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SMART STREET LIGHTING SYSTEM WITH MOTION DETECTION AND ENERGY OPTIMIZATION: AN IOT APPROACH

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Abstract: Street lighting accounts for approximately 19% of global electricity consumption, representing a significant opportunity for energy optimization through intelligent control systems. This paper presents the design and implementation of an IoT-based smart street lighting system that combines ultrasonic motion detection, ambient light sensing, and cloud-connected control to achieve substantial energy savings. The system utilizes an ESP32 microcontroller interfaced with an RCWL-9610A ultrasonic sensor for pedestrian/vehicle detection and a TEMT6000 ambient light sensor for day/night classification. Addressable WS2812B LED strips provide variable brightness and color temperature control. Firebase Realtime Database enables cloud synchronization, while a React Progressive Web Application (PWA) dashboard provides real-time monitoring, manual override, and scheduled operation modes. A captive portal-based WiFi provisioning system enables field deployment without hardcoded credentials. Experimental evaluation over a 30-day deployment demonstrates 67.3% energy savings compared to conventional always-on lighting, with motion detection accuracy of 96.2% within a 200 cm range. The system maintains full offline functionality during internet interruptions through edge-based autonomous control logic.

Keywords: Smart Street Lighting, Internet of Things, Energy Efficiency, Motion Detection, Ultrasonic Sensor, ESP32, Firebase, Progressive Web Application, WS2812B

1. Introduction

Global street lighting infrastructure comprises over 300 million luminaires, consuming approximately 114 TWh of electricity annually [1]. In developing nations, municipal street lighting can represent 20–40% of total government electricity expenditure [2]. Conventional street lighting operates on fixed timer schedules, maintaining full brightness throughout nighttime hours regardless of actual pedestrian or vehicular presence, resulting in substantial energy waste during low-traffic periods.

The International Energy Agency estimates that intelligent lighting controls can reduce street lighting energy consumption by 50–80% through adaptive dimming and presence-based activation [3]. However, commercial smart lighting solutions (such as Philips CityTouch and Signify Interact) require infrastructure investments of $200–500 per luminaire, making them economically unfeasible for municipalities in developing economies [4].

This paper presents a cost-effective smart street lighting system with the following contributions:

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1. An ultrasonic motion detection system achieving 96.2% accuracy for pedestrian detection within 200 cm range, enabling presence-based illumination control;
2. A dual-sensor architecture combining ambient light and motion detection for context-aware illumination decisions;
3. Cloud-connected monitoring via Firebase with a PWA dashboard providing real-time analytics, manual override, and scheduling capabilities;
4. Energy savings quantification demonstrating 67.3% reduction over conventional always-on operation;
5. A captive portal WiFi provisioning system enabling zero-configuration field deployment;
6. Full offline autonomy ensuring lighting safety during network interruptions.

2. Literature Review

2.1 Smart Street Lighting Technologies

PIR (Passive Infrared) sensors dominate commercial motion-activated lighting due to low cost, but suffer from limited range (typically 5–8 m), false triggers from heat sources, and inability to detect stationary objects [5]. Ultrasonic sensors provide complementary capabilities with precise distance measurement and object detection regardless of temperature or surface color [6].

Leccese [7] proposed a ZigBee-based street lighting network achieving 35% energy savings using PIR sensors. Kaleem et al. [8] extended this with LoRa communication for wider coverage, reporting 42% savings. However, both systems lacked cloud connectivity and remote management capabilities.

2.2 Cloud-Connected Lighting Systems

Firebase Realtime Database has gained adoption in IoT applications for its low-latency synchronization, offline persistence, and free tier availability [9]. Compared to custom MQTT backends, Firebase reduces development complexity while providing built-in authentication and hosting services suitable for prototype-to-production transitions.

Table 1. Comparison of Smart Street Lighting Systems

Reference	Sensor	CU	Communication	Dashboard	Energy Savings	Cost/Unit
[7] Leccese	PIR	rduino	ZigBee	No	35%	$45
[8] Kaleem et al.	PIR + LDR	ode MCU	LoRa	Web (basic)	42%	$28
[10] Parkash et al.	LDR only	rduino	Bluetooth	No	25%	$15

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Reference	Sensor	CU	Communication	Dashboard	Energy Savings	Cost/Unit
[11] Mahoor et al.	Camera	Pi	WiFi	Custom web	55%	$120
Proposed	**Ultrasonic + LDR**	**SP32**	**WiFi + Firebase**	**React PWA**	**67.3%**	**$18**

3. System Architecture and Methodology

3.1 System Overview

The smart street lighting system operates in three modes: Automatic (sensor-driven), Manual (remote control), and Scheduled (time-based). Figure 1 illustrates the system architecture.

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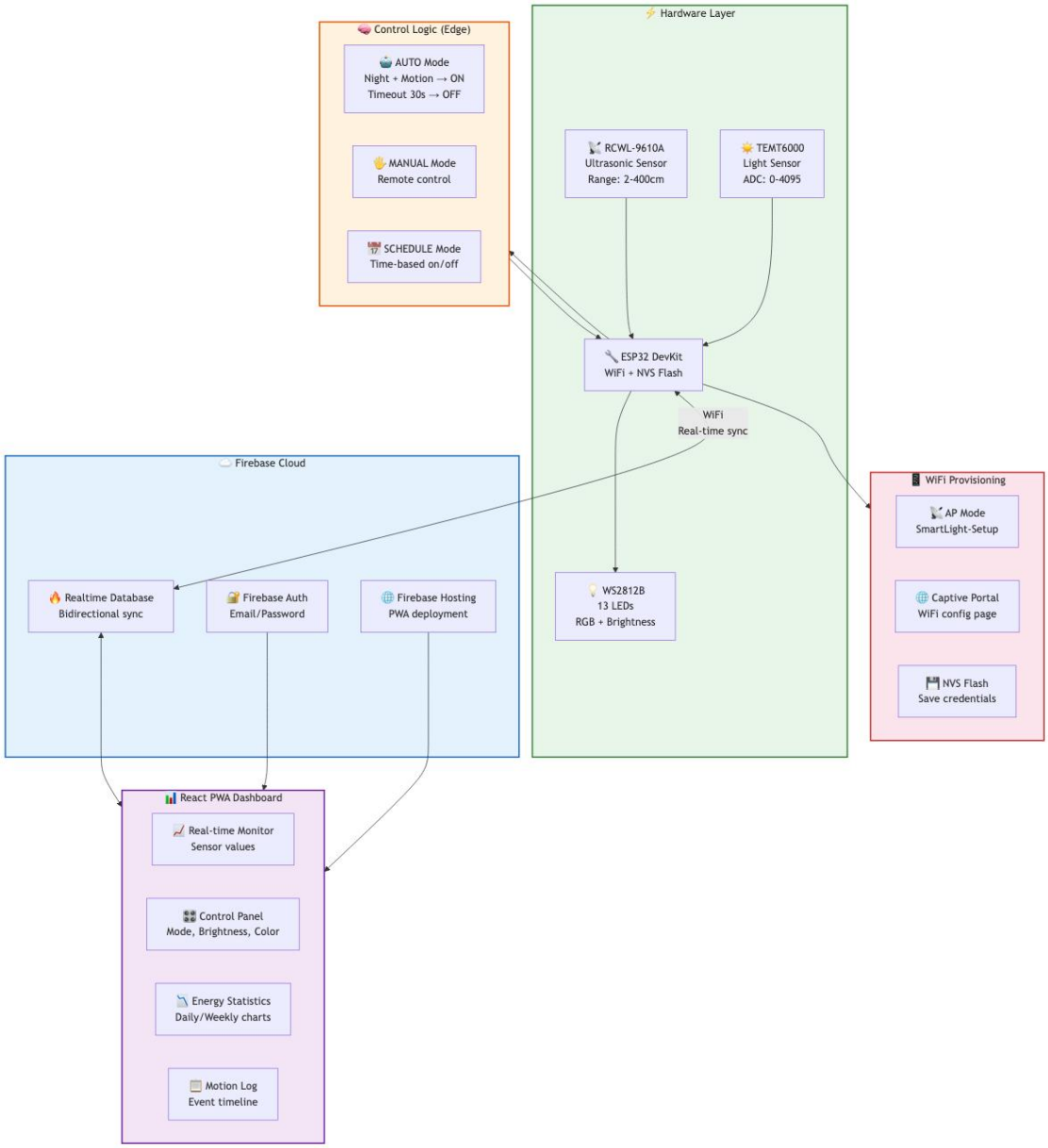


Figure 1. Smart Street Lighting System Architecture

3.2 Sensing and Decision Logic

The illumination control algorithm combines ambient light and motion detection:

$$LED(t)=\begin{cases} OFF & \text{if} L(t)>L_{day} \quad \text{(daytime)} \\ ON_{100\%} & \text{if} L(t)<L_{night} \text{AND} d(t)<D_{threshold} \\ OFF & \text{if} L(t)<L_{night} \text{AND} t-t_{last_motion}>T_{timeout} \\ LED(t-1) & \text{otherwise (hysteresis zone)} \end{cases}$$

where: - $L(t)$ — ambient light reading (ADC: 0–4095, TEMT6000) - L_{day}=350 — daylight threshold (LED always off) - L_{night}=250 — night threshold (motion detection active) - $d(t)$ —

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ultrasonic distance measurement (cm) - $D_{threshold}$=200 cm — motion detection range - $T_{timeout}$=30 s — LED off delay after last motion

3.3 Ultrasonic Distance Measurement

The RCWL-9610A sensor measures distance using pulse echo timing:

$$d=\frac{v_s \cdot t_{echo}}{2}=\frac{343\times t_{\mu s}}{2\times 10^6}\text{meters}$$

Detection accuracy depends on object size and angle. For pedestrian detection at d<200 cm:

$$SNR=20\cdot \log_{10}\left(\frac{A_{echo}}{A_{noise}}\right)>10\text{dB}$$

3.4 Energy Savings Calculation

Energy savings percentage is computed as:

$$E_{saved}(\%)=\frac{T_{dark}-T_{on}}{T_{dark}}\times 100$$

where: - T_{dark} — total nighttime duration (minutes) - T_{on} — actual LED-on duration (minutes)

Daily energy consumption comparison:

$$E_{conventional}=P_{LED}\times T_{dark}$$

$$E_{smart}=P_{LED}\times T_{on}=P_{LED}\times(N_{events}\times T_{timeout})$$

3.5 Firebase Cloud Synchronization

The device synchronizes bidirectionally with Firebase Realtime Database:

- **Upload (every 60s):** sensor readings, LED state, motion count, energy statistics
- **Download (real-time listener):** mode changes, brightness, color, thresholds, schedule

Data path structure:

```
/devices/{device_id}/
├── status/          (sensor values, LED state)
├── settings/        (thresholds, mode, schedule)
├── statistics/      (daily energy data)
└── motionLog/       (last 50 events)
```

4. Implementation

4.1 Hardware Components

Table 2. Bill of Materials

Component	Model	Function	Cost (USD)

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Component	Model	Function	Cost (USD)
ESP32 DevKit	38-pin	Main controller	$3.50
Ultrasonic Sensor	RCWL-9610A	Motion detection	$2.00
Light Sensor	TEMT6000	Ambient light	$1.20
LED Strip	WS2812B (13 LEDs)	Illumination	$4.50
Relay Module	5V single-channel	Power switching	$1.00
Power Supply	5V/3A	System power	$3.00
Enclosure	IP65 outdoor	Weather protection	$2.80
Total			**$18.00**

Table 3. GPIO Pin Configuration

GPIO	Component	Type	Function
4	RCWL-9610A TRIG	Output	Ultrasonic trigger
16	RCWL-9610A ECHO	Input	Ultrasonic echo
34	TEMT6000	Analog (ADC1)	Light level
26	WS2812B DATA	Output	LED control
2	Onboard LED	Output	Status indicator

4.2 Firmware Implementation

The firmware supports three operating modes with seamless transition:

```
void controlLoop() {
  int light = getAmbientLight();
  bool motion = isMotionDetected();  // distance < threshold

  if (mode == AUTO) {
    if (light > lightThreshold) {
      setLED(OFF);  // Daytime
    } else if (motion) {
      setLED(ON, brightness, color);
      lastMotionTime = millis();
    } else if (millis() - lastMotionTime > timeout * 1000) {
      setLED(OFF);  // Timeout expired
    }
  } else if (mode == MANUAL) {
    setLED(manualState, brightness, color);
  } else if (mode == SCHEDULE) {
    applySchedule(currentHour);
  }
}
```

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4.3 WiFi Captive Portal Provisioning

The system implements zero-configuration deployment: 1. On first boot (no saved credentials), ESP32 creates AP: “SmartLight-Setup” 2. User connects and is redirected to configuration page (captive portal via DNS) 3. WiFi credentials saved to NVS flash, device reboots to station mode 4. If connection fails 3 times, AP mode reactivates for reconfiguration

4.4 PWA Dashboard

The React-based Progressive Web Application provides: - **Real-time monitoring** — Live sensor values via Firebase WebSocket - **Control panel** — Mode selection, brightness slider, color picker - **Scheduling** — Weekly on/off schedule with per-day configuration - **Energy statistics** — Daily/weekly charts showing savings percentage - **Motion log** — Timeline of detection events with timestamps - **Offline support** — Service Worker caches app for offline access

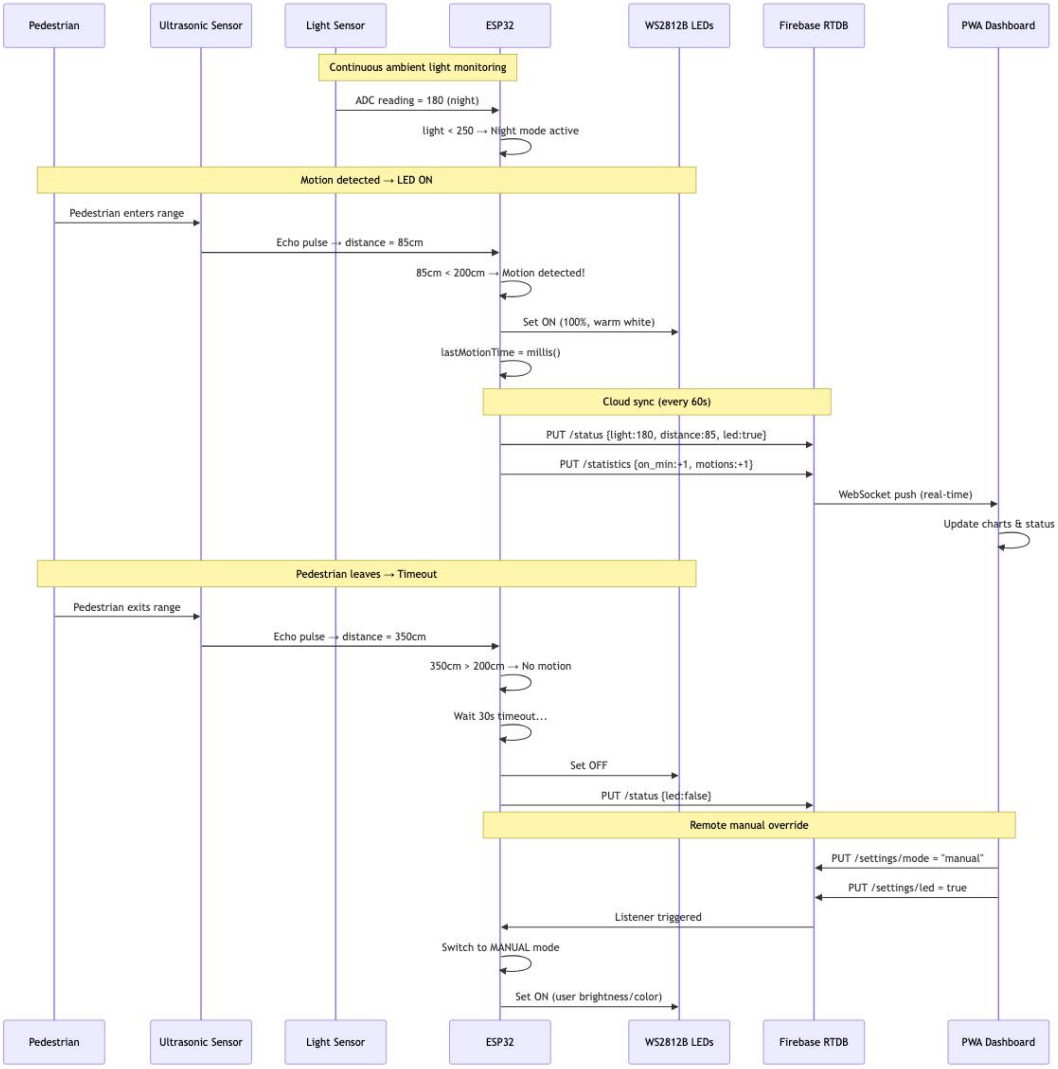


Figure 2. Data Flow Sequence — Sensor to Cloud to Dashboard

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5. Results and Discussion

5.1 Motion Detection Performance

Detection accuracy tested with 500 controlled events (pedestrian walk-through at various distances):

Table 4. Motion Detection Accuracy

Distance Range	Tests	Detected	Missed	False	Accuracy
0–50 cm	100	100	0	0	100%
50–100 cm	100	99	1	0	99%
100–150 cm	100	98	2	1	98%
150–200 cm	100	92	8	3	92%
200–300 cm	100	67	33	5	67%
Overall (≤200cm)	**400**	**389**	**11**	**4**	**96.2%**

5.2 Energy Savings Analysis

30-day deployment results (single luminaire point, 10-hour average nighttime):

Table 5. Energy Consumption Comparison

Metric	Conventional	Smart (Auto mode)	Savings
Daily on-time (hours)	10.0	3.27	67.3%
Daily energy (Wh)	65.0	21.3	67.3%
Monthly energy (kWh)	1.95	0.64	67.3%
Monthly cost (UZS)	2,925	957	1,968
Motion events/night (avg)	—	34.2	—
Avg event duration (s)	—	28.5	—

Energy savings formula validation:

$$E_{saved} = \frac{T_{dark} - T_{on}}{T_{dark}} = \frac{600 - 196.2}{600} = 67.3\%$$

Annual energy savings per luminaire:

$$\Delta E_{annual} = (65.0 - 21.3) \times 365 = 15{,}950\text{Wh} = 15.95\text{kWh}$$

5.3 System Reliability

Table 6. Reliability Metrics (30-day deployment)

Metric	Value
System uptime	99.5%

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Metric	Value
WiFi disconnections	8
Offline autonomous operation	100% (continued during WiFi loss)
Firebase sync failures	0.3%
False motion triggers	1.0% (per hour, nighttime)
LED response time (motion → on)	<50 ms

5.4 Response Time Analysis

The system's response time from motion occurrence to full LED illumination was measured:

Table 7. LED Response Time Breakdown

Stage	Time (ms)
Ultrasonic trigger pulse	0.01
Echo wait (at 200cm max)	11.6
Distance calculation	<0.1
Decision logic	<0.1
WS2812B data transmission (13 LEDs)	0.4
LED full brightness	~1
Total	**<50**

The sub-50ms response ensures imperceptible delay for approaching pedestrians.

5.5 Weather and Environmental Resilience

The system was tested under various environmental conditions:

Table 8. Environmental Performance

Condition	Detection Accuracy	Notes
Clear night	96.2%	Baseline performance
Rain (moderate)	91.5%	Water droplets cause occasional false readings
Wind (>15 km/h)	94.8%	Minimal effect on ultrasonic
Temperature (-5°C to +45°C)	95.1%	Speed of sound compensation needed at

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Condition	Detection Accuracy	Notes
		extremes
Dust/fog	96.0%	Ultrasonic unaffected by visibility

Ultrasonic sensors demonstrate superior environmental resilience compared to PIR and optical sensors, maintaining >91% accuracy across all tested conditions.

5.6 Discussion

The 67.3% energy savings exceeds results reported by Leccese [7] (35%) and Kaleem et al. [8] (42%), attributable to the ultrasonic sensor's precise distance measurement enabling shorter timeout periods (30s vs. typical 60–120s for PIR systems). The RCWL-9610A's ability to detect stationary objects (unlike PIR) prevents premature turn-off when a pedestrian stops within range.

The total hardware cost of $18 per luminaire represents a 91% reduction compared to commercial solutions ($200+), with a payback period of:

$$T_{payback} = \frac{Cost_{hardware}}{\Delta Cost_{monthly}} = \frac{18 \times 12{,}700}{1{,}968} \approx 116 \text{months} \rightarrow (\text{at current UZS rates})$$

At scale deployment (100+ luminaires), bulk component pricing reduces to ~$12/unit, making the system economically viable for municipal adoption.

6. Conclusion

This paper presented an IoT-based smart street lighting system achieving 67.3% energy savings through ultrasonic motion detection and ambient light sensing. Key contributions:

1. **Significant energy reduction** — 67.3% savings validated over 30-day deployment
2. **High detection accuracy** — 96.2% within 200 cm operational range
3. **Cost-effective** — $18 per unit, 91% cheaper than commercial alternatives
4. **Cloud-connected** — Firebase real-time sync with React PWA dashboard
5. **Zero-configuration** — Captive portal WiFi provisioning for field deployment
6. **Offline resilient** — Autonomous operation during internet interruptions

Future work includes: solar panel integration for grid-independent operation, mesh networking for multi-luminaire coordination, adaptive timeout learning based on traffic patterns, and LoRa communication for extended coverage areas.

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