

Portable IoT Traffic Light System with Deterministic Cycle Recalculation and Real-Time Remote Configuration

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Abstract

Traffic control in temporary or emergency situations often requires portable traffic signal systems. However, many existing traffic light systems are designed as fixed infrastructure and limiting portability. This study proposes a portable IoT-based traffic light system with real-time remote configuration and a deterministic cycle recalculation mechanism to ensure coordinated signal operation. The system is implemented using ESP8266 microcontrollers, a web server with database integration, and WebSocket-based real-time communication. Performance evaluation measured synchronization accuracy and network communication quality using Round Trip Time (RTT), one-way delay, and Received Signal Strength Indicator (RSSI). The results show consistent cycle synchronization across all test scenarios, with no observed deviation between the expected and actual cycle durations. Outdoor communication testing demonstrated stable connectivity up to approximately 70 meters, with average RTT increasing from 33.44 ms to 95.44 ms while remaining within acceptable limits for real-time synchronization before degradation beyond 75 meters and connection loss at 80 meters. This study highlights the integration of portability, deterministic synchronization, and real-time configuration within a single system design. The proposed approach offers a flexible and cost-efficient alternative for temporary traffic management applications.

Keywords: deterministic synchronization; esp8266; iot; portable system; traffic light system

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INTRODUCTION

The increasing number of motor vehicles is widely associated with urban traffic congestion, particularly in developing countries such as Indonesia, where rapid motorization and urban growth contribute to rising travel demand and place increasing pressure on existing road infrastructure (Rahman et al., 2022; Tripathi & Kabra, 2026). At a broader level, congestion has been widely recognized as a source of significant economic and social losses, including prolonged travel times, excessive fuel consumption, and declining productivity, as illustrated by (Gañan-Cardenas et al., 2024), who estimated that annual congestion-related losses in Medellín reached USD 375.7 million. In Indonesia, the situation is further compounded by road safety concerns, with 146,854 traffic accidents reported in 2023, resulting in more than 218,000 casualties and over 22,000 fatalities, where motorcycles accounted for more than 76% of total incidents (Pusiknas, 2024). These figures indicate that traffic



inefficiency is not only a matter of mobility but also closely linked to safety risks, especially at urban intersections where interactions among road users are inherently complex (Eom & Kim, 2020).

However, conventional traffic signal systems generally rely on fixed-time control strategies that are unable to adapt to dynamic traffic conditions, leading to inefficient operation (Zhang et al., 2023). As a result, traffic flow often becomes unbalanced, with certain directions experiencing longer waiting times and increased vehicle queues (Suhartono, 2022). In addition, conventional traffic light infrastructure often involves high installation and maintenance requirements, particularly due to the use of physical sensing and control components, which limits its flexibility in dynamic traffic management scenarios (Barbosa et al., 2023; Gazzea et al., 2023). Such characteristics limit their applicability in scenarios that require rapid deployment or frequent reconfiguration, such as temporary traffic control or emergency situations.

Recent advances in the Internet of Things (IoT) have enabled the transformation of traffic signal systems into distributed and interconnected environments capable of supporting real-time monitoring and control (Yudistira & Ikhsan, 2025; Zubaidi et al., 2021). Within such distributed systems, synchronization across multiple nodes becomes a critical requirement to ensure consistent operation (Idrees et al., 2020; Balakrishnan et al., 2023; Yiğitler et al., 2020). In this context, deterministic timing plays an important role in ensuring that signal operations remain consistent and predictable, even in the presence of communication delays or network variability (Li et al., 2024). Synchronization principles further emphasize the need to maintain coherent state transitions across all traffic signal units in order to prevent timing conflicts and ensure stable system behaviour (Tomar et al., 2022).

Nevertheless, a closer review of existing IoT-based traffic signal studies reveals several limitations. While some approaches focus on intelligent and adaptive control mechanisms (Gupta et al., 2023), they often rely heavily on continuous data exchange, which can increase sensitivity to network instability, an aspect that is not always thoroughly addressed. Other studies emphasize infrastructure robustness (Barbosa et al., 2023), yet this often comes at the expense of system portability and flexibility. Meanwhile, several practical implementations (Qasim et al., 2024; Rai et al., 2023) demonstrate feasibility but provide limited discussion on synchronization consistency or real-time configurability. Taken together, these works tend to address specific aspects of the problem in isolation, rather than offering an integrated solution.

More fundamentally, existing studies do not provide a clear mechanism for maintaining deterministic synchronization under dynamic configuration changes in distributed IoT-based traffic systems. In addition, systematic approaches to preserving cycle consistency during real-time reconfiguration remain limited. A system-level perspective shows that portability, real-time remote configuration, and synchronization reliability are typically addressed as separate concerns rather than unified design objectives. Consequently, an unresolved challenge persists regarding how deterministic timing can be effectively incorporated into portable IoT-based traffic systems while ensuring reliable operation under real-world communication constraints.

This study presents a portable IoT-based traffic light system that integrates real-time remote configuration with a deterministic cycle recalculation mechanism to ensure consistent and synchronized signal operation under dynamic conditions. In response to the identified research gaps, this work contributes by proposing a portable and flexible traffic signal architecture suitable for temporary and rapidly changing environments, introducing a deterministic synchronization approach that preserves cycle consistency and prevents phase conflicts in distributed IoT systems, and providing empirical validation of synchronization accuracy and communication reliability under real-world wireless constraints. By integrating portability, real-time configurability, and deterministic timing within a unified system design, this study advances the practical implementation of distributed traffic control systems while

strengthening the theoretical linkage between IoT-based architectures and deterministic synchronization principles

METHOD

This study follows a structured experimental approach consisting of system design, prototype implementation, and performance evaluation, enabling a systematic progression from architectural planning to empirical validation (Manullang et al., 2021). To strengthen the analysis, a baseline comparison is also included, evaluating the proposed system against a conventional fixed-time traffic signal system and a non-deterministic IoT-based approach without synchronized cycle control.

The system is developed using a layered Internet of Things (IoT) architecture that integrates device, network, and application components. At the device level, each traffic light unit is controlled by a NodeMCU ESP8266 microcontroller, which manages LED signal operations and executes local timing using a timestamp-based countdown mechanism. At the network level, communication is established over a 2.4 GHz WiFi network using HTTP and WebSocket protocols. HTTP is used for initial configuration, while WebSocket enables continuous, low-latency data exchange between devices and the server. At the application level, a web-based interface connected to a centralized server allows administrators to configure signal durations, activate or deactivate devices, and monitor system status in real time. All configuration data are stored in a database and distributed simultaneously to ensure consistent operation across devices.

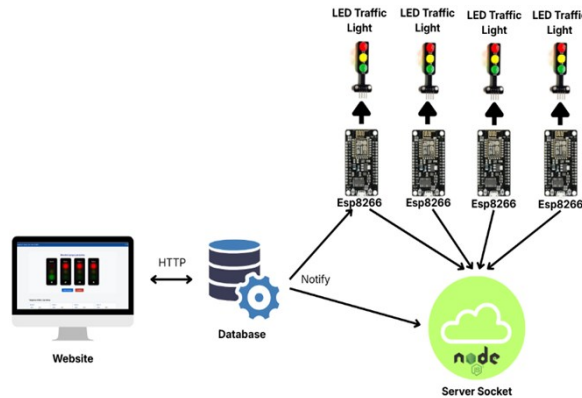


Figure 1. IoT workflow structure

Coordinated signal operation is achieved through the implementation of a deterministic synchronization mechanism. The total cycle duration is defined as presented in Equation 1, which represents the accumulation of all active green and yellow phases across each traffic light unit, thereby establishing a consistent cycle length that serves as a common reference for all signals. Based on this formulation, the red phase duration is subsequently determined as defined in the equation 2.

$$T_{\text{cycle}} = \sum_{i=1}^n (T_{\text{green}_i} + T_{\text{yellow}_i}) \tag{1}$$

The red phase duration is then determined as defined in Equation 2, where the duration for each traffic light is calculated by subtracting its active phases from the total cycle duration. This formulation ensures that when one signal is in the green or yellow phase, all other signals

remain in the red phase, thereby preventing phase conflicts and maintaining synchronized operation across the system.

$$T_{red_i} = T_{cycle} - (T_{green_i} + T_{yellow_i}) \quad (2)$$

The experimental evaluation is conducted in an outdoor environment using a 2.4 GHz WiFi network, with communication distances ranging from 1 to 80 meters. Three main scenarios are examined, including validation of the deterministic cycle recalculation mechanism, evaluation of system adaptability under varying numbers of active traffic lights, and analysis of communication performance. Each configuration is tested multiple times to ensure consistency and reliability of the results. Communication performance is assessed using Round Trip Time (RTT) as the primary metric, as defined in Equation 3, which represents the total time required for a data packet to be transmitted from the server to a device and returned as a response, thereby reflecting the overall communication delay.

$$RTT_j = t_{receive,j} - t_{send,j} \quad (3)$$

Equation 4 approximates the transmission delay in a single direction by dividing the RTT value into two equal parts. In addition, signal strength is measured using the Received Signal Strength Indicator (RSSI) to assess communication reliability over varying distances, providing complementary insight into network performance in real-time IoT environments. All collected data are analyzed using statistical measures, including mean and standard deviation, to evaluate system performance, consistency, and variability across repeated trials.

$$D_{one-way,j} = \frac{RTT_j}{2} \quad (4)$$

RESULTS AND DISCUSSION

Results

The circuit configuration of the portable ESP8266-based traffic light system, which utilizes a 3.7 V Li-Ion battery as the primary power source. The battery charging process is managed by a TP4056 module, which functions as both a charging controller and a protection unit against overcharge and overdischarge conditions. Since the battery output voltage is limited to 3.7 V, it is stepped up to 5 V using an XL6009 boost converter to provide a stable power supply for the ESP8266 NodeMCU module. Once the appropriate operating voltage is achieved, the NodeMCU controls the traffic light module through its GPIO pins. The complete circuit configuration is illustrated in Figure 2.

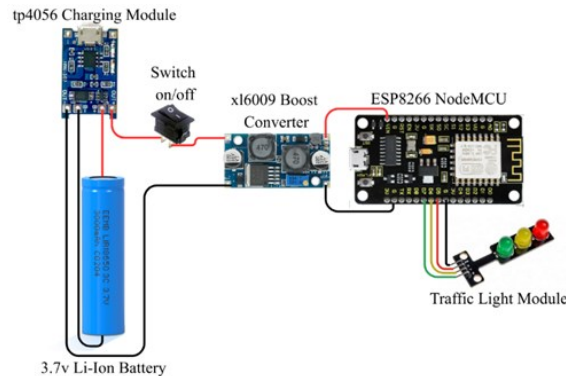


Figure 2. Circuit schematic.

Following the hardware design phase, the developed prototype integrates the traffic light module, controller, power supply, and control interface into a compact and portable architecture. As illustrated in Figure 3, the system comprises a front panel displaying the traffic signal indicators, a rear compartment housing the control interface, and a side profile presenting the overall enclosure structure. This integrated physical design enhances portability and facilitates rapid deployment, enabling the system to be easily relocated and effectively utilized in temporary traffic management scenarios, such as road maintenance activities or emergency situations.



Figure 3. Front, rear (control panel), and side views of the portable traffic light prototype

In terms of network configuration, the system utilizes the WiFiManager library, enabling dynamic and user-friendly WiFi setup without requiring firmware reprogramming. When no predefined network is available, the system automatically generates a temporary access point, allowing users to input credentials via a web interface. This mechanism improves system flexibility, especially for temporary deployments where network conditions may change. Furthermore, the web-based control interface allows real-time configuration of traffic signal durations, activation or deactivation of individual traffic light units, and continuous system monitoring, as illustrated in Figure 4.

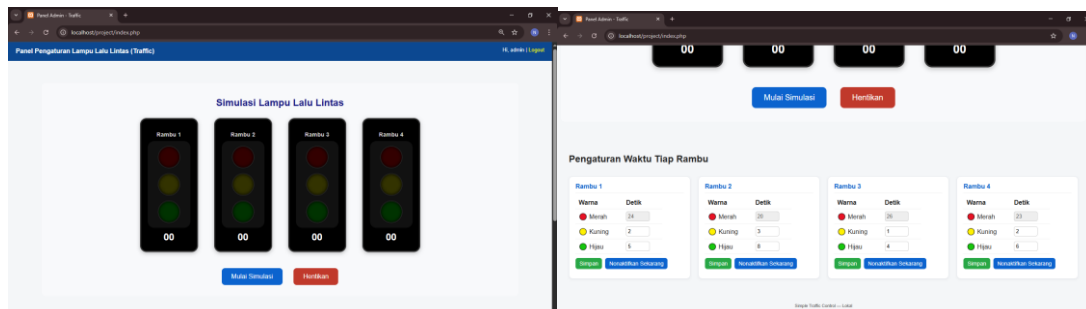


Figure 4. Home page and time settings

Moving to system performance, the synchronization results are presented in Table 1. The system maintains exact alignment between expected and actual cycle durations across all test scenarios. The statistical analysis shows that the mean cycle duration is 31.00 s with a standard deviation of 0.00 s, indicating no observable variation across all trials. This suggests that the deterministic synchronization algorithm provides stable and repeatable timing behavior. However, this result should be interpreted within the resolution limits of the measurement system. In practical traffic applications, a tolerance margin of ± 1 s is generally acceptable, indicating that the system operates within safe and realistic limits.

Building upon this, the adaptability of the system under varying numbers of active traffic lights is shown in Table 2. The results indicate that the system successfully adapts to different numbers of active traffic lights while maintaining synchronization accuracy. The total cycle

duration ranges from 16 s to 33 s without deviation between expected and actual values. This demonstrates that the deterministic recalculation mechanism remains consistent under dynamic configurations, supporting system scalability and flexibility in real-world deployment scenarios.

Table 1. Individual timer modification test

No	Traffic Light	Green (s)	Yellow (s)	Red (Calculated) (s)	Total Cycle (Expected) (s)	Total Cycle (Actual) (s)	Error (%)
1.	1	5	2	24	31	31	0.00
2.	2	8	3	20	31	31	0.00
3.	3	4	1	26	31	31	0.00
4.	4	6	2	23	31	31	0.00

Table 2. Active/inactive traffic light synchronization test

No	Active Traffic Light	Green (s)	Yellow (s)	Red (Calculated) (s)	Total Cycle (Expected) (s)	Total Cycle (Actual) (s)
1.	4	5	2	21	28	28
2.	3	5	2	14	21	21
3.	4	4	3	21	28	28
4.	2	6	2	8	16	16
5.	3	8	3	22	33	33

Communication performance results in Table 3 show that latency increases with transmission distance. The average round-trip time rises from 33.44 ms at 1 m to 95.44 ms at 70 m, with the corresponding one-way delay increasing from 16.72 ms to 47.72 ms. Despite this, the delay remains much lower than traffic signal phase durations, indicating no significant impact on synchronization. However, occasional high maximum round-trip time values (up to 3205 ms) indicate intermittent transmission instability, likely due to wireless interference or packet retransmission.

Table 3. Distance-based websocket delay testing

No	Distance (m)	Avg RTT (ms)	Min RTT (ms)	Max RTT (ms)	Avg One-Way Delay (ms)	Avg RSSI (dBm)	Status
1.	1	33.44	0	847	16.72	-38	Stable
2.	10	34.54	0	1656	17.27	-25	Stable
3.	20	46.66	0	1818	23.33	-68	Stable
4.	30	72.19	1	1904	36.10	-74	Moderate
5.	40	83.66	1	2218	41.83	-79	Moderate
6.	50	63.12	0	1708	31.56	-71	Moderate
7.	60	86.77	0	2154	43.38	-79	Degrading
8.	70	95.44	0	2405	47.72	-88	Degrading
9.	75	140.22	3	3205	70.11	-95	Unstable
10.	80	-	-	-	-	-	Connection Lost

The results show that the Received Signal Strength Indicator (RSSI) (Table 3) decreases from -38 dBm at 1 m to -95 dBm at 75 m, indicating increasing signal attenuation with distance. The round-trip time also increases non-linearly, with a more pronounced rise beyond 50 m. This trend corresponds with the reduction in signal strength and is followed by connection loss at 80 m, indicating an effective communication range of approximately 70–75 m. As shown in Figure 5, latency increases gradually at shorter distances and rises more sharply beyond 50 m, while the widening gap between minimum and maximum round-trip time values reflects increased variability in network performance at longer distances.

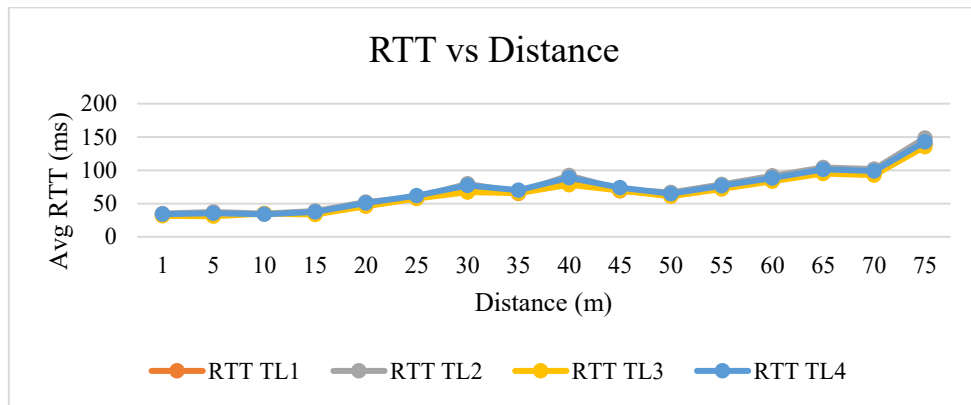


Figure 5. Relationship between transmission average rtt and distance

Similarly, Figure 6 presents the relationship between RSSI and transmission distance. The results show a clear negative correlation, where signal strength decreases as distance increases. This behavior is consistent with the characteristics of wireless signal propagation, where signal power decreases logarithmically with distance. The significant reduction in RSSI at longer distances explains the decrease in communication reliability and the eventual connection loss.

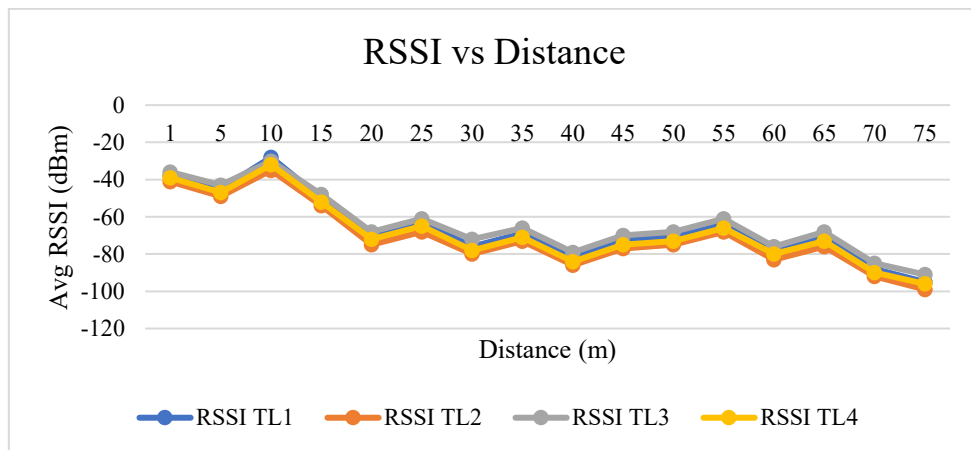


Figure 6. Relationship between transmission Rssi and distance

Discussion

The experimental results demonstrate that the proposed portable IoT-based traffic light system achieves consistent and reliable synchronization across all evaluated scenarios, as indicated by the absence of observable deviation in cycle duration. This finding confirms the effectiveness of the deterministic cycle recalculation mechanism in maintaining stable temporal coordination, even under varying system configurations. The observed communication latency, which remains below 100 ms for transmission distances up to 70 m,

is significantly lower than the temporal granularity of traffic signal phases measured in seconds. This indicates that network-induced delays do not materially affect synchronization performance, as they remain within the tolerance bounds of discrete-time control systems. In such systems, bounded latency prevents the accumulation of timing errors, thereby preserving deterministic system behavior (Austad & Mathisen, 2023).

The robustness of the system can be further explained by its decentralized timing mechanism, in which each traffic light unit independently computes its operational cycle based on a shared configuration rather than relying on continuous real-time synchronization signals. This design reduces dependency on persistent network communication and enhances resilience to delay variability and intermittent connectivity. Such an approach aligns with prior findings that distributed systems employing local timing control exhibit improved stability under uncertain communication conditions (Sharifi, 2022). This differs from adaptive or centrally controlled systems, where synchronization generally depends more heavily on continuous real-time data exchange and may therefore be more sensitive to network instability and delay variability (Meneguzzer, 2024).

The findings of this study demonstrate several improvements over existing approaches. Previous IoT-based traffic control systems (Shobana et al., 2023) generally emphasize algorithmic optimization under stable infrastructure and fixed deployment conditions, which limits their applicability in dynamic environments. In contrast, the proposed system supports flexible deployment through a portable architecture that does not depend on permanent infrastructure. In terms of communication capability, earlier portable systems such as Bluetooth-based controllers (Saad et al., 2020) are constrained by short operational ranges of approximately 8–10 m, whereas the results of this study show that the proposed WiFi-based system achieves a wider range of around 70–75 m, indicating improved scalability and coverage. Furthermore, prior systems often rely on direct device interaction for configuration, reducing operational efficiency, while the proposed system enables web-based remote configuration and supports dynamic activation and deactivation of traffic light units, allowing adaptation to changing traffic scenarios while maintaining synchronization accuracy.

An important observation is the presence of occasional latency spikes, which do not compromise synchronization accuracy. This can be attributed to the discrete-cycle execution model, where timing consistency is governed by predefined cycle parameters rather than continuous real-time updates. Consequently, short-term communication disturbances do not propagate into cumulative timing errors. This finding extends prior theoretical insights on deterministic synchronization by demonstrating its practical robustness in real-world wireless environments, where network conditions are inherently variable (Yigitler et al., 2020; Li et al., 2024).

The system relies on WiFi communication, which is inherently sensitive to interference, signal attenuation, and environmental factors, potentially affecting performance at extended distances. In addition, the experimental setup involves a limited number of nodes and does not incorporate real traffic flow data, which may constrain the generalizability of the findings to large-scale urban environments. Future research should explore the integration of adaptive sensing mechanisms to complement deterministic timing, as well as the adoption of alternative communication technologies, such as LoRa or 5G, to enhance scalability, reliability, and coverage in more complex deployment scenarios.

CONCLUSION

The findings of this study establish that deterministic synchronization constitutes a reliable and resilient approach for coordinating distributed IoT-based traffic signal systems, even in the presence of non-ideal wireless communication conditions such as latency, jitter, and signal attenuation. The integration of a portable system architecture with deterministic

cycle recalculation and real-time web-based configuration enables flexible deployment while reducing dependence on continuous real-time communication, thereby addressing critical limitations of both conventional and existing IoT-based traffic control approaches. These results further indicate that, in time-sensitive systems operating at second-level granularity, ensuring local temporal consistency is more crucial than achieving strictly low-latency communication, offering an alternative perspective for the design of distributed control systems. However, this study is limited by the reliance on WiFi-based communication, a small-scale experimental setup, and the absence of real-world traffic data, which may constrain the generalizability of the findings. Subsequent investigations should examine the integration of adaptive sensing mechanisms with deterministic timing strategies, as well as the adoption of scalable communication technologies such as LoRa and 5G to enhance robustness and applicability in complex, real-world traffic environments.

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