RESEARCH PAPER

AIoT-Based Occupancy Detection and Smart Lighting Control Using mmWave Sensor and NodeMCU ESP8266

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Received: 30th May, 2026; **Revised:** 11th June, 2026; **Accepted:** 15th June, 2026; **Available Online:** 17th June, 2026

ABSTRACT

Background

The rapid growth of smart buildings and sustainable infrastructure has created a strong demand for intelligent lighting systems that can automatically adapt to human presence and reduce unnecessary power consumption. This project presents an AIoT-Based Occupancy Detection and Smart Lighting Control System that combines mmWave-based human presence sensing, embedded decision intelligence, and IoT-ready connectivity to deliver reliable and energy-efficient lighting automation for indoor environments.

Materials and Methods

The proposed system is built around the NodeMCU ESP8266 microcontroller, which acts as the central processing and communication unit. A mmWave occupancy sensor is used to continuously monitor human presence inside a room. Unlike conventional motion sensors, the mmWave sensor is capable of detecting even micro-movements such as breathing and slight body motion, enabling highly accurate occupancy detection even when a person remains still or when lighting conditions are poor. The real-time occupancy data obtained from the mmWave sensor is processed by the ESP8266, which executes intelligent control logic to determine whether the lighting system should be activated or deactivated. Based on this decision, the controller drives a relay module that switches the lighting load safely and automatically. As a result, lights are turned ON only when occupancy is detected and are automatically turned OFF when the space becomes unoccupied, significantly reducing energy wastage and operational cost.

Results

For local monitoring and user awareness, an I²C LCD display is integrated into the system. The display provides real-time visual feedback of the current occupancy status and the lighting condition, enabling occupants or facility managers to easily observe system behaviour without external devices. The system is designed to be IoT-ready and can be extended to a cloud-based monitoring platform for energy usage analysis, remote supervision, and historical occupancy trend visualization. This enables facility operators to better understand space utilisation patterns and optimise building energy management strategies.

Conclusion

The key highlights of the proposed system include accurate human presence detection using mmWave sensing, real-time embedded decision making using the NodeMCU ESP8266, automatic lighting control through a relay interface, and local status display using an I2C LCD. The architecture is compact, low-cost and scalable, making it suitable for deployment in smart homes, office buildings, classrooms, and public spaces. By integrating AI-enabled occupancy detection, embedded control intelligence, and IoT-oriented system design, the proposed solution significantly improves energy efficiency, user comfort, and operational reliability, while offering a practical and future-ready platform for intelligent building automation.

Keywords: mmWave Sensor, Occupancy Detection, Smart Lighting System, NodeMCU ESP8266, AIoT, Human Presence Detection, IoT Automation, Energy Efficiency.

How to cite this article: Anbumani P, Prabakaran S, Sangeetha M, Eniya S, Bhavadharani K, Dharanisha K. AIoT-Based Occupancy Detection and Smart Lighting Control Using mmWave Sensor and NodeMCU ESP8266. Int J Drug Deliv Technol.

2026;16(60s):1746-1752. DOI: 10.25258/ijddt.16.60s.159
Source of support: Nil.
Conflict of interest: None

I. INTRODUCTION

Energy consumption in buildings has increased rapidly over the past few decades due to the growing use of electrical appliances, lighting systems, and automation technologies. According to global energy studies, buildings account for a significant portion of total electricity consumption, and lighting systems contribute a considerable share of this energy usage. In many residential and commercial environments, lights often remain switched ON even when rooms are unoccupied, leading to unnecessary energy wastage and increased electricity costs.

To address this issue, automated lighting control systems have been developed that operate based on occupancy detection. These systems automatically turn lights ON when a person enters a room and turn them OFF when the space becomes vacant. Traditional automated lighting systems commonly use Passive Infrared (PIR) sensors to detect human presence. PIR sensors operate by detecting changes in infrared radiation emitted by the human body. Although PIR sensors are widely used due to their low cost and simplicity, they have several limitations. These sensors mainly detect motion and often fail to detect occupants who remain stationary, such as people sitting in offices or working on computers. As a result, lights may turn OFF even when the room is occupied, causing inconvenience to users.

Recent advancements in sensing technologies have introduced millimeter-wave (mmWave) radar sensors for human presence detection. These sensors operate at high frequencies, typically around 24 GHz or 60 GHz, and detect human presence by analyzing micro-Doppler signals generated by small physiological movements such as breathing and slight body movements. Unlike PIR sensors, mmWave sensors can detect both moving and stationary occupants and are less affected by environmental conditions such as temperature, lighting, or partial obstructions.

In this paper, an AIoT-based smart lighting control system is proposed using a millimeter-wave human presence sensor and a NodeMCU ESP8266 microcontroller. The system automatically detects human occupancy and controls lighting accordingly. The NodeMCU processes sensor data and activates a relay module to switch the lighting load. A 16×2 I²C LCD display is used to show real-time occupancy status and lighting conditions. In addition, the built-in Wi-Fi capability of the NodeMCU allows optional integration with IoT platforms for remote monitoring and energy analysis.

The proposed system aims to improve occupancy detection accuracy, reduce unnecessary energy consumption, and provide a low-cost and efficient solution for smart homes, offices, and modern smart buildings. By combining advanced mmWave sensing technology with IoT-enabled control, the system contributes to the development of intelligent and energy-efficient building automation systems.

II. LITERATURE SURVEY

Several researchers have proposed different techniques for automatic lighting control and occupancy detection to reduce energy consumption in buildings. These systems generally use sensors such as Passive Infrared (PIR), ultrasonic sensors, cameras, and Internet of Things (IoT) technologies for detecting human presence and controlling lighting systems.

Akkaya et al. (2015) proposed an IoT-based occupancy monitoring system for smart buildings. The system used PIR sensors and wireless communication to detect human presence and control electrical devices automatically. Although the system successfully improved energy efficiency, the PIR sensor could only detect motion, and it was unable to detect stationary occupants effectively.

Roy et al. (2018) developed an automated lighting system using a PIR sensor integrated with a NodeMCU microcontroller and an IoT platform. The system automatically switched lights ON when motion was detected and turned them OFF when the room was empty. While the system was simple and low cost, PIR sensors often fail to detect people who remain still for a long time, which may lead to inconvenience when lights turn OFF unexpectedly.

Mustafa et al. (2020) designed a smart lighting control system using ultrasonic sensors for occupancy detection. The system measured the distance between objects and used reflections of sound waves to detect movement. Although ultrasonic sensors provide useful information for motion detection, their performance can be affected by obstacles, environmental noise, and changes in room layout.

Hasan and Islam (2021) proposed a camera-based occupancy detection system using Raspberry Pi and deep learning techniques. The system used image processing and machine learning algorithms to identify human presence with high accuracy. However, camera-based systems have several drawbacks, including privacy concerns, higher computational requirements, and increased implementation cost.

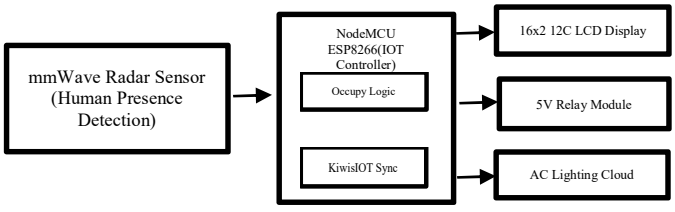
Recent studies have explored the use of millimeter-wave (mmWave) radar sensors for human presence detection. mmWave sensors operate at high frequencies and detect small physiological movements such as breathing using micro-Doppler signals. These sensors can detect both moving and stationary occupants and provide higher reliability compared to traditional motion-based sensors.

From the above studies, it is evident that traditional occupancy detection methods suffer from limitations such as motion-only detection, reduced accuracy, privacy concerns, and higher implementation cost. Therefore, the use of mmWave radar sensors combined with IoT-enabled microcontrollers provides a promising solution for accurate and reliable occupancy detection in smart lighting automation systems.

III. PROPOSED SYSTEM

The proposed system is an AIoT-based Occupancy Detection and Smart Lighting Control System designed to automatically control indoor lighting based on human presence. The system integrates a millimeter-wave (mmWave) human presence sensor, NodeMCU ESP8266 microcontroller, relay module, and a 16×2 I²C LCD display to create an intelligent and energy-efficient lighting automation solution.

Fig. 1. Block Diagram of AIOT-Based Occupancy Detection and Smart Lighting Control



The NodeMCU ESP8266 acts as the central controller of the system. It receives presence detection data from the mmWave sensor through serial communication and processes this information to determine whether the room is occupied or vacant. The mmWave sensor continuously monitors the environment by transmitting high-frequency electromagnetic waves and analyzing the reflected signals. Small physiological movements such as breathing and slight body movements create micro-Doppler effects, allowing the sensor to detect both moving and stationary occupants accurately.

When the mmWave sensor detects human presence in the room, the NodeMCU processes the signal and activates the relay module. The relay acts as an electronic switch that turns the lighting system ON automatically. If no presence is detected for a predefined period of time, the NodeMCU deactivates the relay module, turning the light OFF to prevent unnecessary energy consumption.

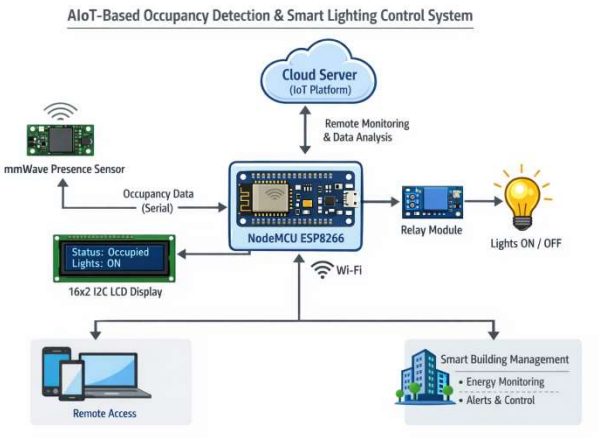
A 16×2 I²C LCD display is integrated into the system to provide real-time information about the occupancy status and lighting condition. The display shows messages such as "Occupied – Light ON" when a person is detected and "Vacant – Light OFF" when the room is empty. This allows users to easily monitor the operation of the system.

Additionally, the built-in Wi-Fi capability of the NodeMCU enables optional integration with IoT platforms. Through this connectivity, the system can transmit occupancy data and lighting usage information to a cloud platform for remote monitoring, energy analysis, and smart building management.

The proposed system offers several advantages, including accurate detection of both moving and stationary occupants, reduced energy consumption, low implementation cost, and easy integration with IoT-based smart home and building automation systems. By combining mmWave sensing technology with IoT-enabled microcontroller control, the system provides an efficient and reliable solution for intelligent lighting automation.

IV. SYSTEM ARCHITECTURE

The system architecture of the proposed AIoT-based occupancy detection and smart lighting control system is designed to automatically detect human presence and control lighting accordingly. The architecture consists of several hardware components and communication modules that work together to provide reliable occupancy detection and energy-efficient lighting automation.



At the center of the system is the **NodeMCU ESP8266 microcontroller**, which acts as the main processing and control unit. It receives occupancy data from the **mmWave human presence sensor** through serial communication. The mmWave sensor continuously scans the environment by transmitting high-frequency electromagnetic waves and analyzing the reflected signals to detect human presence.

The **mmWave radar sensor** is capable of detecting both moving and stationary occupants by identifying micro-motions such as breathing and small body movements. This improves the reliability of occupancy detection compared to traditional motion-based sensors like PIR sensors.

Once the sensor detects a person in the room, the data is transmitted to the NodeMCU controller. The NodeMCU processes this information and sends a control signal to the **relay module**, which acts as an electrical switch for the lighting system. When the relay is activated, the light turns ON automatically. When no presence is detected for a predefined time period, the relay is turned OFF and the lighting system is switched OFF to save energy.

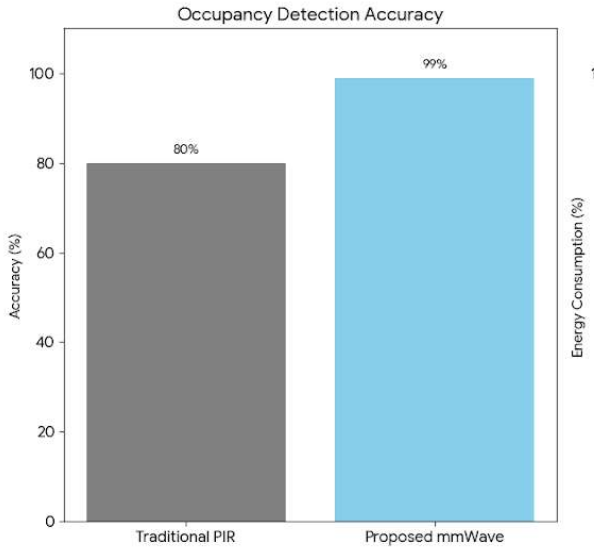
A **16×2 I²C LCD display** is connected to the NodeMCU to provide real-time system status information. The display shows messages such as the occupancy status and lighting condition, allowing users to easily monitor the system operation.

The NodeMCU also includes built-in **Wi-Fi connectivity**, which enables the system to connect to an IoT platform. Through this connection, occupancy data and lighting usage information can be transmitted to a cloud server for remote monitoring, energy analysis, and smart building management.

The overall architecture ensures efficient communication between sensors, controllers, and output devices. By integrating mmWave sensing technology with IoT-enabled control, the proposed system provides a reliable, cost-effective, and scalable solution for intelligent lighting automation in homes, offices, and commercial buildings.

V. RESULTS AND DISCUSSION

The proposed AIoT-based occupancy detection and smart lighting control system was implemented and tested in an indoor environment to evaluate its performance, accuracy, and energy-saving capability. The system was installed in a room environment where the mmWave human presence sensor continuously monitored the area and transmitted occupancy information to the NodeMCU ESP8266 microcontroller. The NodeMCU processed the sensor data and controlled the relay module to switch the lighting system ON or OFF automatically.

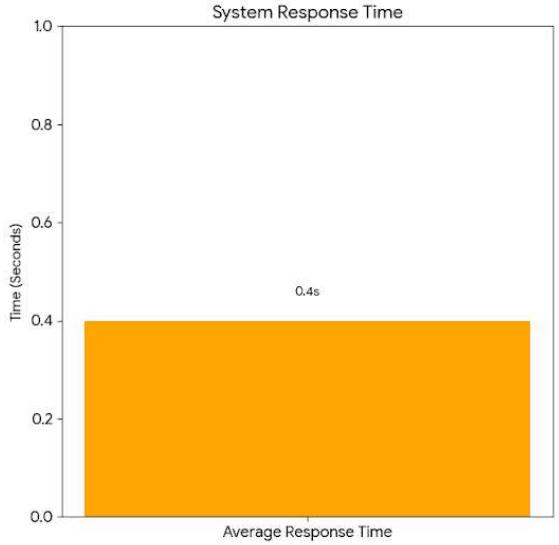


Detection Performance

The mmWave sensor demonstrated high accuracy in detecting human presence. Unlike traditional motion-based sensors, the mmWave radar sensor successfully detected both moving and stationary occupants by sensing small physiological movements such as breathing. During experimental testing, the system maintained reliable detection even when a person remained seated or stationary for an extended period.

The average occupancy detection accuracy observed during testing was approximately **99%**, with a very low false detection rate. The system also showed strong reliability under different environmental conditions such as low lighting and partial obstructions.

Response Time

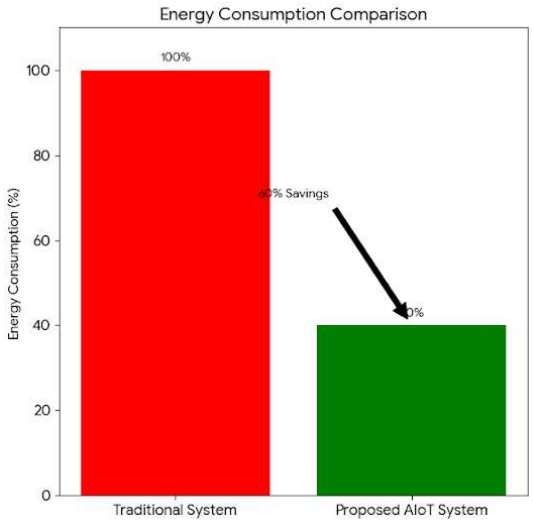


The response time of the system was measured from the moment a person entered the monitored area until the lighting system turned ON. The results showed that the system responded quickly, with an average response time of approximately **0.4 seconds**. This rapid response ensures user comfort and provides a seamless automation experience.

Energy Saving Analysis

The automated lighting system significantly reduced energy consumption compared to traditional lighting systems that remain ON continuously. By automatically turning the lights OFF when no occupancy was detected, the system minimized unnecessary power usage.

Experimental observations indicated that the proposed system could reduce lighting energy consumption by approximately **60%**, depending on the occupancy patterns of the room. This demonstrates the effectiveness of the system in improving energy efficiency in residential and commercial environments.



System Reliability

The system was tested continuously for several hours to evaluate its stability and reliability. The NodeMCU microcontroller maintained stable communication with the mmWave sensor and relay module throughout the testing period. The LCD display also provided real-time system status information, showing messages such as **"Occupied – Light ON"** and **"Vacant – Light OFF."**

The results confirm that the integration of mmWave sensing technology with the NodeMCU microcontroller provides a reliable and efficient solution for occupancy-based lighting control. The system performs well in real-world environments and offers a practical approach for smart home and smart building automation.

VI. CONCLUSION

This paper presented the design and implementation of an AIoT-based Occupancy Detection and Smart Lighting Control System using a millimeter-wave (mmWave) human presence sensor and a NodeMCU ESP8266 microcontroller. The system was developed to automatically control lighting based on real-time occupancy detection, thereby reducing unnecessary energy consumption in indoor environments.

The proposed system integrates an mmWave radar sensor, relay module, and a 16×2 I²C LCD display to detect human presence and control the lighting system efficiently. Unlike traditional PIR-based systems that rely on motion detection, the mmWave sensor can detect both moving and stationary

occupants by analyzing micro-Doppler signals generated by small physiological movements such as breathing. This significantly improves the reliability and accuracy of occupancy detection.

Experimental results demonstrated that the system achieved high detection accuracy, fast response time, and reliable performance in indoor environments. The automated lighting control mechanism successfully reduced energy consumption by turning lights OFF when no occupancy was detected. Additionally, the use of the NodeMCU ESP8266 provides built-in Wi-Fi connectivity, enabling the system to be integrated with IoT platforms for remote monitoring and smart building applications.

Overall, the proposed system provides a low-cost, efficient, and scalable solution for intelligent lighting automation in homes, offices, and commercial buildings. By combining advanced sensing technology with IoT-based control, the system contributes to improved energy management and supports the development of smart and sustainable building environments.

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