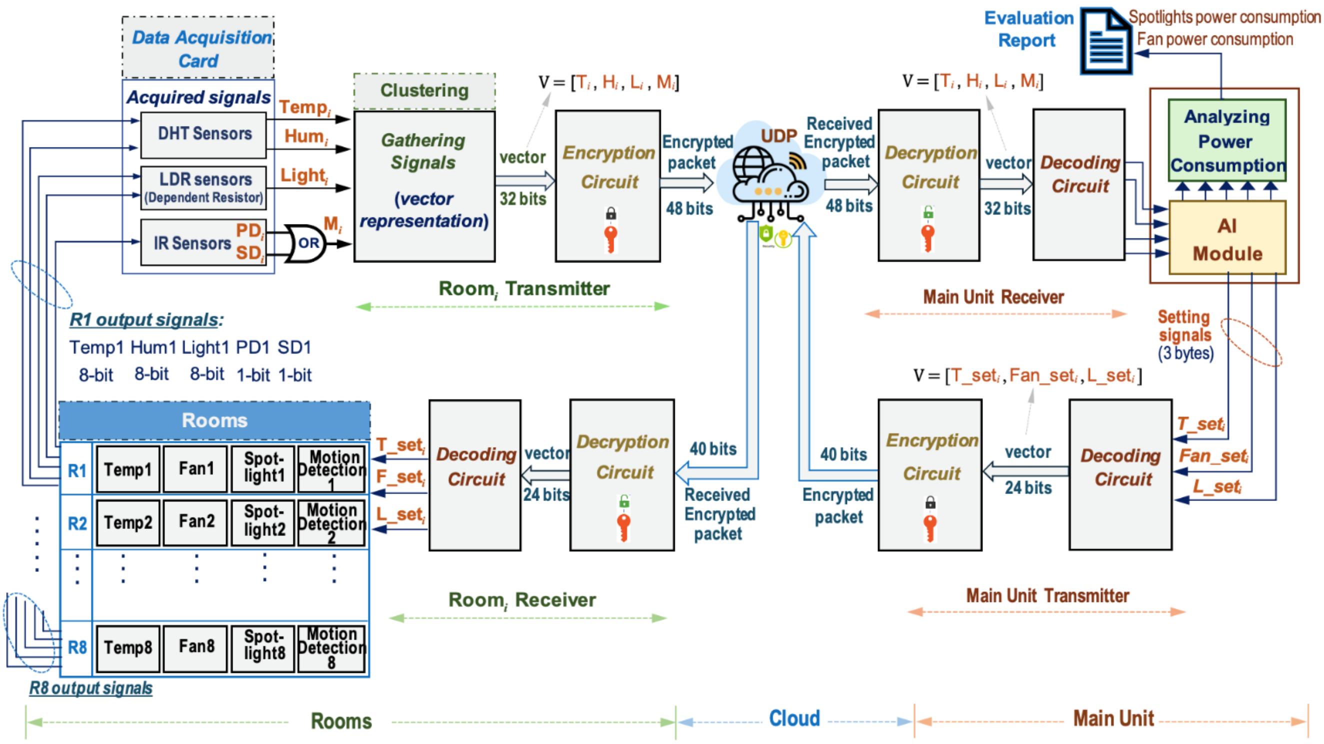

Figure. 1 General framework architecture for the proposed power-saving building automation system

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3. The proposed power-saving system architecture

In this work, encoding and decoding based on logic-multiplexing circuits are utilized to realize smart home automation systems. Fig. 1 depicts the general framework of the proposed power-saving architecture for smart buildings. The proposed system comprises two main parts: rooms and the main unit. At the beginning of a scan cycle, the main unit reads input data values through sensing units, performs the required computation based on the developed AI module for decision-making, and then sends the output commands to the rooms through the UDP protocol. Notably, the scanning cycle of sensing signals can be performed sequentially or in parallel, as discussed in Section 3.2. The proposed embedded system aims to increase energy efficiency and ensure an effective adaptive algorithm for controlling temperature, light, and motion detection in comparison to existing traditional systems, thus enabling automation and remote operation of smart homes.

3.1 Mathematical modeling of the proposed architecture for power-saving

In this section, we provide the mathematical model used to minimize energy consumption in a smart home equipped with environmental and human motion detection sensors. We use the model to formulate the proposed system and define its objectives for achieving minimal power consumption, as expressed in Eq. 1.

$$P_{minimize} = \int_0^T P(t)\, dt \tag{1}$$

This can be further expressed as the baseline power ($P_{baseline}$) consumed by essential devices and the power consumption of (bulbs) and Air Conditioning (AC), as in Eq. 2. The aim is to minimize power consumption ($P(t)$) while maintaining comfort. Since we consider the optimization of power consumption for spotlights (bulb) and AC, then we express the power consumption of these appliances as in Eq. 3.

$$P(t) = P_{baseline} + P_{light\_AC}(t) \tag{2}$$

$$P_{light_{AC}} = \begin{cases} \left(T_{desired} - T(t)\right) + light\, , if \;\; \mathcal{O}(t) = 1 \\ \quad and\, T(t) \neq T_{desired} \\ 0\, , \quad Otherwise \end{cases} \tag{3}$$

Where $T_{desired}$ represents the desired temperature degree to maintain comfortable environmental conditions, we set the value of it in the range of 21-24°C. Also, the function $\mathcal{O}(t)$ denotes the occupancy function used to determine whether a room is empty or not and is expressed as in Eq. 4.

$$\mathcal{O}(t) = \begin{cases} 1\, , \; if \quad M_i = 1 \\ 0\, , \quad Otherwise \end{cases} \tag{4}$$

Furthermore, since we assumed a smart home with eight rooms, each equipped with one DHT sensor to read (temp, hum) signals, one LDR sensor for light intensity estimation, and two PIR sensors for human motion detection, then the collected data signals from all IoT sensors installed in rooms at a specified time *t* can be stored in a 2D matrix as denoted in Eq. 5.

$$S_{IoT\_data} = \begin{bmatrix} \sum_{i=1}^{N_{th}} S_{th,i}(t) \\ \sum_{j=1}^{N_l} S_{l,j}(t) \\ \sum_{k=1}^{N_m} S_{m,k}(t) \end{bmatrix} \tag{5}$$

Where $S_{th,i}$, $S_{l,j}$, and $S_{m,k}$ represent sensed signals from DHT, LDR, and PIR motion detection sensors, respectively. While N_{th} , N_l , and N_m indicating the number of temp-hum, light, and motion detection sensors, respectively. Therefore, this paper proposes a framework architecture that aims to minimize the power consumption of each room by reading multiple sensors' signals (denoted in Eq. 5), analyzing them, and then sending back equivalent control signals to each room to maintain comfortable environmental conditions. These control or setting values are generated from the developed AI module, which we discuss later in Section 3.4. We represent them in the AI module function employed to estimate the optimal values of setting signals as expressed in Eq. 6.

$$E(t) = f_{AI\ Module}\left(T_{set_i,} F_{set_i,} L_{set_i}\right) \tag{6}$$

Where E(t) denotes the comfortable environmental state, achieved with the optimal values of control signals.

3.2 Encoding and decoding data processing

Here, we discuss the process of data encoding and decoding circuits of the rooms and the main unit. Our proposed approach focuses on minimizing data rates by compressing IoT-sensed signals into a single data packet via vector processing for room-level

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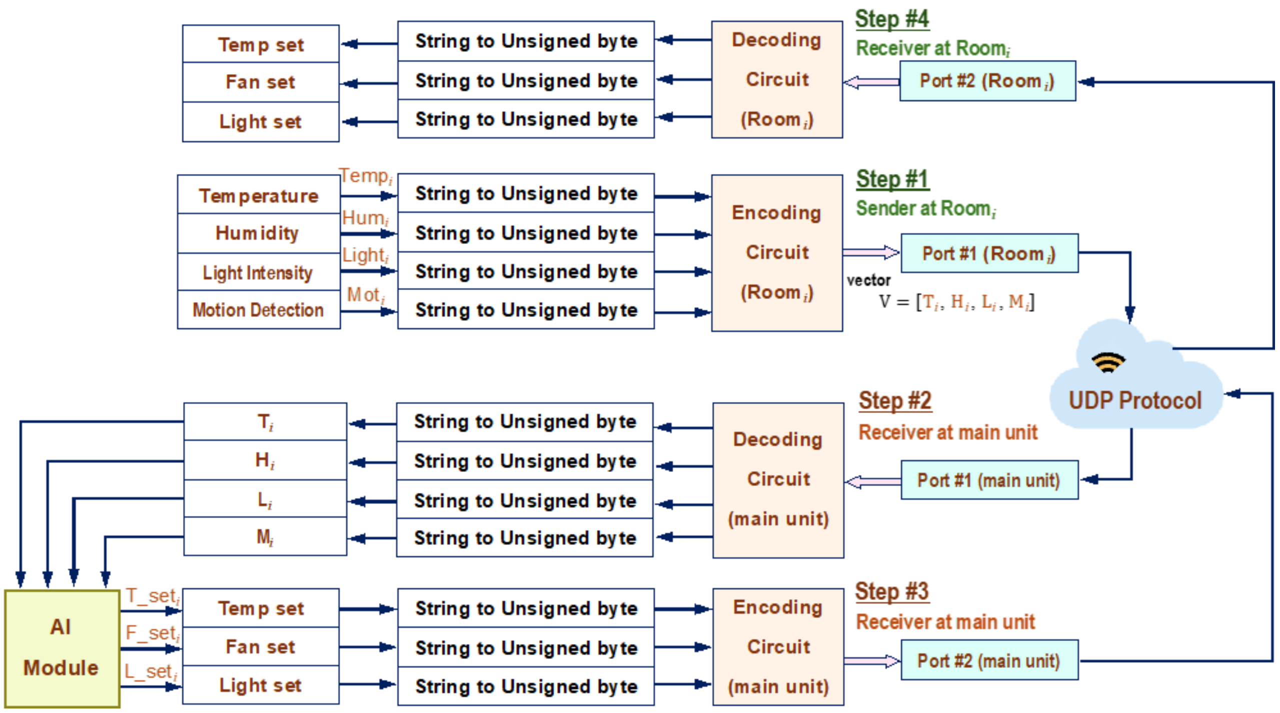

Figure. 2 Encoding and decoding processing algorithm using UDP protocol showing the port numbers of the main unit and Room$_i$

parallelism. As observed in Fig. 2, in step #1, the input signals of the sensors are first converted to a string, and then the encoding circuit bundles them in a vector containing four elements with a length of 32-bit. These elements need to be evaluated and processed by the AI module at the main unit. Thus, the decoding circuit at the main unit decodes the received vector, converts the strings to unsigned bytes, and then forwards them to the AI module, illustrated in step #2. In this case, the input signals are sent as a vector via a single port instead of sending each input signal on a port. Hence, the encoding-decoding process allows for avoiding the requirement of 4 ports for each room. In step #3, the AI module provides the optimal values of control signals to the encoding circuit of the main unit to be clustered into a vector with a length of 3 bytes. After that, the control vector is transmitted to a specific room that is under monitoring for potential operational adjustment of its appliances. In step #4, the decoding circuit of room-ith decodes the received control vector into three setting signals, converts them to unsigned bytes, and assigns each control signal to its corresponding device. The encoding-decoding processing offers two primary favorable attributes. First, it reduces the number of transmitted packets by clustering all sensed signals from a room and encoding them in a single packet. This packet is then sent over a single port and received at the main unit on another port. Thus, only two ports were required to transmit and receive the packet of signals from each room. Furthermore, we employ the encoding-decoding process between the rooms and the main unit when sending the status signals of a room to the main unit and vice versa when receiving the control vector that adjusts the setting of a room's appliances.

On the other hand, to divide the processing time of the proposed AI module among eight rooms in the building, Round Robin Scheduling (RRS) is utilized for reading input data and sending control signals. It utilizes a circular queue to slice the processing time into 8-time slots by employing time division multiplexing (TDM), which is generally from 10 to 100 ms. A setup time of 25 ms is considered, thus the RRS algorithm assigns the processing for 25 msec for each room based on the TDM, as shown in Fig. 3. Moreover, the round-robin algorithm was mainly used to minimize the number of send/receive ports at the main unit. As observed in the upper section of Fig. 3, the processing device allocated for the main unit is configured within only two ports, one for the UDP receiver and the other for the UDP transmitter terminal. Hence, the processing is performed sequentially. This indicates that a complete processing cycle of all eight rooms requires 200 msec since each takes 25 msec, leading to reducing congestion and network traffic, which we discuss in Section 4.2.

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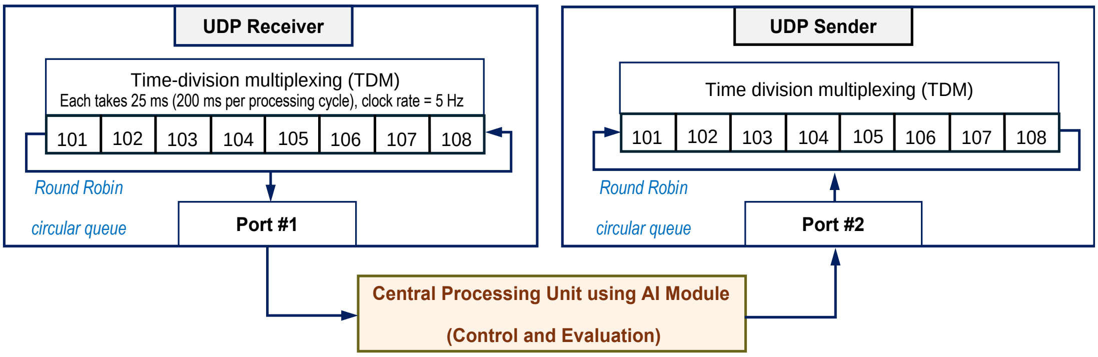

Main Unit Send and Receive Processes

Room #	UDP Sender	UDP Receiver
Room 101	Port #1	Port #2
Room 102	Port #1	Port #2
Room 103	Port #1	Port #2
Room 104	Port #1	Port #2
Room 105	Port #1	Port #2
Room 106	Port #1	Port #2
Room 107	Port #1	Port #2
Room 108	Port #1	Port #2

Rooms and their port numbers for the sender and receiver

Figure. 3 UDP protocol illustrates data transmission and reception with the round-robin scheduling algorithm, while the lower part depicts port numbers for each room

On the other hand, the lower part of Fig. 3 shows the required number of ports, where each room requires a device with two ports (port #1 and #2) for data transmitting and receiving. Therefore, 16 ports are assigned to the building scenario with eight rooms. Furthermore, to improve the processing speed of the AI module and allow it to perform the input vectors of the eight rooms faster, the main unit TX/RX channel is configured with 16 ports, where 8 ports are assigned for receiving data from all rooms concurrently and the other 8 ports configured for sending control vectors to the rooms for smart driving of rooms' appliances. This design is further discussed in Section 3.4.

3.3 Logic Encryption and Decryption Circuits

Sending data over a cloud-sharing service necessitates securely transmitting. Therefore, to improve network security and prevent unauthorized activities of a potential attack from corrupting the plaintext, i.e., data integrity of transmitted packets, the data is encrypted through the developed logic-based encryption approach. Fig. 4 illustrates the circuits used to encrypt and decrypt the input signals, represented in a 1D array (vector). The 32-bit received from the encoder circuit, discussed in Section 3.2, is encrypted via a bitwise operator (Exclusive-OR) with 32-bit random numbers known by both encryption and decryption circuits at the rooms and the main unit. Then the encrypted data is converted from an unsigned byte to a string to be combined in a single packet. After that, an aggregation and reordering circuit is utilized for another level of encryption using two encryption keys scramble along with 4 strings, thereby generating an encrypted packet represented by 6-byte ciphertext. The packet is sent from Room$_i$ to the main unit to check the status of the room under monitoring and send back control signals. The ciphertext is scrambled information that can only be processed by the system while it is unreadable to general users, thus preventing any compromise of precious data. Notice that the conversion between unsigned byte and string is mainly performed in the encryption/decryption process.

A symmetric encryption technique is utilized, in which the same key is used at rooms for encryption and the main unit for the decryption of input and control signals. Similarly, another key is used at the main unit for encryption and at rooms for decrypting the settings control vector. This process expedites the data processing since all control signals are processed concurrently. Furthermore, the string keys are stored in a 1D array that contains 20 keys. To increase the robustness of encryption, we modify the scrambling keys by selecting 2 keys out of 20 every hour, thus maintaining a more complicated encryption approach, which we discuss in Section 3.5.

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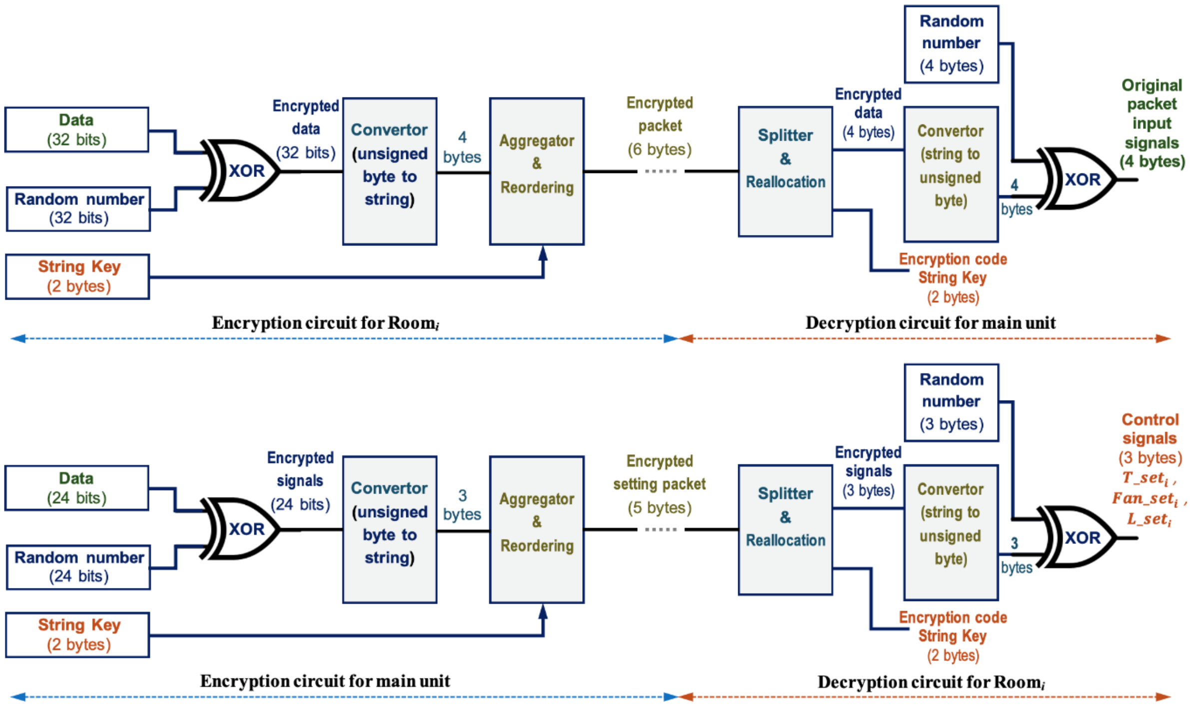

Figure. 4 Circuit schematic for encryption and decryption processes at Room$_i$ and main unit

Fig. 4 illustrates the encryption and decryption circuits at ROOM$_i$ and the main unit. As observed, the circuit diagram for the main unit encryption/decryption, Fig. 4 (upper right and lower left), is the same as for that of the rooms, Fig. 4 (upper left and lower right), except for the number of bits here is different since the main unit sends three control signals (T_set$_i$, Fan_set$_i$, and L_set$_i$). Therefore, 3 bytes are encrypted bitwise with another 3 bytes that represent random numbers defined by both the rooms and main unit. Meanwhile, the string key is utilized for further encryption of the generated strings via the shuffling process that involves scrambling and reordering.

3.4 Proposed AI Module

The proposed AI module is designed to optimize building operations while making real-time decisions that improve energy efficiency. The upper part of Fig. 5 illustrates the structure of the proposed AI module. The module consists of two main stages, including pre-processing and control. The pre-processing phase is used to check whether individuals exist in the monitored room or not. While the control stage is utilized to provide accurate wide-range decisions, which are made based on a well-defined Multi-Input-Multi-Output (MIMO) fuzzy logic controller to perform vector processing. This is due to the system involving examining multiple inputs and producing multiple output signals based on the fuzzy rules. The MIMO controller is designed to provide explicit decisions, making it suitable for integration into complex systems where the context is unclear or ambiguous. Moreover, the fuzzy logic controller was mainly developed to provide centralized control of the rooms to increase the response time to IoT-based units and improve processing accuracy. In the preprocessing phase, the module first performs pre-processing based on the received motion detection signal (M_i). Notably, the motion detection signals of the primary (PD_i) and secondary (SD_i) diagonals of room-ith were bitwise summed using an OR-logic operation ($M_i = PD_i + SD_i$), shown in Fig. 1, to determine whether individuals existed in the scanned room. In the case of a person in the room, either both input signals become logic '1' or one of them, i.e., the primary or secondary diagonal. Therefore, the 2-to-1 multiplexer circuit passes the received vector of linguistic variables to the MIMO Fuzzy Logic controller, otherwise, it turns OFF appliances, such as spotlights and fans of the cooling system. Thus, the encoding approach based on the mux circuit assists in reducing the width of the state-holding register and the computing complexity of the controller, processing three input singles (3 unsigned bytes) rather than manipulating four signals. The output of the controller is a control vector involving three setting signals (T_set$_i$, Fan_set$_i$, and L_set$_i$), which represent the control signal of the temperature, fan speed, and the number of spotlights in the ON state for room-ith, respectively.

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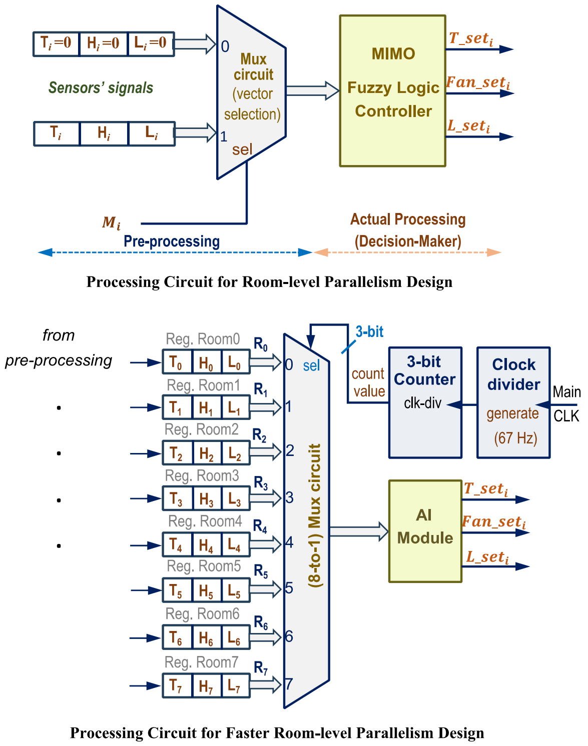

Figure. 5 Circuit schematic of the proposed AI module. (Upper) room-level parallelism, (lower) faster room-level when all rooms send data packets simultaneously

On the other hand, the lower portion of Fig. 5 shows the circuit schematic of design organization for faster room-level parallelism when all rooms send environmental signals to the main unit simultaneously to provide faster processing. In this configuration, the RRS is replaced within an 8-to-1 MUX circuit and a clock divider, the latter is used to generate a custom clock rate. The input of the multiplexer circuit is eight registers, each with a 3-byte width. While the selection is taken from a counter with a range of 0 to 7, which counts based on a generated clock rate of 67Hz so that it passes a data packet from a room register to the AI module every 15 msec. In this case, the RRS algorithm is replaced with logic multiplexing to provide fast execution time, achieving a speedup of 40% compared to the design of our approach with RRS. However, this speed improvement is achieved at the expense of requiring a higher number of transmitting/receiving ports at the main unit, i.e., 16 ports are used at the main unit versus 2 ports in the case of employing the RRS. Likewise, it incurs higher register transfer level resources, we further discuss this in Section 4.2.

3.5 Keychain Generation

Utilizing a single key for encryption and decryption processes reduces the complexity of operations to allow seamless and rapid data encryption and decryption. Nevertheless, it is imperative to maintain the key itself secure in case it becomes compromised. This is crucial because if the key is hacked, hackers access the original input data signals obtained from sensors, they can then send malicious control signals. Consequently, it is essential to maintain the keys changed frequently.

The circuit depicted in Fig. 6 (a) for the keychain process illustrates the modification process of changing the key hourly. It loads a new keychain from a 1D array containing 24 elements (keys). Key1 is selected based on the iteration value of the for-loop, whereas key2 is indexed by the loop iteration value plus the control value for further shuffling of the selection process. A timer-set with a delay of 36×10^5 msec was used to increment the loop iteration every hour. Interestingly, when the synchronization of generating a new key becomes disrupted for a specific period of time, for instance, 1 sec, a new packet will be sent every 25 msec. This indicates that within 1 sec, there will be 40 instances of unknown encrypted data packets being received. After that, the new modified key becomes known for all rooms and the main unit, thus the synchronization will resume correct operations for the next received data packet, i.e., the (41st) data packet.

The graphical programming of the AI module is shown in Fig. 6 (b) for AI module. As observed, the upper portion represents the decryption and decoding processes. First, the received ciphertext is split into four strings, each representing an IoT-based signal. They are then decrypted using logic decryption with Exclusive-ORs and passed to the MIMO fuzzy controller. When no individual is in the monitored room, the value 99 is used to indicate absence and send zeros to the controller. The lower portion of Fig. 6 (b) AI module depicts the MIMO fuzzification and defuzzification processes. These are followed by the encoding and encrypting of the control signals for the room being monitored.

Furthermore, the top section of Fig. 6 (c) for room 101 shows the process of encoding and encrypting signals from the IoT-based sensors in room 101, which are then transmitted as an encoded-encrypted vector to the main unit over the UDP protocol. For each room, two-channel ports are assigned for Transmit (TX) and Receive (RX), for instance, room 101 has the port numbers 61512 and 61513, respectively. Meanwhile, the bottom section depicts the received control packet used to alter the operation of appliances in the monitored room.

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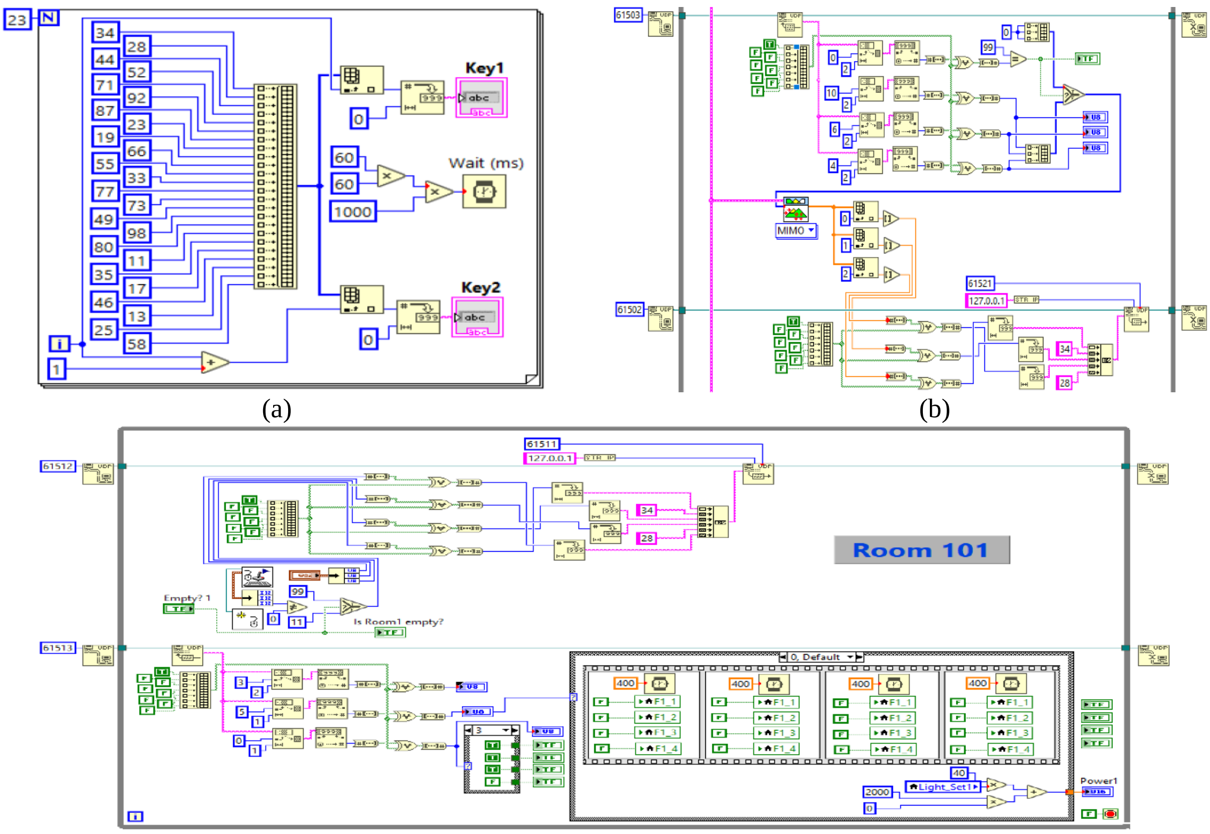


Figure. 6 LabVIEW block diagram for the proposed power-saving system. Note that only the processing circuit for room 101 is shown, thus there are seven other processing circuits: (a) Keychain generating process, (b) AI module, and (c) Encoding-based process for room 101

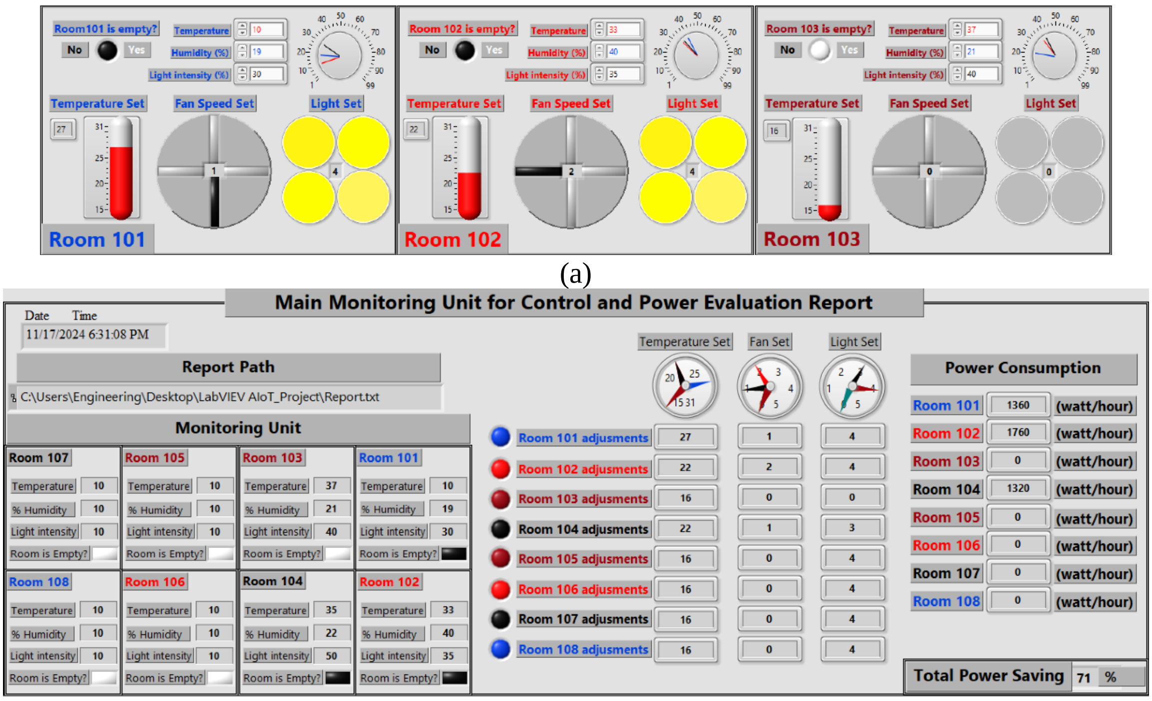
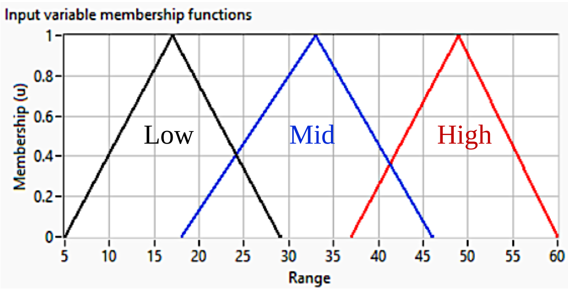
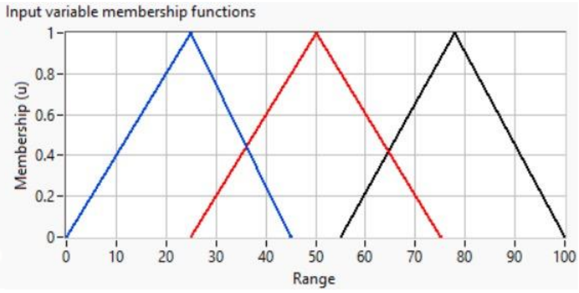


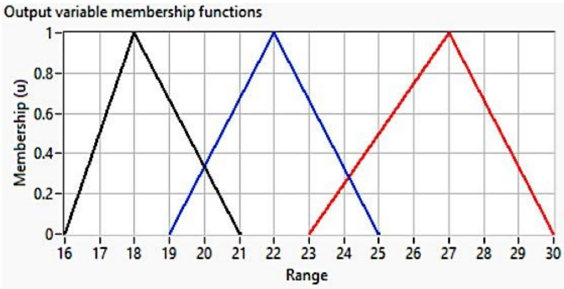
Figure. 7 Front panel for the GUI monitoring of rooms 101 through 103 and main unit monitoring for control and power-saving simulation report: (a) GUI monitoring for rooms 101 to 103 and (b) Main unit GUI monitoring



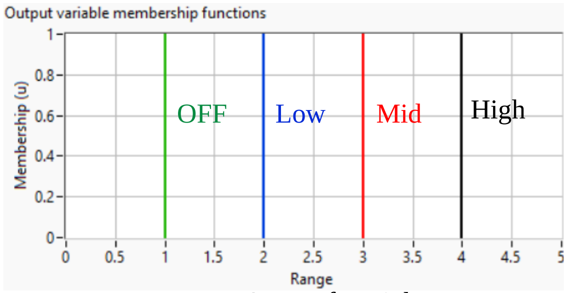
Input for Temperature



Input for Light



Output for Temperature



Output for Light

Figure. 8 Fuzzy membership functions for input and out of temperature and light

3.6 LabVIEW monitoring design

In this section, we discuss the developed GUI for the proposed power-saving and monitoring system used for smart buildings. The upper part of Fig. 7 illustrates the indicators and the graphical representations that show the temperature degree, fan rotation speed, status of spotlights, and room status to indicate whether an individual exists or not. Notice that we only show the graphical programming of three rooms out of eight. While in the lower part of Fig. 7, we show the main unit monitoring and power consumption evaluation of all rooms. As observed, the left side depicts the sensed values from the sensors for each room, in the middle, the control signals are illustrated for the eight rooms. Finally, the right side lists the power consumption (watt/h) per room and the total saving power, which we discuss in detail in the next section. Additionally, the system provides excellent transparency in the monitoring process, allowing end-users to operate the LabVIEW front panel without needing to understand the back-end programming. This user-friendly graphical interface simplifies interaction between the back-end and front-end. Thus, the proposed system features a distributed architecture that offers favorable advantages, including scalability, which enables it to be deployed in larger buildings. Furthermore, it improves security by encrypting and decrypting data packets transmitted between client computers in individual rooms and the main server unit.

4. Results and discussion

Here, we evaluate the performance of the proposed method. Extensive experiments and simulations are conducted to evaluate the performance of the proposed AI-based controller in terms of power consumption saving. The system generates a daily evaluation report that analyzes the distribution of consumed power across the AC fans and spotlights (bulbs) in each room. Note that the experimental results were obtained only for a single room by connecting the sensors to a PCI-6250 data acquisition card (NI DAQ), whereas the evaluation for eight rooms was performed using LabVIEW simulations as in [14]. Table 1 lists the home appliances and their specifications applied in the conducted LabVIEW simulations. Each room comprises an Air Conditioner (AC) of 2 KWh and four spotlights, each with 40 Wh. Thus, the potential maximum power consumption per room is 2.16 KWh, and 17.28 KWh for the building when all installed appliances turn on with maximum settings. Eq. 7 expresses the formula for determining the minimized power consumption.

$$P_{light\_AC}(t) = \sum_{i=0}^{N} P_{L_{set_i}}(t) + P_{Fan_{set_i}}(t) \quad (7)$$

Where $P_{L_{set_i}}(t)$ and $P_{Fan_{set_i}}(t)$ is equal to $(L_{set_i} \times 40)$ and $(Fan_{set_i} \times 2000)$, respectively. Also, N represents the number of rooms in a smart building. Also, to evaluate the achieved percentage of power-saving, Eq. 8 is used, where the P_{max} and P_{light_AC} represent power consumption without and with employing the proposed smart automation system, respectively.

$$Power\_saving = \left(\frac{P_{max} - P_{light\_AC}}{P_{max}}\right) \times 100\% \quad (8)$$

Likewise, the speedup was evaluated based on Eq. 9 by considering the response time (RT) of each system configuration.

$$Speedup = \left(\frac{RT_{base\ sys} - RT_{proposed\ sys}}{RT_{base\ sys}}\right) \times 100\% \quad (9)$$

Where $RT_{base\ sys}$ indicates the response time of the conventional design of serial data sending and $RT_{proposed\ sys}$ denotes the response time of the proposed system. Moreover, for the MIMO fuzzy controller, the membership functions are triangular functions with three ranges (Low, Mid, and High). Fig. 8 illustrates the fuzzy membership functions for input/output of the temperature and light. The setup environmental parameters are temperature (°Celsius) and humidity (%).

4.1 Power consumption evaluation

Here, we evaluate the proposed system in terms of potential power-saving while maintaining comfortable environmental conditions. As shown in Table 2, extensive experiments and simulations were conducted to analyze power consumption in a smart building with eight rooms. The minimum power reduction per hour for rooms was 22.22%, considering there is no empty room (first row). However, under the same environmental conditions, the system realizes improved power reduction since it turns off unnecessary appliances in empty rooms. In this context, the power-saving improved by 9.72% when one room turns all appliances off for one hour. When there are five to six empty rooms, the proposed power-saving approach achieves roughly 85% reduction in power consumption. Additionally, to maintain an appropriate temperature degree in each room, the system continuously monitors the building in real-time and adjusts the operation of air conditioning as needed on an hourly basis. Overall, on average, our proposed architecture achieves 52.6% energy-saving during specific hours of operations (12 hours) within a 24-hour period. This confirms the effectiveness of the proposed power-saving system for smart buildings. Furthermore, we tested the system under various operational scenarios, including periods when individuals were present in the building and when they were absent. Thus, operating the system for extended hours, including nighttime, would likely lead to a further reduction in power consumption.

Table 1. Setting parameters of power consumption calculation for installed appliances.

Fan Set	Light Set	Power Consumption	Status
0	0	0	Room is empty
0	1-to-4	0 + Light_Set × 40	AC is OFF
1	1-to-4	1200 + Light_Set × 40	$Fan_{set} = 1$
2	1-to-4	1600 + Light_Set × 40	$Fan_{set} = 2$
3	1-to-4	2000 + Light_Set × 40	$Fan_{set} = 3$

Table 2. Evaluation of power-saving considering different environmental conditions and times.

Date	Time	Temperature (°C)	Humidity (%)	Light Intensity (%)	# of Empty Rooms	Power consumption (KWh)	Power saving (%)
3-Oct-24	1:00 PM	45	20	90	0	13.44	22.22
3-Oct-24	2:00 PM	43	20	90	1	11.76	31.94
3-Oct-24	3:00 PM	41	23	90	2	10.08	41.67
3-Oct-24	4:30 PM	38	25	80	3	8.4	51.39
3-Oct-24	5:30 PM	30	25	50	0	10.56	38.89
3-Oct-24	6:30 PM	29	25	50	2	7.92	54.17
3-Oct-24	7:30 PM	29	26	40	4	5.28	69.44
3-Oct-24	8:30 PM	28	27	35	6	2.64	84.72
4-Oct-24	9:00 AM	37	30	60	0	10.24	40.74
4-Oct-24	10:00 AM	38	29	60	1	8.96	48.15
4-Oct-24	11:00 AM	39	28	62	3	6.4	62.96
4-Oct-24	11:30 AM	40	28	63	5	2.56	85.19

Table 3. Comparison of the implemented design configurations for the proposed system architecture.

Design Configuration	**Register Transfer Level**				**Execution Time (msec)**	**Speedup (%)**
	MUX (2-to-1)	**MUX (8-to-1)**	**# of Registers (byte)**	**XOR (2-input)**		
Design #1 serial implementation (conventional)	–	–	127	256	320	baseline
Design #2 (Room-level Parallelism)	24	–	212	896	200	37.5
Design #3 (Faster-Room-level Parallelism)	192	24	233	896	120	62.5

Table 4. Bandwidth comparison of the implemented design configurations.

Design Configuration	**Network Bandwidth and Ports**						**Packets reduction per cycle**	**Ports overheads (%)**
	# of Packets per cycle		**Packet width**		**# of Ports**			
	send	**receive**	**TX**	**RX**	**TX**	**RX**		
Design #1 serial implementation (conventional)	32	32	3-byte	3-byte	9	9	baseline	baseline
Design #2 (Room-level Parallelism)	8	8	6-byte	5-byte	9	9	3x	–
Design #3 (Faster-Room-level Parallelism)	8	8	6-byte	5-byte	16	16	3x	77.77

Table 5. Comparison of power-saving features between the proposed architectures and selected prior work for smart building automation systems.

Method	**Methodology Characteristics**		**Power Consumption (KWh)**		**Power saving (100%)**
	Processing Approach	**# of users/rooms**	**Regular**	**Optimized**	
SECS [26]	SmartCom Architecture	4	62.5	40.4	35.36
HEMS [14]	Raspberry Pi (linear programming)	4	78.5	60.34	23.13
Smart Load Simulator (SLS) [27]	HVAC system	4	27.4	13.97	49
Smart classroom [24]	ML Algorithms	1	11.31	6.84	39.52
Proposed Design #2 (Room-level Parallelism)	Encoding-based Architecture	8	17.28	8.19	52.6
Proposed Design #3 (Faster-Room-level Parallelism)	Encoding-based Architecture	8	17.28	8.19	52.6

4.2 Design evaluation at register transfer level

In this section, we evaluated the proposed approach in terms of register transfer level (RTL), number of ports, and packet width for the TX/RX channels. To evaluate the proposed encoding-based architecture at the register transfer level (RTL), we synthesized the circuit schematics for three configurations: the conventional design (baseline), room-level parallelism, and faster room-level parallelism. The synthesis was performed using Nexys Artix-7 (100T) FPGA platform from Xilinx with the Vivado Design Suite 2023.2 as the Integrated Development Environment (IDE). The baseline design adapts the conventional concept of serially scanning the rooms and sending each IoT-based sensor signal to the main unit for processing, which we consider the baseline design. Thus, this design does not necessitate implementing the encoding-decoding for the data packet since each sensor's signal is transmitted individually. Each data packet takes 10 msec processing time, thus each room requires 40 msec, and the overall processing time for a building within eight rooms is 320 msec. The room-level parallelism architecture, which uses round-robin scheduling for serially scanning and controlling the room conditions, involves parallel reading and controlling the sensors' signals at room level with 200 msec processing cycle time, each room takes 25 msec.

On the other hand, the third design configuration involves parallel processing at the room level as well, however, it provides a faster processing cycle (120 msec) since the RRS is not required in this configuration. Moreover, this design demands allocating two ports for each room at the main unit so that each room can send its sensors' conditions to the main unit for processing and receive its corresponding setting signals through the assigned ports. Table 3 lists the RTL resource utilization, execution time, and speedup for each design configuration. In terms of hardware resource utilization, our proposed design that employs RRS incurs a comparable RTL for register count and XOR gates to that of design #3. However, it incurs only 24 (2-to-1) mux circuits compared to 192 for design #3. Besides, the third design necessitates using 24 (8-to-1) mux circuits with eight 1-byte width registers to allow receiving multiple sensors' signals concurrently. Another advantage of design #2 over #3 is that it requires only assigning two ports for TX/RX at the main unit instead of 16 ports. Meanwhile, it achieves a speedup of 37.5% compared to the baseline design. Design #3 offers the best speedup (62.5%), but it incurs the highest design overheads in terms of RTL resources and the number of ports. Furthermore, Table 4 presents the specifications of the network bandwidth. As observed, our proposed design that leverages room-level parallelism (design #2) offers the best specifications in terms of the number of ports and sent/received data packets per monitoring cycle. Moreover, it achieves 3x reduction in the number of transmitted/received packets between the rooms and the main unit, but this was realized at the expense of using three and two extra bytes in the TX and RX channel packet width, respectively.

In Table 5, we compare our presented architecture to some recently published studies that aim to address power consumption in smart buildings through automated control systems. As observed, our proposed architecture achieves competitive power-saving. This demonstrates that the proposed encoding-based approach is an energy-saving technique that can provide a significant reduction in power consumption for customers by shifting high-energy appliances to non-peak times while ensuring user comfort. More importantly, most of the prior approaches focused mainly on energy efficiency while neglecting the investigation of system response time as well as the protection of data integrity of transmitted packets over the network. In contrast, our proposed framework architecture for room-level parallelism offers the best trade-off in terms of speed performance, power-saving, security, and design complexity. This is primarily attributed to the use of logic encoding-decoding along with low-complexity encryption-decryption approaches that facilitate seamless monitoring and secure controlling of all appliances installed in a room simultaneously.

In short, the achieved findings validate that the proposed power-saving system is effective in reducing power consumption. This is accomplished through the developed encoding-based architecture that utilizes a MIMO fuzzy-based controller with round-robin scheduling. Our controller enhances vector processing by accommodating more variability in inputs, thereby offering valuable flexibility in reasoning. Consequently, intelligent control signals are made to manage the operations of installed home appliances. Additionally, the system provides smart monitoring and assesses power consumption in real-time, allowing unnecessary appliances to be turned off when not needed with the aim of decreasing wasted energy and effectively distributing the generated power. More importantly, the proposed system utilizes an encoding and decoding method that enables distributed parallel processing for collaborative execution across multiple interconnected IoT devices installed in eight rooms to achieve an energy-efficient smart home automation system.

5. Conclusion

In recent years, IoT-based approaches have been extensively examined to provide energy efficiency and smart monitoring for a variety of realms, such as smart buildings, manufacturing processing, human activities, medical diagnosis and treatment, etc. In this paper, a real-time monitoring system for energy-saving smart buildings is proposed. The system utilizes IoT-based sensors that read environmental signals, such as collecting temperature, humidity, light intensity, and human existence based on motion detection sensors. These signals were first encoded in a single data packet, converted to string variables, encrypted within a modified keychain, and transmitted to the developed AI module for smart decision-making. The AI module involves a logic-based preprocessing step for linguistic variable reduction followed by a MIMO fuzzy logic-controlled that offers multiple thresholds to represent several logic values. The performance of the proposed energy-efficient system architecture was evaluated through extensive simulations, considering a smart building with eight rooms and a centralized processing main unit. The obtained findings demonstrate the effectiveness of the proposed AI module for IoT-based smart buildings by delivering an average power-saving of 52.6% compared to normal system operations. Considering the speed performance, the proposed architecture offers a speedup of 37.5% compared to the baseline sequential implementation that involves transmitting a single string of input data of a room each time. This confirms that integrating data encoding-decoding with the fuzzy-based controller achieves improved speed performance cooperation among the IoT-based units. Moreover, compared to the baseline configuration, the proposed system with round-robin scheduling utilizes acceptable register transfer level (RTL) resources necessary for encoding, decoding, encryption, decryption, and state holding of the sensed data signals. In summary, the proposed architecture can potentially support energy-efficient systems by offering centralized processing for improved decision-making, thereby assisting in preventing undesired power consumption and distributing the generated power more accurately.

Conflicts of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, methodology, software, validation, formal analysis, investigation, resources, and data curation have been implemented by both authors. Writing-original draft preparation, writing-review and editing, visualization, Supervision, and project administration have been implemented by the first author.

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