ELKHA : Jurnal Teknik Elektro, Vol. 18 No.1, April 2026, pp. 25 - 32
ISSN: 1858-1463 (print), 2580-6807 (online)

WSN-Based IoT Water Tank Monitoring with Accuracy and QoS Evaluation

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Abstract **– This study presents a Wireless Sensor Network (WSN)-based Internet of Things (IoT) water tank monitoring system designed to provide reliable real-time monitoring and performance evaluation. The proposed system utilizes NodeMCU ESP8266 modules and ultrasonic sensors to measure water levels across multiple tanks within a distributed WSN architecture. Previous studies on IoT-based water monitoring have largely focused on system implementation, conceptual frameworks, or application-oriented solutions, while comprehensive experimental validation of sensing accuracy and network communication performance is often limited. In particular, integrated evaluation approaches that simultaneously assess sensor measurement accuracy and network Quality of Service (QoS) performance in multi-node WSN deployments remain relatively underexplored. To address this gap, this study applies an integrated evaluation framework that combines ultrasonic sensing accuracy testing and QoS delay analysis, based on the Telecommunication and Internet Protocol Harmonization Over Networks (TIPHON) standard. Experimental results show that the system achieved average measurement accuracies of 96.59%, 97.21%, and 97.37% for Tanks 1, 2, and 3, respectively. Network performance evaluation under non-Line-of-Sight (non-LoS) indoor conditions produced an average transmission delay of 28.75 ms, which falls within the "very good" category according to TIPHON QoS criteria. These results demonstrate that the proposed WSN–IoT architecture provides reliable sensing performance and stable communication for domestic water tank monitoring applications.**

Keywords: Internet of Things (IoT); Wireless Sensor Network (WSN); Water Level Monitoring; Ultrasonic Sensor Accuracy; Network Delay.

I. Introduction

The availability of clean water is a fundamental necessity that must be managed efficiently, particularly in storage systems utilizing water tanks. Water levels in storage tanks fluctuate dynamically due to varying consumption patterns, making continuous monitoring essential to prevent shortages, overflow, and inefficient water utilization. Recent studies have demonstrated that IoT-based monitoring systems significantly improve operational efficiency by enabling real-time sensing and remote accessibility [1], [2], [3], [4]. In residential and small-scale applications. Several implementations have been developed using ultrasonic sensors and microcontroller platforms to automate monitoring and notification processes [5], [6], [7], [8], [9]. However, many of these systems focus primarily on functional implementation without comprehensive performance validation, particularly regarding sensing accuracy and communication reliability.

The rapid development of IoT technologies has enabled the integration of sensors, wireless communication, and cloud-based platforms in water monitoring applications [10], [11], [12], [13], [14]. Various architectures have been implemented using WiFi and LoRaWAN communication protocols to support real-time transmission and remote monitoring [4], [12], [15], [16]. In addition, recent review studies emphasize the growing role of intelligent IoT frameworks, machine learning integration, and scalable sensor network architectures in sustainable water resource management [11], [17], [18]. Optical and advanced sensing approaches have also been explored to enhance monitoring capability in water-related applications [19]. These developments indicate that IoT-based water monitoring solutions are increasingly scalable and adaptable for distributed deployment scenarios.

WSNs provide a flexible infrastructure for distributed environmental monitoring systems. Previous research highlights that WSN architectures enable modular deployment, efficient data aggregation, and scalable multi-node communication [17], [20]. In water-related applications, WSN-based systems have been widely adopted for water quality monitoring, smart water management, and environmental surveillance [13], [14], [21]. Several recent studies have implemented IoT-based monitoring systems for rivers, irrigation systems, flood mitigation, and tank control applications [22], [23], [24], [25], [26], [27]. Despite these advancements, most implementations emphasize system deployment and application functionality, with limited investigation into integrated performance validation under practical network conditions.

Although ultrasonic sensors are commonly used for water level detection due to their affordability and ease of integration, quantitative validation of measurement accuracy is not consistently reported [3], [12], [15]. Furthermore, communication performance evaluation—particularly delay analysis—remains insufficiently explored, even though delay directly affects the

Manuscript received 2026-02-03; revised 2026-03-09 ; accepted 2026-03-10

responsiveness and reliability of real-time monitoring systems [21], [20]. In practical deployments, non-LoS conditions caused by walls or structural obstructions may introduce signal attenuation and increased transmission delay. However, experimental validation under such realistic conditions is rarely discussed in previous studies [22], [23], [24], [25], [26], [27]. Therefore, an integrated evaluation framework that combines sensing accuracy validation and delay-based QoS analysis within a multi-node WSN architecture remains an open research need. A comparison of representative IoT-based water-monitoring studies and the proposed system is presented in Table 1 to highlight these differences in monitoring focus, system architecture, and experimental evaluation.

Table 1. Comparison of Representative IoT-Based Water Monitoring Studies and the Proposed System

Study	Monitoring Focus	System Architecture	Experimental Evaluation
Ref. [3]	IoT-based water storage tank monitoring (review study)	Conceptual overview of IoT technologies	No experimental validation of sensing accuracy or network QoS performance
Ref. [12]	Water quality monitoring using AI-based prediction	IoT–WSN framework for water quality parameters	Evaluation focused on machine learning prediction performance rather than sensor accuracy or network QoS analysis
Previous IoT water level monitoring studies	Water level monitoring applications	Typically single-node IoT architecture or simple monitoring systems	Limited validation mainly based on functional testing or basic response observation
Proposed Study	Multi-tank water level monitoring	Multi-node WSN–IoT architecture using NodeMCU ESP8266 and ultrasonic sensors	Quantitative ultrasonic sensing accuracy validation and transmission delay analysis based on TIPHON QoS standard under non-LoS conditions

Previous studies have widely explored IoT–based systems for monitoring water levels in tanks, rivers, and irrigation infrastructures using ultrasonic sensors and microcontroller platforms such as ESP8266, as reported in [22], [23], [24], [25], [26], [27]. These studies primarily focus on system implementation and basic functional validation, with performance evaluation often limited to sensor readings, prototype demonstrations, or simple response-time observations. However, the evaluation approaches are generally descriptive and do not employ standardized QoS frameworks to systematically assess network communication performance. Addressing these gaps, this study proposes and evaluates a WSN–IoT-based water tank monitoring system utilizing NodeMCU ESP8266 and ultrasonic sensors in a multi-tank deployment scenario. The system integrates distributed sensor nodes and a sink node within a scalable WSN framework to enable real-time monitoring. This research emphasizes the quantitative validation of ultrasonic measurement accuracy and the analysis of communication delay under non-LoS conditions, as evaluated against the TIPHON QoS standard [28]. By integrating sensing accuracy assessment and delay-based QoS evaluation within a unified WSN–IoT architecture, this study provides a structured, experimentally validated performance evaluation framework that strengthens the methodological contribution beyond conventional implementation-focused studies.

II. METHODOLOGY

This study begins with a literature review to gain a comprehensive understanding of the concepts and technologies involved in the development of a water tank level monitoring system. The literature review was conducted by examining reference books, articles from accredited national journals, and conference proceedings on IoT, WSN, ultrasonic sensors, NodeMCU ESP8266, and network QoS. The results of this review served as as a foundation for determining the research approach and defining testing methods in accordance with the research objectives. The overall stages of the research process are illustrated in Figure 1, which presents the research flowchart describing the sequential and iterative steps from literature review to system evaluation.

Following the literature review, a system requirements analysis was conducted to identify the hardware, software, and functional specifications of the proposed water tank level monitoring system. This stage defined the main system components, including ultrasonic sensors for water level measurement, a microcontroller as the control unit, a wireless communication module for data transmission, and a monitoring platform for real-time observation. The analysis also determined measured parameters and operational conditions during testing to ensure reliable monitoring performance. The relationships among system components and data flow are illustrated in the block diagram in Figure 2. Although the IoT monitoring architecture used in this study is conceptually similar to previous implementations reported in [3], [24], and [25], the proposed system adopts a multi-node wireless sensor network architecture with three sensing nodes deployed on separate water tanks, enabling distributed monitoring within a single IoT network under indoor non-LoS conditions, differing from predominantly single-node monitoring architectures reported in previous studies.

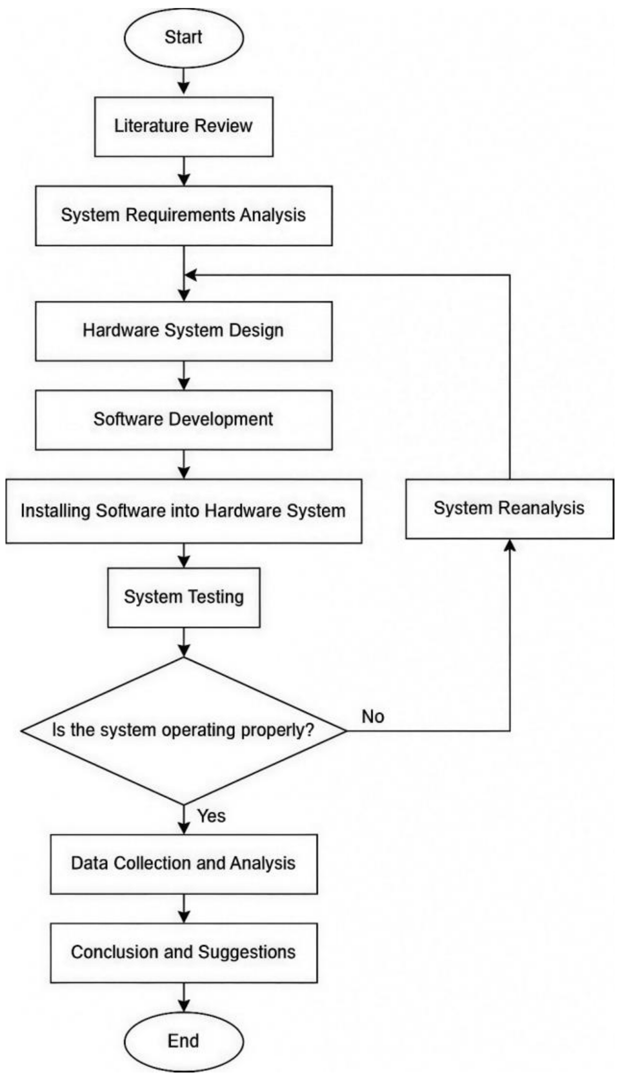

Figure 1. Research flowchart

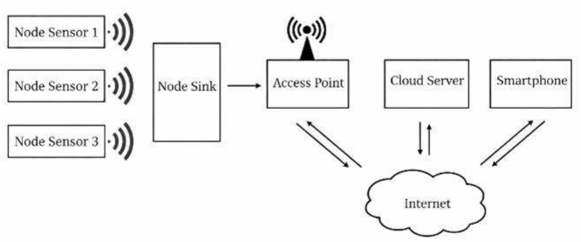

Figure 2. System block diagram

After the system requirements were defined, the hardware system was designed by selecting and integrating the main components, namely the NodeMCU ESP8266, the HC-SR04 ultrasonic sensor, the power supply, and other supporting components. The ultrasonic sensor was installed at the top of the water tank to measure the distance to the water surface, while the NodeMCU ESP8266 served as the data processing unit and the wireless data transmitter. The hardware design was carried out with consideration of system reliability and ease of testing. The electronic circuit configuration of the sensor node is presented in Figure 3, which illustrates the connection between the NodeMCU ESP8266 and the HC-SR04 ultrasonic sensor using TRIG and ECHO signal lines connected to digital pins D1 and D2, respectively, and the power supply connected via the 3V3 and GND pins.

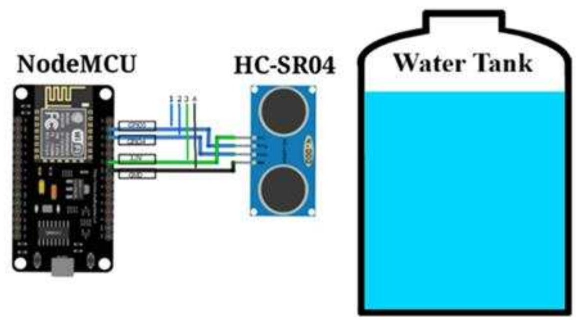

Figure 3. The electronic circuit of the sensor node

In addition to the sensor node design, the sink node hardware was developed to manage data aggregation and transmission to the cloud server. The electronic circuit of the sink node, shown in Figure 4, utilizes two NodeMCU ESP8266 modules. The first module functions as a data receiver from three sensor nodes on different water tanks, while the second module forwards the data to the Blynk cloud server for visualization. Communication between the modules is established through digital pins D5 and D6. The use of two NodeMCU modules is a technical design choice to distribute processing tasks, allowing one module to handle data reception while the other manages data transmission to the IoT monitoring platform.

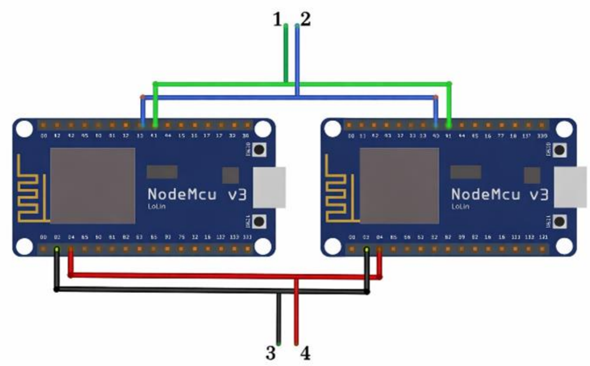

Figure 4. The electronic circuit of the sink node

WSN topology of the IoT-based water tank level monitoring system during testing is illustrated in Figure 5. In this topology, each sensor node consists of a NodeMCU ESP8266 integrated with an HC-SR04 ultrasonic sensor installed on each water tank to measure water levels. The measurement data are transmitted wirelessly to the sink node over a communication distance of approximately ±13 meters and subsequently forwarded through an access point to the Blynk cloud server. The processed information can then be monitored in real time using the Blynk application on a smartphone. The realized hardware implementations of both the sensor nodes and the sink node used during the testing phase are shown in Figure 6.

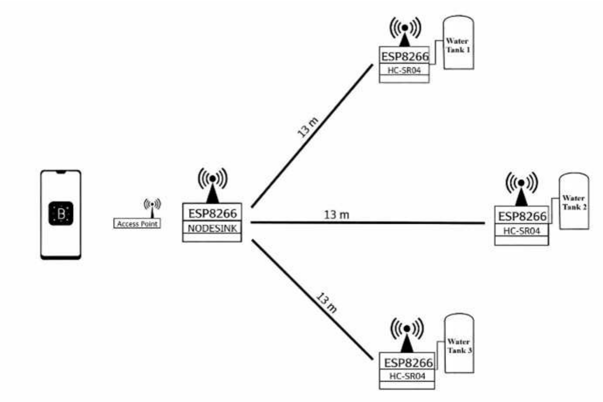

Figure 5. WSN topology of the IoT-based water tank level monitoring system during testing

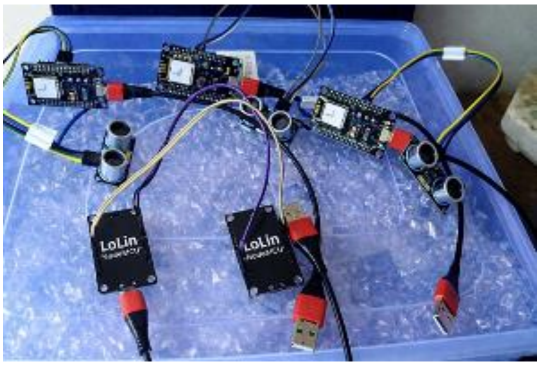

Figure 6. Implemented electronic circuits of sensor nodes and sink node

The next stage of the research involved developing software to control the system's overall operation. Programming of the NodeMCU ESP8266 was carried out using the Arduino IDE as the development environment. The software was designed to read water-level data from the ultrasonic sensor, process the measurement results, and transmit the data wirelessly to the sink node. The sink node then uploads the received data to the Blynk cloud server, allowing the information to be processed and displayed in real time on the Blynk application via a smartphone. The operational flow of the software system is illustrated in Figure 7, which describes the sequence of data acquisition, processing, transmission, and visualization.

After the software development was completed, the program was installed on the hardware system by uploading the code to the NodeMCU ESP8266 modules, followed by an initial functional check to ensure that no configuration errors occurred. The installation process was conducted in stages, with compatibility between the software and hardware components verified. This step was necessary to confirm that the system was ready to proceed to comprehensive testing under real operating conditions. The placement of the sensor nodes and the sink node during the testing phase is depicted in Figure 8, which illustrates the spatial arrangement of the monitoring system components.

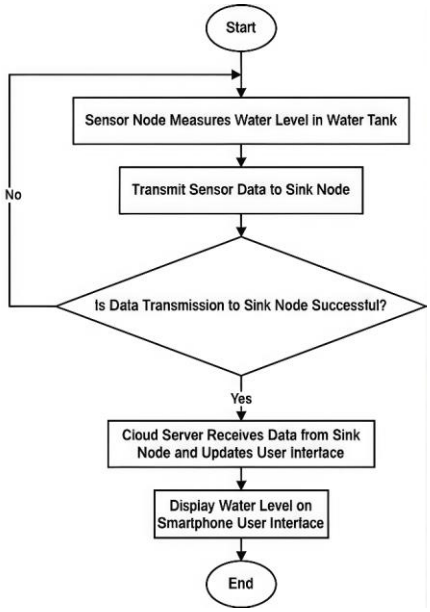

Figure 7. Flowchart of the software system operation

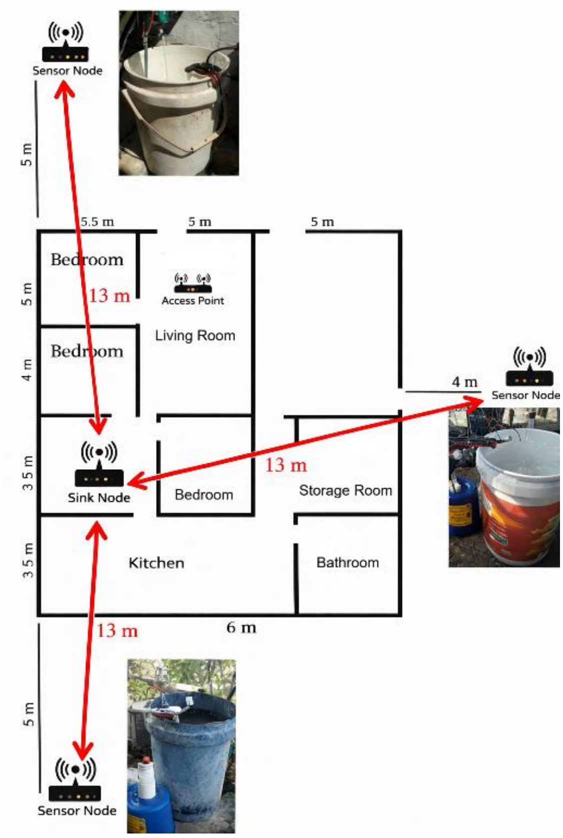

Figure 8. Deployment layout of the monitoring system during testing

System testing was conducted to evaluate the performance and functionality of the water tank level monitoring system. The evaluation included functional testing of the ultrasonic sensor for water-level detection, assessment of data communication between the NodeMCU ESP8266 modules and the Blynk application, and system stability under defined operating conditions. The tests were performed on a prototype water tank with a predefined height, as specified in the research scenario. During testing, the sensor nodes were placed outside the building, while the sink node was located indoors. Wireless communication was established over a distance of approximately ±13 meters with walls and room partitions creating non-LoS conditions. This scenario was used to evaluate communication performance in a realistic deployment environment. The real-time monitoring interface displayed in the Blynk application, showing water-level indicators and historical graphs for three tanks, is presented in Figure 9.

Figure 9. User interface of the water tank level monitoring system on the Blynk application

Finally, a comprehensive evaluation was conducted to verify that the proposed system met the predefined performance criteria for sensing accuracy and communication reliability. When the system performance did not fully meet the expected thresholds, further diagnostic analysis was performed to identify potential issues in the hardware components, such as sensor calibration or wiring stability, as well as within the software configuration, including data transmission and processing routines. Necessary adjustments and refinements were then implemented, followed by repeated testing to ensure optimal and stable operation. This procedure followed the iterative validation process outlined in the research flowchart, ensuring systematic performance improvement. In the final stage, all experimental data collected from system testing, including water level measurements, calculated sensor accuracy, and network QoS parameters, particularly delay, were analyzed in depth to evaluate the overall system effectiveness, leading to the formulation of conclusions and recommendations for future development.

III. Results and Discussion

This section presents the experimental evaluation results of the proposed WSN–IoT-based water tank monitoring system. The performance analysis focuses on two primary aspects: the measurement accuracy of the ultrasonic sensor and the network QoS performance, particularly transmission delay, assessed under non-LoS indoor conditions to validate sensing reliability and communication stability.

A. *Water Level Measurement Accuracy*

The system-measured water level was calculated using the following equation:

$$H_s = H_t - H_e \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where:

H_s = water level measured by the system (cm)

H_t = total height of the water tank (cm)

H_e = empty space height inside the tank measured by the ultrasonic sensor (cm)

The measurement accuracy was calculated as:

$$A = 100\% - \left(\frac{|H_s - H_m|}{H_m} \times 100\%\right) \quad \ldots\ldots\ldots \quad (2)$$

where:

A = measurement accuracy (%)

H_s = water level measured by the system (cm)

H_m = water level measured manually using a conventional measuring tool (cm)

Table 2. Accuracy Test Results of The System on Tank 1

Test	Manual Measurement (cm)	System Measurement (cm)	Accuracy (%)
1	8	9	87.50
2	12	12	100
3	15	15	100
4	17	18	94.12
5	20	21	95
6	23	23	100
7	25	25	100
8	27	29	92.59
9	28	28	100
10	30	31	96.67

Measurement accuracy was evaluated across three water tanks during the filling process with ten trials for each tank. System readings were compared with manual measurements, which served as reference values. For Tank 1 (Table 2), the system achieved an average accuracy of

96.59% with an average deviation of about 0.6 cm, indicating reliable sensor performance for water-tank monitoring applications.

Table 3. Accuracy Test Results of The System on Tank 2

Test	Manual Measurement (cm)	System Measurement (cm)	Accuracy (%)
1	6	6	100
2	9	9	100
3	11	12	90.91
4	14	14	100
5	15	17	86.67
6	17	17	100
7	20	20	100
8	22	23	95.45
9	25	25	100
10	28	28	100

The accuracy test for Tank 2 (Table 3) shows that the proposed system achieved an average accuracy of 97.21% with an average deviation of approximately 0.4 cm compared to manual measurements. Minor discrepancies observed across several trials remained within the ±1 cm tolerance, indicating stable and consistent sensing performance under dynamic water-level conditions.

Table 4. Accuracy Test Results of The System on Tank 3

Test	Manual Measurement (cm)	System Measurement (cm)	Accuracy (%)
1	10	10	100
2	12	12	100
3	15	16	93.33
4	17	19	88.24
5	20	20	100
6	22	22	100
7	24	25	95.83
8	27	28	96.30
9	29	29	100
10	31	31	100

The experimental results for Tank 3 (Table 4) show that the proposed system achieved an average measurement accuracy of 97.37% with an average deviation of approximately 0.5 cm compared to manual measurements. All observed discrepancies remained within the ±1 cm tolerance limit, confirming stable and reliable sensing performance in the multi-node WSN deployment.

Overall, the measurement results demonstrate that the proposed system achieves accuracy exceeding 96% across all tested tanks, which is consistent with previous ultrasonic-based IoT monitoring studies reporting accuracy between 92% and 97% depending on environmental conditions and calibration quality [3], [7]. Compared with advanced sensing approaches such as optical fiber-based monitoring systems [19], the ultrasonic solution offers a practical balance between cost efficiency and measurement reliability. While many IoT-based water tank monitoring studies [22], [23], [24], [25], [26], [27] mainly focus on system implementation, this study complements implementation with quantitative validation through repeated accuracy testing and delay-based QoS evaluation within a unified WSN–IoT monitoring framework.

B. Network QoS Analysis

The packet delay was calculated using the following equation:

$$\text{Delay} = T_r - T_s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \quad (3)$$

where:

T_r = the packet receive time, and

T_s = the packet send time.

The total delay for multiple packets was calculated as:

$$\text{Total Delay} = \sum_{i=1}^{n} (T_{r_i} - T_{s_i}) \ \ldots\ldots \quad (4)$$

where n = the total number of analyzed packets.

Table 5. QoS (Delay) Test Results of the System

Test	QoS Delay (ms)	TIPHON Category
1	20.04631	very good
2	15.07075	very good
3	35.17349	very good
4	20.03608	very good
5	30.03976	very good
6	25.09567	very good
7	26.05658	very good
8	30.07442	very good
9	45.09336	very good
10	40.78515	very good
Average Delay	28.74716	very good

Network communication performance was evaluated by measuring delays under non-LoS indoor conditions with potential signal obstruction from walls and partitions. Based on ten experimental trials (Table 5), the system achieved delays ranging from 15.07 ms to 45.09 ms with an average delay of 28.75 ms. According to the TIPHON QoS standard [28], these values fall within the very good category, indicating reliable near real-time data transmission. The TIPHON QoS standard was adopted in this study to provide a practical reference for delay classification in IP-based communication networks. Although more advanced QoS metrics such as packet loss, jitter, and throughput are often used in comprehensive network performance evaluations, delay was selected as the primary indicator because the proposed system focuses on periodic sensor data transmission for real-time monitoring. In such applications, delay directly influences system responsiveness, while the transmitted data packets are relatively small and generated at low frequency, which reduces the impact of throughput and jitter on overall system performance. Therefore, delay analysis using the TIPHON classification provides a sufficient indication of communication performance for the intended indoor monitoring scenario. Future work will consider additional QoS metrics, including packet loss and jitter, to provide a more comprehensive evaluation of network performance.

The low average delay demonstrates that the ESP8266-based WiFi communication architecture can deliver near-real-time data transmission even under obstructed indoor conditions. Low latency is essential in WSN-based water monitoring systems to ensure timely data processing and system responsiveness [17], [20], while network delay performance is also influenced by topology and environmental interference [21]. Compared with previous IoT-based water monitoring studies such as [3], [5], and [24], which primarily focus on single-node implementations or basic monitoring functionality, this study implements a multi-node WSN topology and evaluates communication reliability through delay-based QoS analysis under realistic non-LoS indoor deployment conditions. These results confirm that the proposed architecture provides stable and reliable communication for residential-scale water tank monitoring applications.

In practical indoor WSN deployments, several environmental factors may influence communication performance, including multipath propagation and interference from other WiFi devices operating in the same frequency band. Signal reflections from walls, furniture, and other obstacles can cause variations in transmission delay and packet stability due to multipath effects. Interference from nearby WiFi networks may also contribute to occasional fluctuations in transmission. Despite these potential disturbances, the experimental results demonstrate that the proposed system maintains stable communication performance with relatively low delay during operation. WiFi communication was selected in this study because of its high data rate and low latency, which are advantageous for real-time monitoring applications in indoor environments. Compared with LoRaWAN, which is typically designed for long-range and low-power communication, WiFi offers faster data transmission within limited coverage areas, making it suitable for short-range indoor monitoring systems. Power consumption analysis was not included in this study since the primary focus was on sensing accuracy and communication performance; however, energy-efficiency evaluation will be considered in future work for long-term WSN deployments.

It should be noted that the use of two NodeMCU modules at the sink node (Figure 4) is not intended as an architectural innovation but rather as a technical design choice to distribute processing tasks between data reception and data transmission. In this configuration, preliminary data handling is performed locally at the sink node, thereby reducing the processing load on the cloud platform. This approach improves communication efficiency and enhances system stability within the proposed WSN–IoT monitoring framework. Overall, the experimental findings confirm that the proposed WSN–IoT-based water tank monitoring system achieves high sensing accuracy and excellent network performance. By integrating quantitative ultrasonic measurement validation with delay-based QoS analysis under realistic non-LoS conditions, this study provides a structured, experimentally validated evaluation framework, demonstrating that the system is technically reliable, scalable, and suitable for real-time domestic water tank monitoring applications.

IV. Conclusion

This study presented the design and experimental evaluation of a WSN–IoT-based water tank monitoring system integrating ultrasonic sensing with ESP8266-based WiFi communication. The experimental results demonstrate that the system achieved high measurement accuracy across the tested tanks, with average accuracies of 96.59%, 97.21%, and 97.37%, and measurement deviations below ±1 cm, indicating stable sensing performance under dynamic water-filling conditions. Network evaluation conducted under non-LoS indoor environments showed an average transmission delay of 28.75 ms, which falls within the very good category according to the TIPHON QoS standard. These results indicate that the proposed architecture is technically feasible and suitable for small-scale multi-node indoor monitoring applications. While the current implementation was validated using three sensor nodes, the system architecture is designed to support additional nodes, and larger-scale deployments will be explored in future work to further evaluate system scalability.

Acknowledgement

The authors would like to thank all parties who have contributed to the completion of this research.

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