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IOT-ENABLED SEGMENTED CONTROL OF LED BATTEN FOR ENERGY EFFICIENT SMART LIGHTING APPLICATIONS

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Abstract: LED technology makes lighting systems ever more efficient; they sometimes lack fine-grained control over illumination zones, which causes energy waste. This work introduces a new segmented LED batten (LED tube lights) driven by a low-cost Wi-Fi microcontroller ESP8266 and a high-voltage, high-current Darlington transistor array controller ULN2803 IC under IoT technology. The eight independently controlled parts of the LED batten are reachable via a mobile- and web-based interface providing both ON/OFF and PWM-based dimming control. Unlike typical LED batten, which operates as a single unit, the suggested design splits the LED batten into eight separate segments, each capable of being separately controlled (on/off and dimming) using IoT and manually too. Based on real-time needs, users can dynamically choose the number and brightness of active segments, therefore saving a lot of energy compared to typical totally-on LED battens. Achieving up to 87% energy savings, experimental data confirms the efficiency of the technology. This scalable, low-cost, adaptable method provides a fresh route for intelligent, energy-efficient lighting solutions fit for commercial buildings and smart homes.

IndexTerms - **Smart Lighting; Segmented LED Batten; IoT-based Lighting Control; Energy Efficiency; ESP8266; Web-Based Control; Smart Home Automation; ULN2803 Driver.**

I. Introduction

Electric lighting accounts for a large portion of the world's energy use and significantly influences overall energy consumption [1]. Even with developments in LED technology, conventional lighting systems sometimes run in binary mode, either totally on or off—which results in significant energy loss. The Internet of Things (IoT) has given fresh chances to improve energy economy by means of smart lighting control [2]. Nevertheless, without intra-fixture segmentation, contemporary IoT-based lighting solutions mostly concentrate on dimming or scheduled control.

This work presents an IoT-enabled segmented LED batten that lets users turn on the desired portion of a single lighting source only. This method seeks to close a major gap in current smart lighting solutions by greatly lowering energy usage while preserving user comfort and flexibility.

II. RELATED WORK

Recent developments in smart lighting have incorporated IoT technology to create dynamic, user-responsive environments [3]. Systems including smart streetlights use ESP8266 modules for dynamic dimming depending on ambient conditions and mesh networking [4]. While addressable LED strips offer per-LED control, their typical purpose is ornamental rather than general illumination [5].

Reducing energy usage in commercial buildings has shown promise with occupancy-based lighting control systems [6]. Similarly, people often apply PWM dimming methods to efficiently adjust LED brightness [7]. On segmenting traditional white LED devices to create separate, user-driven illumination zones inside a single luminaire, less is known, nevertheless. Our approach especially helps to fit standard LED battens with segment-level control using web-based IoT interfaces.

III. METHODOLOGY

A. SYSTEM ARCHITECUTE

To achieve segmentation of LED batten, it Combines a Wi-Fi Microcontroller module, an array of Darlington transistors IC, and a segmented LED batten made of eight independently controlled parts, each comprising 15 LEDs which specifically includes following components:

- **LED Batten:** Analog LED batten divided into eight segments, each connected to a GPIO pin of the ESP microcontroller.
- **Microcontroller (ESP8266 - NodeMCU):** To manage wireless communication, the control logic and individual segments
- **ULN2803 Darlington array IC:** To drive each LEDs segment
- **Rotary Encoder:** For manual and wired operation which control power delivered to the segments.
- **User Interface:** Web-based interface for remote controls accessible through mobile or personal computer.
- **Power Supply:** A regulated power source ensuring consistent performance across all segments.

1) LED Batten

Usually, LEDs utilized in analog battens are 3-volt devices. Applying a 3-volt difference between the positive and negative ends of an LED will optimally light it up. Figure 1 shows each group of LEDs on an analog LED strip, the "building block." [8] [9] [10].

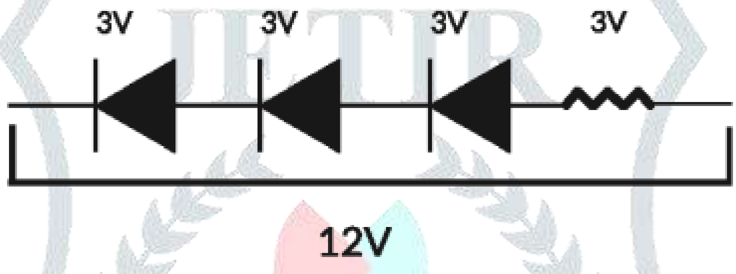

Figure 1 (a) Schematic view

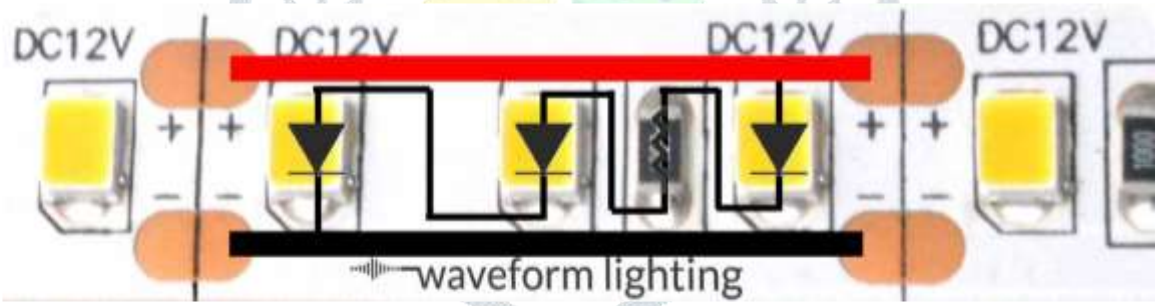

Figure 1 (b) Physical view overlaping schematic

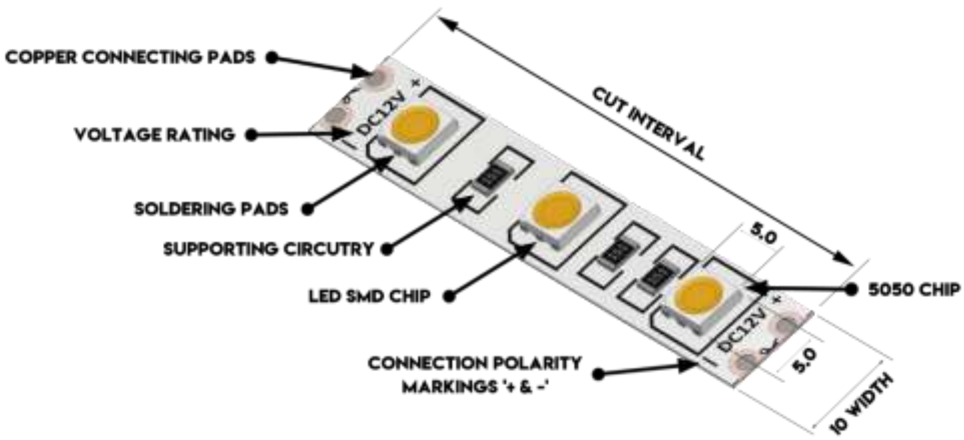

Figure 1 (c) Physical view (LED Strip Light Internal Schematic (Waveform lighting [10])

The specified voltage of an LED batten is primarily determined by:

a) The specified voltage of the LEDs and components used *b)* The configuration of the LEDs on the LED strip.

When LEDs are connected in parallel, the voltage remains the same but the current splits equally among each of the parallel circuits [9][10].

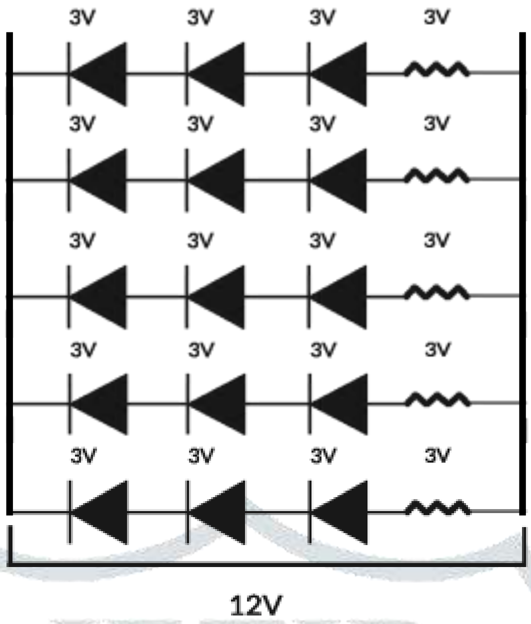

Figure 2 parallel configured analog LED strip clustered in group of 3 LEDs

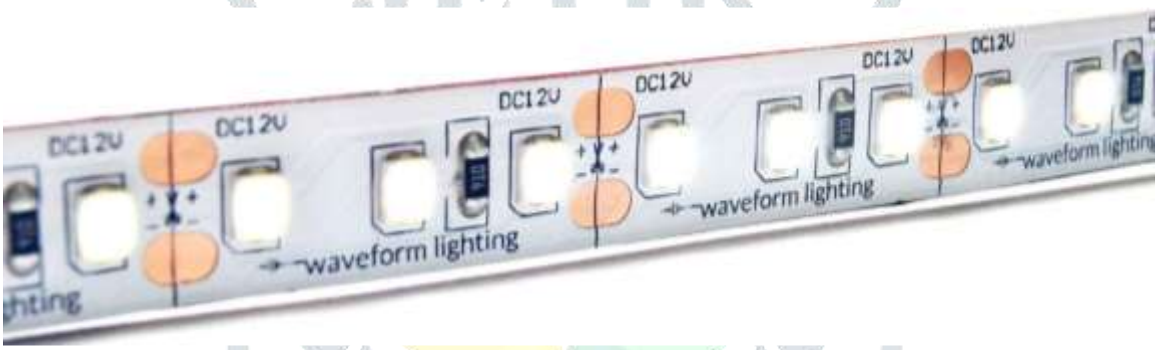

Figure 3 A typical segment of an analog LED batten

In the design, standard analog LED batten as shown in fig 3 is used, which is divided into eight distinct segments.

2) ESP8266 Wi-fi microcontroller

The ESP8266 is a low-cost Wi-Fi microchip with full TCP/IP stack and microcontroller capability, widely used in Internet of Things (IoT) applications. Developed by Espressif Systems, it allows microcontrollers to connect to a Wi-Fi network and make simple TCP/IP connections using Hayes-style commands. Its popularity among developers and researchers is largely due to its affordability, compact size, open-source community support, and compatibility with platforms like Arduino and Micro Python. The ESP8266 has been integral in enabling wireless connectivity in embedded systems, particularly in smart home automation, remote sensing, and wearable technology projects [11].

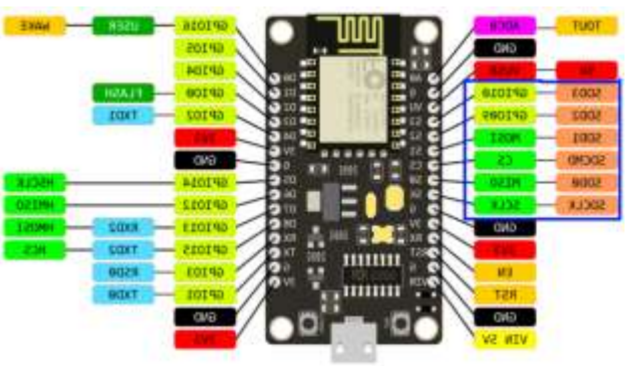

Figure 4 NodeMCU: ESP8266 Wi-Fi microcontroller Development Module

3) IC ULN 2893

The ULN2803 is a high-voltage, high-current Darlington transistor array IC commonly used for driving inductive loads such as relays, motors, and LEDs. It contains eight NPN Darlington pairs with common emitters and integral suppression diodes for inductive load driving, making it ideal for interfacing logic-level signals with higher voltage/current requirements. The ULN2803 is widely used in embedded systems and automation applications due to its ability to sink up to 500 mA per channel and operate at voltages up to 50V, providing a simple and effective solution for amplifying digital outputs from microcontrollers and other logic circuits [12].

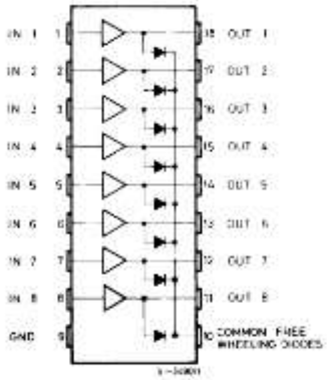

Figure 5 ULN2803 IC Pin connection diagram

4) Rotary Encoder

A rotary encoder is an electro-mechanical device that converts the angular position or motion of a shaft or axle into digital or analog signals, making it essential for applications requiring precise position, speed, or direction sensing. Rotary encoders are widely used in robotics, industrial controls, and consumer electronics for tasks such as menu navigation, motor control, and shaft feedback. They come in two primary types: incremental and absolute. Incremental encoders generate pulses that indicate movement, while absolute encoders provide a unique output for each shaft position. Their compact size, durability, and reliability make them a preferred choice for real-time rotational tracking in embedded and automation systems [13].

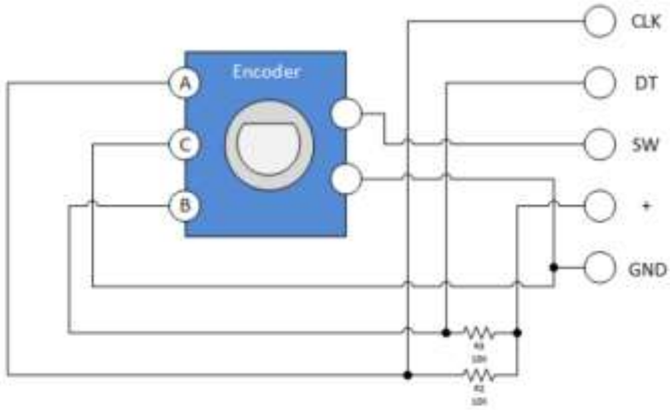

Figure 6 Rotary Encoder Connection Diagram

5) Power Supply

A 12V LED batten power supply is a constant voltage driver designed to convert high-voltage AC (typically 110V–240V) into a stable 12V DC output, suitable for powering LED batten lights. These power supplies are essential for ensuring consistent brightness, energy efficiency, and longevity of LED fixtures. They come in various configurations, including waterproof (IP67-rated) models for outdoor use, dimmable versions compatible with TRIAC or PWM dimmers, and compact designs for indoor installations. Key features often include over-voltage, over-current, and short-circuit protection, making them reliable for both residential and commercial applications [14].

B. Hardware Implementation

The circuit schematic shown in Figure 7 illustrates a lighting control system based on the ESP8266 NodeMCU, intended for the management of an LED batten divided into eight separately controlled segments. The ESP8266 microcontroller connects to a ULN2803 driver IC using its GPIO pins, which can handle the 12V power needed for each LED section. Each LED segment connects to a common 12V power source on the positive side, while their negative sides are separately routed through the ULN2803 outputs, enabling the ESP8266 to control the segments by creating a path to ground as needed. The circuit incorporates a rotary encoder for manual modification of LED segment states, providing an intuitive control technique that operates independently of Wi-Fi connectivity. The diagram shows a voltage regulator that lowers the 12V supply to a stable 5V, which is suitable for powering the ESP8266 board, ensuring that the microcontroller and its components work reliably.

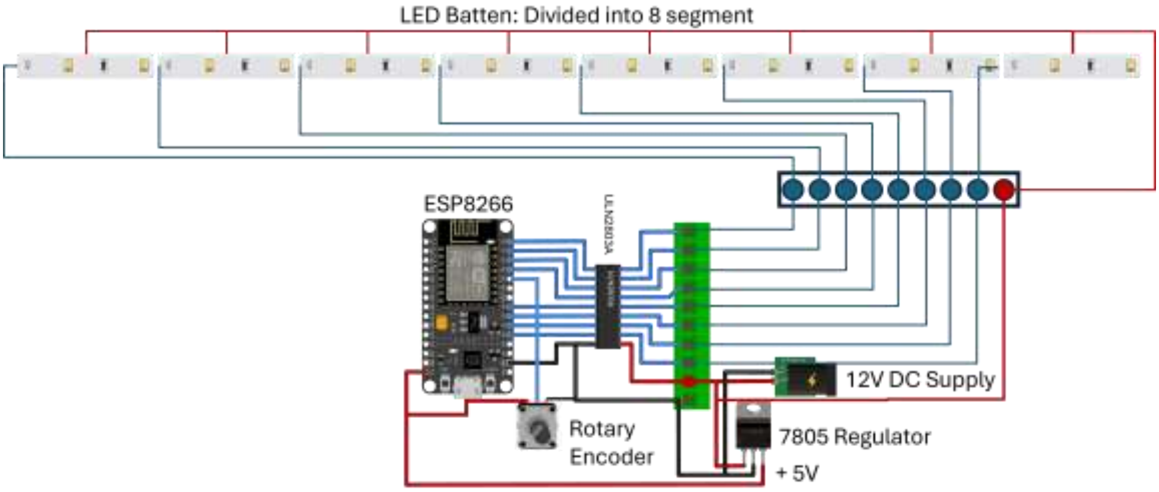

Figure 7 Experimental Setup

C. Software Implementation

Figure 8 illustrates the operational flow of the LED segment control system. Upon initialization, the system initially picks the control method, either by web-based interaction or manual operation using a rotary encoder. In web-based mode, the user can select between incremental control—utilizing a slider to adjust LED brightness or the number of active segments incrementally—or random mode, where a distinct button enables consumers to choose between basic ON/OFF functions or PWM-based brightness regulation. The system can also function manually using the rotary encoder to directly modify LED segments without reliance on a network. Regardless of the selected mechanism, the system executes commands to update segment states accordingly. Upon executing the directives, the system reverts to a state of readiness for further inputs, thereby guaranteeing ongoing responsive functionality.

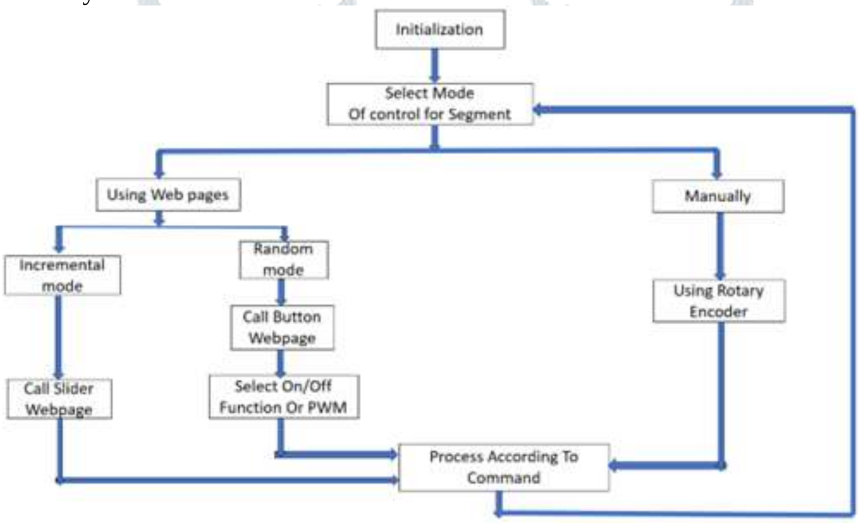

Figure 8: Flowchart of Hardware-Software Interaction

Figure 9: Web Interface - Button Control Page

Figure 10: Web Interface - Slider Control Page

IV. EXPERIMENTAL SETUP

Experiments were conducted in a controlled indoor environment with a stable 230V AC input. Power consumption was measured using a calibrated digital wattmeter across different segment activation scenarios. Response times were recorded using network timestamping and oscilloscope-based verification.

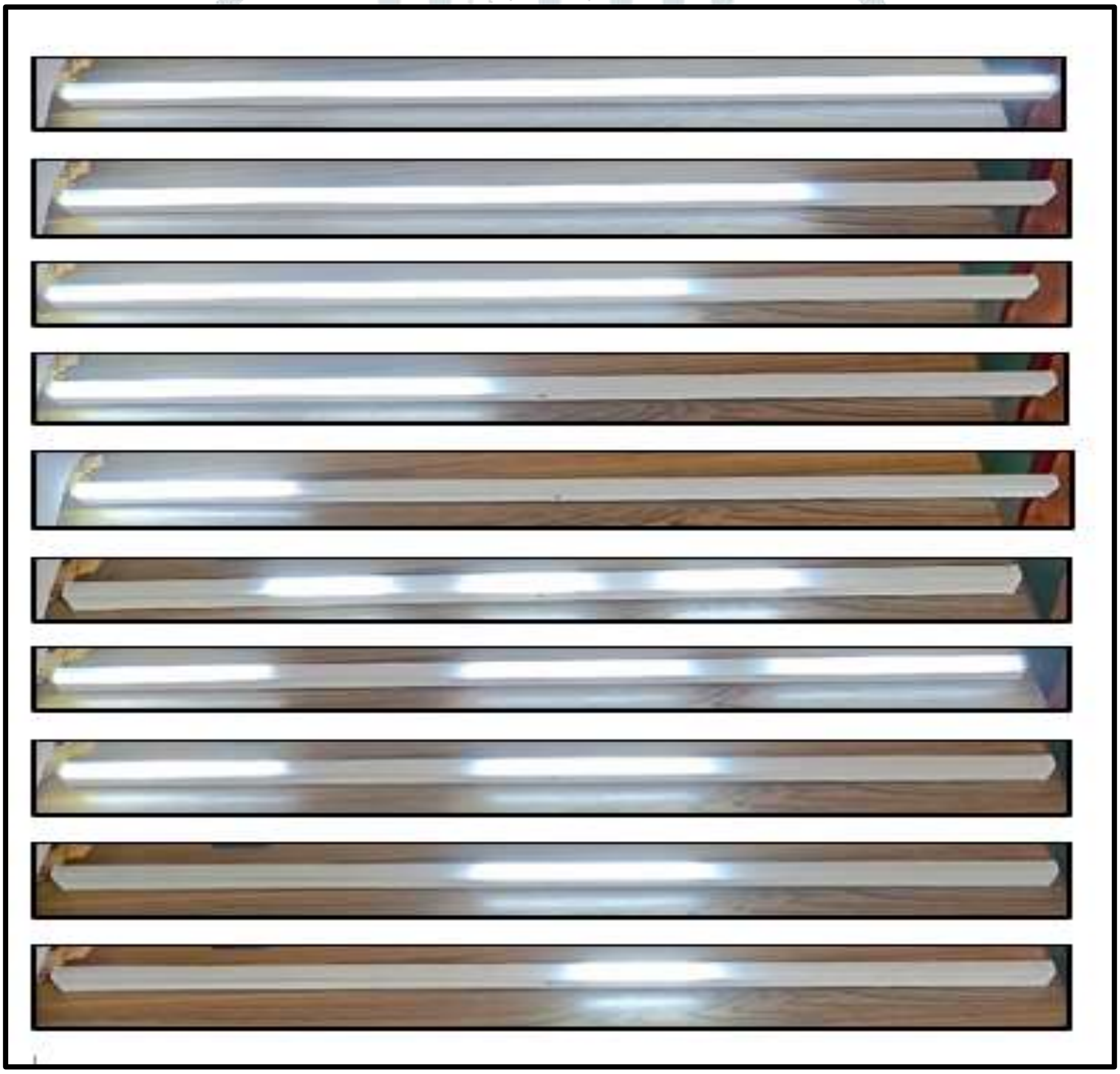

Figure 11: Lighting Pattern Under Various Segment Activations

V. RESULT AND ANALYSIS

5.1 Power Consumption Analysis

Table 5.1 demonstrates the correlation between the number of activated LED segments and the system's power usage. As the quantity of active segments escalates from 1 to 8, both current and power consumption increase proportionately. For example, with a single segment activated, the system draws 230 mA and consumes 3.45 W; however, with all eight segments activated, the current draw increases to 1330 mA and the power consumption rises to 19.95 W. This linear trend indicates that each additional segment progressively increases the total load, validating power consumption scales consistently with the number of lighted segments—crucial for creating energy-efficient lighting control systems.

Table 5.1: The experimental measurement for power consumption by each segment

Number of segments ON	current(mA)	Power Consumption (w)	Energy Saved (%)
1	230	3.45	82.71
2	437	6.555	67.14
3	599	8.985	54.96
4	749	11.235	43.68
5	892	13.38	32.93
6	1050	15.75	21.05
7	1192	17.88	10.38
8	1330	19.95	0

The data and graph reveal a nearly linear relationship between the number of active segments and total power consumption, validating the hypothesis that segmentation enables proportional energy savings.

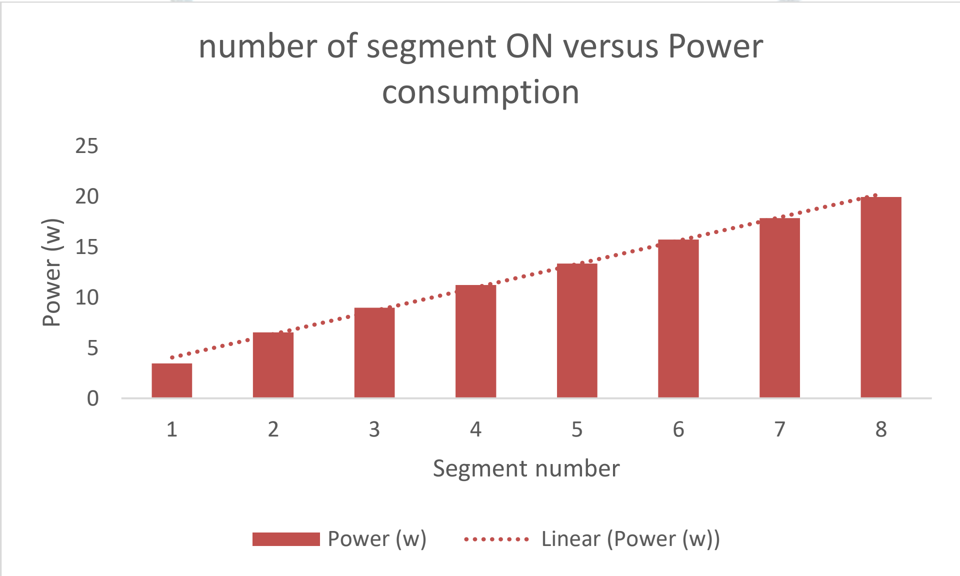

Figure 12 Number of segments ON versus power consumption

5.2 Response Time Performance

The system exhibited an average switching latency of approximately 150 ms under local Wi-Fi conditions and up to 1.5 seconds when accessed remotely over the Internet. This level of responsiveness is acceptable for smart home applications.

VI. DISCUSSION

The segmented LED batten offers a significant advancement over traditional lighting control methods. Unlike full luminaire dimming, segmentation provides spatial control, allowing users to light only the required portions of a room, thereby optimizing energy usage.

This approach can be further enhanced by integrating environmental sensors, such as motion detectors or ambient light sensors, to automate segment activation based on occupancy or natural light availability. Additionally, implementing low-power modes on the ESP8266 could further reduce standby energy consumption.

Potential limitations include the non-uniform illumination pattern when fewer segments are active, and the slight complexity added to the luminaire's wiring and control circuitry. Nonetheless, the energy savings and user flexibility benefits outweigh these minor drawbacks.

VII. CONCLUSION

This study presents a novel IoT-enabled segmented LED batten system that significantly enhances energy efficiency and user control in smart lighting applications. Experimental results confirm up to 87% energy savings with minimal latency, demonstrating the system's practical viability.

Future work will explore integrating machine learning algorithms for predictive lighting control and expanding the system to support multi-batten environments interconnected via IoT frameworks like MQTT.

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