Edge-Intelligent IoT System for Smart Water Usage Monitoring and Leak Detection

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Abstract—Growing demand for water resources and the lack of continuous monitoring mechanisms have made leakage detection a major challenge in existing water distribution systems. This paper proposes an edge-intelligent Internet of Things (IoT) framework for smart water usage monitoring and real-time leak detection. The system analyzes water flow data at the edge using a sliding time-window and threshold-based decision logic to identify abnormal flow behavior with reduced latency. Detected system states are communicated to an IoT cloud platform for realtime visualization and alert generation. The proposed approach minimizes false leak indications caused by transient fluctuations while ensuring reliable detection under normal operating conditions. Simulation results validate the effectiveness of the system in accurately distinguishing leak and non-leak scenarios. This work demonstrates the potential of integrating IoT and edge intelligence to develop scalable and efficient smart water management solutions for modern infrastructure.

Index Terms—IoT, Edge Computing, Smart Water Systems, Leak Detection, Real-Time Monitoring

I. Introduction

Efficient management of water resources has become a significant challenge due to increasing demand, urbanization, and infrastructure limitations. Undetected water leakage and abnormal consumption patterns contribute substantially to resource wastage and economic loss in residential, commercial, and industrial environments. Conventional water monitoring methods are largely manual and periodic, making them inadequate for timely leak identification and effective water usage control.

Recent advances in the Internet of Things (IoT) have enabled the development of smart monitoring systems that provide continuous data acquisition, real-time analysis, and remote accessibility. IoT-based water management solutions leverage sensors, communication networks, and cloud platforms to monitor usage patterns and generate actionable insights. However, systems that rely solely on cloud-based processing may experience higher latency and increased network dependency, which can affect responsiveness in real-time leak detection applications.

To overcome these challenges, edge intelligence has emerged as a promising paradigm for processing data closer to the source. By performing local analysis at the edge, systems can achieve faster response times, reduced bandwidth usage, and improved reliability. This paper presents an edgeintelligent IoT system for smart water usage monitoring and leak detection. The proposed system employs threshold-based analysis combined with a sliding time-window technique to accurately distinguish between normal usage and leak conditions while minimizing false detections. The analyzed data and system status are transmitted to an IoT cloud platform for real-time visualization and alert generation. The proposed approach demonstrates the effectiveness of integrating IoT and edge intelligence for building scalable and efficient smart water management systems.

II. Related Works

The use of Internet of Things (IoT) technologies for water usage monitoring has been extensively studied to improve resource management and reduce water losses. Early research primarily focused on deploying IoT-enabled sensors integrated with cloud platforms to collect, store, and analyze water flow data for identifying abnormal usage and leakage conditions [1]. These systems demonstrated improved visibility, remote accessibility, and automation when compared to traditional manual monitoring approaches.

Cloud-based IoT architectures have proven effective for large-scale data aggregation and centralized analytics. However, their dependence on cloud processing introduces challenges such as increased latency, higher communication overhead, and reliance on continuous network connectivity, which can limit their suitability for real-time leak detection applications [3].

To address these limitations, fog and edge computing paradigms have been explored in IoT-based water monitoring systems [2]. By enabling local processing closer to the sensing layer, edge computing reduces response time, improves system reliability, and minimizes unnecessary data transmission. Recent studies report that incorporating intelligent analysis at the edge significantly enhances leak detection accuracy and supports faster decision-making compared to cloud-only solutions [5].

In addition, several works have investigated data-driven and machine learning–based approaches for water leak detection. Although these methods improve detection accuracy, they often require large datasets, high computational resources, and complex model training procedures, making them less suitable for low-power or real-time edge deployments [4].

Despite these advancements, existing solutions continue to face challenges such as false leak detection caused by shortterm fluctuations in water flow and limited adaptability to varying consumption patterns. The proposed work builds upon existing research by employing a sliding time-window–based threshold analysis at the edge, enabling reliable real-time leak detection while minimizing false alarms and maintaining system scalability.

III. Methodology

The proposed system is developed using an edge-intelligent Internet of Things (IoT) framework for smart water usage monitoring and real-time leak detection. The methodology enables continuous monitoring of water flow, local analysis at the edge, automated decision-making, and cloud-based visualization. To clearly explain the system operation, both a high-level workflow and a detailed system flow are illustrated using flowchart diagrams.

Fig. 2 presents a high-level block flowchart of the proposed system. It provides a simplified view of the sequential

processing stages, starting from water flow data generation and ending with cloud-based visualization and alert generation.

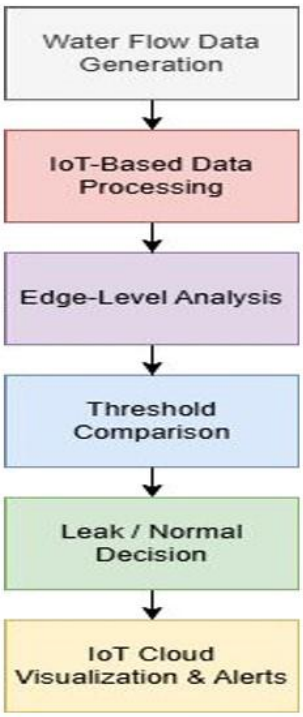
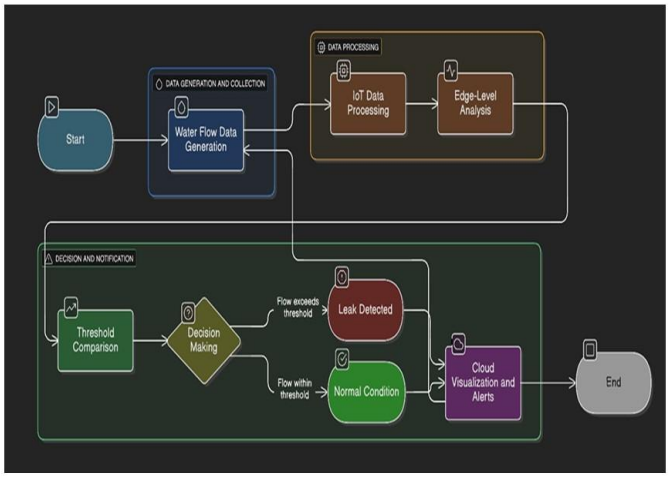


Fig. 1. Flowchart of the IoT-based water monitoring system

A. Data Acquisition

Water flow data is generated to represent real-time water usage conditions. This data simulates the output of a water flow sensor deployed in residential or commercial water distribution

Fig. 2. High-level block flowchart of the IoT-based water monitoring system



systems. The generated data includes normal consumption patterns as well as abnormal conditions such as continuous flow caused by leakage.

B. IoT-Based Data Processing

The acquired water flow data is processed using IoTbased data handling techniques. This stage ensures continuous monitoring and structured data transfer between system components. It acts as an interface between the data source and the edge-level analysis unit.

C. Edge-Level Analysis

Edge-level intelligence is applied to analyze water flow data locally. A sliding time-window approach is used to evaluate recent flow values over a predefined interval. This technique helps in reducing the effect of short-term fluctuations and improves the reliability of leak detection.

D. Threshold Comparison and Decision Making

The average flow value obtained from the sliding window analysis is compared against a predefined threshold. If the calculated value exceeds the threshold, the system identifies the condition as a leak; otherwise, it is classified as normal operation. This automated decision-making process enables timely detection of abnormal water usage.

E. Cloud Visualization and Alerts

After classification, the processed water usage data and system status are transmitted to an IoT cloud platform for realtime visualization. The cloud interface allows users to monitor water consumption patterns remotely. In the event of a leak detection, alert notifications are generated to inform users for immediate action.

A detailed system flow diagram illustrating the interaction between data generation, IoT-based processing, edge-level analysis, decision-making, and cloud notification is shown in Fig. ??. This detailed representation highlights the integration of edge intelligence and cloud services in achieving real-time monitoring and leak detection.

IV. System Architecture

The proposed system architecture is designed to support smart water usage monitoring and leak detection using an edge-intelligent Internet of Things (IoT) framework. The architecture defines the structural components of the system and their interactions, focusing on data flow and system integration rather than algorithmic processing. This modular design enables scalability, low-latency operation, and reliable monitoring.

The water flow sensing component acts as the data source of the system and is responsible for generating water usage measurements. In this work, water flow data is simulated to represent real-time sensor output; however, the same architecture can be implemented using physical flow sensors in practical deployments.

The edge computing unit serves as the primary local processing block within the system. It receives water flow data from the sensing component and hosts the intelligence required for system state evaluation. By performing processing at the edge, the architecture reduces reliance on continuous cloud connectivity and supports faster response to abnormal conditions.

An IoT communication interface connects the edge computing unit to the cloud platform. This interface ensures reliable data transmission and enables seamless integration between edge and cloud layers. The communication layer is designed to handle real-time data updates while minimizing network overhead.

The cloud platform provides centralized data management and monitoring capabilities. It supports real-time visualization of water usage patterns, alert management, and historical data storage. The cloud layer also allows multiple edge nodes to be integrated into a unified monitoring framework, enabling system scalability.

The user interface represents the application layer through which users interact with the system. It provides access to water usage dashboards, system status information, and alert notifications. This interface enables users to remotely monitor and respond to leak conditions in a timely manner.

Overall, the proposed system architecture establishes a clear separation between data acquisition, edge intelligence, cloud

services, and user interaction, ensuring efficient operation and flexibility for future extensions.

V. Results and Discussion

The proposed edge-intelligent IoT-based water monitoring system was evaluated using simulated water flow data to assess its effectiveness in detecting leakage conditions and normal operating states. The simulation was designed to represent real-time water usage behavior commonly observed in residential and commercial environments.

Fig. 3 illustrates the water flow monitoring results over a fixed time duration. Under normal operating conditions, the water flow values remain within the predefined threshold limits. A sudden and sustained increase in flow is introduced to simulate a leak condition. When the flow exceeds the leak threshold, the abnormal behavior is clearly observed, validating the effectiveness of continuous monitoring.

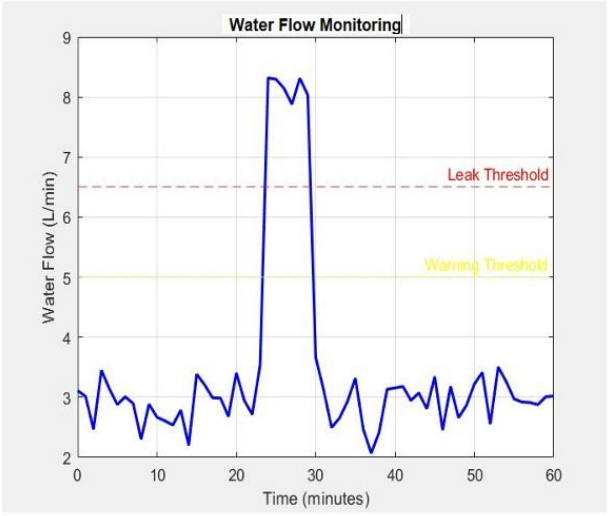


Fig. 3. Water flow monitoring with warning and leak threshold levels

Fig. 4 presents the edge-level leak detection results. Normal flow conditions are represented by green markers, while detected leak conditions are highlighted in red. The edgelevel processing accurately distinguishes between normal and abnormal flow values, demonstrating reliable leak detection performance.

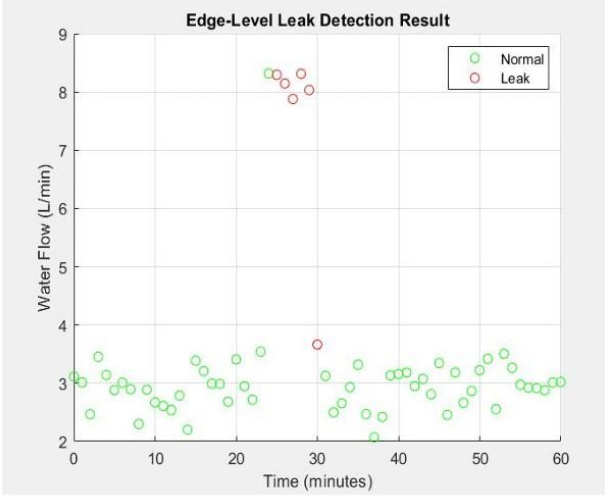
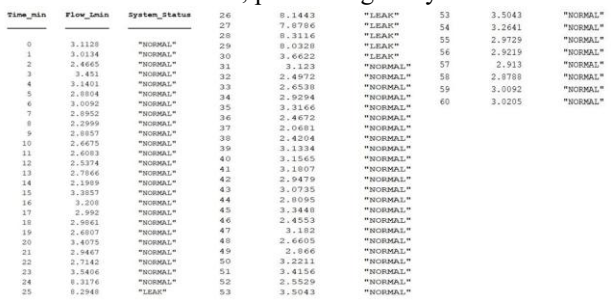


Fig. 4. Edge-level leak detection results showing normal and leak conditions

Table 5 shows the system status classification corresponding to the observed water flow values at different time instances. The table confirms that the system correctly labels leak conditions when the flow exceeds the threshold and classifies normal conditions otherwise.

The results demonstrate that the use of a sliding timewindow approach reduces false leak detections caused by short-term fluctuations. Furthermore, performing analysis at



Time_min	Flow_lmin	System_Status
0	3.1128	"NORMAL"
1	3.0134	"NORMAL"
2	2.4665	"NORMAL"
3	3.451	"NORMAL"
4	3.1401	"NORMAL"
5	2.8804	"NORMAL"
6	3.0092	"NORMAL"
7	2.8952	"NORMAL"
8	2.2999	"NORMAL"
9	2.8857	"NORMAL"
10	2.4675	"NORMAL"
11	2.6083	"NORMAL"
12	2.5374	"NORMAL"
13	2.7866	"NORMAL"
14	2.1999	"NORMAL"
15	3.3857	"NORMAL"
16	3.208	"NORMAL"
17	2.992	"NORMAL"
18	2.9961	"NORMAL"
19	2.6807	"NORMAL"
20	3.4075	"NORMAL"
21	2.9467	"NORMAL"
22	2.7142	"NORMAL"
23	3.5406	"NORMAL"
24	0.3176	"NORMAL"
25	0.2948	"LEAK"
26	0.1443	"LEAK"
27	7.8786	"LEAK"
28	8.3116	"LEAK"
29	8.0328	"LEAK"
30	3.6622	"LEAK"
31	3.123	"NORMAL"
32	2.4972	"NORMAL"
33	2.6538	"NORMAL"
34	2.9294	"NORMAL"
35	3.3166	"NORMAL"
36	2.4672	"NORMAL"
37	2.0681	"NORMAL"
38	2.4204	"NORMAL"
39	3.1334	"NORMAL"
40	3.1565	"NORMAL"
41	3.1807	"NORMAL"
42	2.9479	"NORMAL"
43	3.0735	"NORMAL"
44	2.8095	"NORMAL"
45	3.3448	"NORMAL"
46	2.4553	"NORMAL"
47	3.182	"NORMAL"
48	2.6605	"NORMAL"
49	2.866	"NORMAL"
50	3.2211	"NORMAL"
51	3.4156	"NORMAL"
52	2.5529	"NORMAL"
53	3.5043	"NORMAL"
53	3.5043	"NORMAL"
54	3.2641	"NORMAL"
55	2.9729	"NORMAL"
56	2.9219	"NORMAL"
57	2.913	"NORMAL"
58	2.8788	"NORMAL"
59	3.0092	"NORMAL"
60	3.0205	"NORMAL"

Fig. 5. System status classification based on water flow values

the edge enables faster decision-making compared to cloudonly approaches. The processed data and system status can be transmitted to the IoT cloud platform for real-time visualization and alert generation.

Overall, the experimental results validate the effectiveness of the proposed methodology in accurately identifying leak conditions while maintaining reliable monitoring under normal operating scenarios. These findings highlight the suitability of the proposed system for smart water management applications.

TABLE I
Water Flow–Based Leak Detection Decision

Water Flow (L/min)	Flow Condition	System Status
≤5.0	Normal Usage	NORMAL
5.0 < Flow < 6.5	Abnormal Usage	WARNING
≥6.5	Continuous High Flow	LEAK

VI. Performance Analysis

This section analyzes the performance of the proposed edgeintelligent IoT-based water monitoring system in terms of detection accuracy, latency, robustness, computational efficiency, and scalability. The objective is to evaluate the system's effectiveness for real-time leak detection and continuous monitoring under varying water usage conditions.

A. Detection Effectiveness

The proposed system demonstrates effective leak detection by reliably distinguishing between normal and abnormal water flow patterns. Leak conditions characterized by sustained high flow values exceeding the predefined leak threshold were consistently identified, while normal consumption patterns were accurately classified. The use of a sliding time-window–based evaluation improved detection reliability by filtering transient variations, thereby reducing false leak indications.

B. Latency Performance

Real-time responsiveness is a key requirement for smart monitoring systems. By executing data analysis and decisionmaking at the edge, the proposed system significantly reduces detection latency compared to cloud-dependent approaches. Leak detection decisions are generated locally, ensuring timely identification of abnormal conditions and enabling faster corrective action.

C. Robustness and Stability

The system exhibits stable performance under dynamic water usage scenarios. Short-duration flow spikes and temporary fluctuations do not result in false leak detection due to the averaging effect introduced by the sliding window mechanism. This robustness enhances system stability and ensures dependable operation during normal and irregular usage patterns.

D. Computational Overhead

The threshold-based decision logic employed in the proposed system is computationally lightweight and does not require complex mathematical operations or model training. This low computational overhead makes the system suitable for deployment on resource-constrained edge devices while maintaining real-time processing capability.

E. Scalability and Practical Deployment

The modular system architecture supports scalable deployment by allowing multiple edge nodes to operate independently while interfacing with a centralized cloud platform. Edge-level processing reduces network bandwidth usage by transmitting only processed results instead of continuous raw data streams. These characteristics make the proposed system practical for deployment in large residential complexes, industrial environments, and smart city water management infrastructures.

VII. Conclusion

This paper presented an edge-intelligent Internet of Things (IoT) based system for smart water usage monitoring and real-time leak detection. The proposed methodology combines continuous water flow monitoring with edge-level data analysis to identify abnormal usage patterns efficiently. A threshold-based decision mechanism, supported by a sliding time-window approach, was employed to distinguish between normal and leak conditions while minimizing false detections caused by short-term fluctuations.

Simulation results demonstrated that the system accurately detected leak conditions and maintained reliable performance during normal operation. The integration of edge-level processing reduced response latency and improved system reliability compared to cloud-only approaches. The analyzed data was successfully visualized using an IoT cloud platform, enabling real-time monitoring and alert generation.

Overall, the proposed system highlights the effectiveness of integrating IoT with edge intelligence for developing scalable, automated, and efficient smart water management solutions suitable for residential, commercial, and smart city applications.

VIII. Future Scope

The proposed edge-intelligent IoT-based water monitoring system can be further extended in several directions to enhance its practical applicability and performance. Real-time deployment can be achieved by integrating actual water flow sensors and embedded IoT hardware platforms for live data acquisition and processing.

Advanced data analytics and machine learning techniques can be incorporated to improve leak detection accuracy and enable predictive analysis for early identification of potential leak conditions. Adaptive thresholding methods may also be implemented to handle varying usage patterns across different environments.

The system can be enhanced with mobile and web-based notification mechanisms such as SMS, email, or mobile applications to provide instant alerts and usage insights to users. Additionally, the proposed approach can be scaled for large buildings, industrial facilities, and smart city water management systems by integrating multiple sensing nodes and centralized monitoring dashboards.

Acknowledgment

The author would like to express sincere gratitude to Dr.Pratibha K for her valuable guidance, continuous encouragement, and technical support throughout this work. The author also thanks RV College of Engineering for providing the necessary academic environment and facilities to carry out this project successfully.

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