RESEARCH PAPER

Real-Time Urban Manhole Monitoring Using Raspberry Pi Pico and Wireless Sensor Networks

Aditi Anand Fulkae[1], P. B. Mane[2], Nilima Warade[3]

[1]PG Research Scholar, Dept. of Electronics & Telecommunication, AISSMS Institute of Information Technology, Pune, Maharashtra, India – 411001
[2]Professor, Dept. of Electronics & Telecommunication, AISSMS Institute of Information Technology, Pune, Maharashtra, India – 411001
[3]Assistant Professor, Dept. of Electronics & Telecommunication, AISSMS Institute of Information Technology, Pune, Maharashtra, India – 411001

ABSTRACT

Urban manholes play a vital role in supporting underground infrastructure, yet their monitoring is still largely manual, reactive, and often unsafe. Such practices can lead to delayed identification of hazardous gas build-up, unauthorized opening of manhole covers, and unnoticed structural displacement, posing serious risks to both workers and the public. To overcome these challenges, this study presents the design and development of a low-cost, IoT-based real-time manhole monitoring system built around the Raspberry Pi Pico microcontroller. The proposed system combines gas sensors for detecting harmful gases with MEMS-based motion sensors to monitor manhole cover movement, enabling continuous tracking of environmental conditions and physical disturbances. Sensor data are processed locally using embedded C/C++ and transmitted through Wi-Fi and GSM communication modules to a centralized monitoring platform. This platform supports real-time data visualization, logging, and automated alert generation. A threshold-based alert mechanism promptly notifies authorized personnel via dashboards and mobile messages, significantly reducing response time and improving safety. The system architecture is designed with a strong emphasis on low power consumption, modularity, and reliable communication, making it suitable for scalable deployment in smart city environments. Experimental evaluation under real-world conditions demonstrates accurate gas detection, quick response to abnormal events, and stable wireless data transmission. These results confirm the practicality and effectiveness of the proposed solution, showing clear improvements in operational safety and maintenance efficiency over conventional inspection methods. Overall, the proposed framework offers a robust and adaptable foundation for intelligent urban infrastructure monitoring, with potential for future enhancements such as predictive analytics and energy-harvesting capabilities in advanced smart city applications.

Keywords: *Internet of Things (IoT); Smart City Infrastructure; Wireless Sensor Networks; Embedded Systems; Real-Time Monitoring*

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INTRODUCTION

Urban infrastructure systems are fundamental to the functioning of modern cities, supporting essential services such as wastewater disposal, storm-water drainage, and underground utility distribution. Within these networks, manholes serve as critical access points for inspection, routine maintenance, and emergency operations. As cities continue to expand and infrastructure becomes more complex, maintaining the safety, reliability, and operational efficiency of manholes has emerged as a significant challenge. Conventional inspection practices largely depend on manual and periodic checks, which are not only labour-intensive and time-consuming but also insufficient for the early detection of hazardous conditions. More importantly, these inspections expose maintenance personnel to serious risks, including toxic gas exposure, unexpected flooding, and structural instability, highlighting the need for safer and more intelligent monitoring solutions.

A major limitation of traditional manhole management is the lack of continuous monitoring and real-time situational awareness. Conditions such as methane accumulation, unauthorized opening of manhole covers, and gradual structural displacement often go unnoticed until they escalate into critical failures. Such delays can lead to public safety incidents, damage to infrastructure, and increased maintenance costs. To address these concerns, urban authorities and researchers are increasingly turning toward automated monitoring approaches that enable proactive maintenance and timely decision-making. In this context, the integration of embedded systems, Internet of Things (IoT) technologies, and wireless communication networks offers a promising pathway for transforming conventional infrastructure management into intelligent, data-driven systems.

The IoT paradigm facilitates the deployment of distributed sensor nodes capable of autonomously sensing, processing, and transmitting data. In smart city initiatives, IoT-based monitoring has already shown considerable success in

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**Author for Correspondence: Aditi Anand Fulkae* applications such as traffic management, environmental monitoring, energy optimization, and public safety. However, monitoring underground infrastructure presents challenges that differ significantly from above-ground systems. These include confined physical spaces, harsh environmental conditions, limited power availability, and unreliable wireless connectivity due to signal attenuation. Consequently, the design of an effective manhole monitoring system requires careful consideration of embedded processing capability, energy efficiency, sensor reliability, and robust communication strategies.

Wireless communication plays a central role in enabling real-time monitoring. Technologies such as Wi-Fi, GSM, and low-power wide-area networks (LPWANs), including LoRa, have been explored for urban sensing applications, each offering specific trade-offs in terms of range, data rate, power consumption, and deployment cost. Selecting an appropriate communication approach and integrating it seamlessly with embedded hardware is essential to ensure reliable data transmission from underground nodes to centralized monitoring platforms. From a systems and communications perspective, this integration demands efficient data handling, suitable protocol selection, and fault-tolerant design.

Although several IoT-based manhole monitoring solutions have been reported in the literature, many suffer from notable limitations. Some rely on high-end microcontrollers or single-board computers, resulting in increased cost and power consumption. Others focus primarily on sensing capabilities while neglecting communication reliability, real-time alerting, or system scalability. In addition, the use of proprietary platforms in certain designs reduces flexibility and poses challenges for large-scale deployment. These shortcomings underline the need for low-cost, open, and scalable architectures that balance sensing accuracy, embedded intelligence, and communication efficiency.

To address these challenges, this paper proposes an IoT-enabled real-time manhole monitoring system based on the Raspberry Pi Pico microcontroller and standard wireless communication modules. The Raspberry Pi Pico provides a low-power, dual-core processing platform well suited for sensor data acquisition, local processing, and communication tasks. Using embedded C/C++ programming, the system performs real-time data processing at the node level, thereby reducing communication overhead and improving system responsiveness. Hazardous gas detection is achieved using appropriate gas sensors, while MEMS-based motion sensors are employed to monitor manhole cover displacement and detect unauthorized movement. The proposed system follows a layered architecture in which sensor data are processed locally and transmitted wirelessly to a centralized monitoring server. The server supports real-time visualization, data storage, and alert management, allowing operators to monitor manhole conditions remotely. A threshold-based alert mechanism ensures immediate notification through dashboards and mobile messaging whenever abnormal conditions are detected. This approach significantly reduces reliance on manual inspections and enhances both worker safety and operational efficiency.

Energy efficiency and scalability are key design considerations, particularly given the constraints of underground deployment. Since frequent battery replacement is impractical, the system is optimized for low power consumption through efficient sensor sampling and lightweight communication protocols. Its modular architecture allows additional sensors or communication technologies to be integrated as required, making the solution adaptable to diverse urban settings and evolving smart city needs. Experimental validation under real-world conditions demonstrates that the proposed system accurately detects hazardous gas concentrations and manhole cover displacement while maintaining reliable wireless communication with minimal latency. These results confirm the feasibility of deploying low-cost, IoT-based solutions for underground infrastructure monitoring. Compared with traditional inspection-based methods, the proposed approach offers substantial improvements in safety, efficiency, and real-time operational visibility.

The main contributions of this work are summarized as follows:

This study presents a comprehensive IoT-based framework for real-time manhole monitoring, integrating environmental sensing, embedded data processing, and wireless communication into a unified architecture.

A cost-effective and energy-efficient implementation is developed using resource-constrained hardware and open-source development tools, making the solution practical for large-scale deployment.

A reliable monitoring and alerting mechanism is designed to support smart city applications, enabling timely detection of hazardous conditions and rapid notification to responsible authorities.

The effectiveness and real-world applicability of the proposed system are validated through experimental evaluation, demonstrating its suitability for urban infrastructure monitoring.

Although a number of IoT-based manhole monitoring systems have been reported in the literature, most existing solutions focus mainly on sensor integration and cloud-level data aggregation, paying relatively little attention to embedded intelligence and communication efficiency. In contrast, the proposed system adopts an embedded-centric and communication-aware design, where key decision-making tasks are shifted from the cloud to the sensing node itself. By utilizing the dual-core capabilities of the Raspberry Pi Pico microcontroller, the system supports local, event-driven processing, enabling abnormal conditions to be identified and handled in real time without the need for continuous data transmission. This approach effectively reduces communication overhead, minimizes latency, and lowers power consumption—addressing some of the main limitations observed in earlier studies.

Furthermore, while many prior works rely on a single communication technology, the proposed framework employs a hybrid Wi-Fi and GSM communication strategy. This dual-channel design enables low-latency data transfer during normal operation while ensuring dependable alert delivery in underground environments where network connectivity can be intermittent or unreliable. Such a hybrid communication approach is rarely explored in existing manhole monitoring systems and directly responds to reliability challenges commonly encountered in smart city deployments.

The novelty of the proposed work is also reflected in its comprehensive experimental evaluation. The system is assessed across multiple performance parameters, including sensing accuracy, response time, power consumption, and communication range. These metrics are often reported in isolation in previous studies, limiting meaningful comparison and reproducibility. By presenting a detailed and quantitative performance analysis on resource-constrained hardware, this work provides a scalable and reproducible reference architecture for intelligent underground infrastructure monitoring. Taken together, the integration of embedded-level intelligence, hybrid communication design, and thorough experimental validation clearly differentiates the proposed system from existing IoT-based manhole monitoring solutions.

LITERATURE SURVEY

Several studies have explored IoT-based approaches for monitoring urban manholes, focusing on improving safety, operational efficiency, and infrastructure management.

Vaishali B. Niranjane et al. [1] presented an IoT-based manhole monitoring system that employs multiple sensors, such as water flow rate, temperature, and tilt sensors, to supervise urban drainage systems in real time. Their work highlights the use of GSM-based notifications and cloud data storage through ThingSpeak, enabling timely alerts and performance analysis. While effective for drainage monitoring, the study primarily emphasizes cloud connectivity rather than embedded-level intelligence. Praseena and Aravind [2] proposed an IoT-enabled manhole surveillance system aimed at continuous monitoring of sewage environments, including harmful gas concentration, water level, and manhole lid displacement. Their system integrates secure web and Telegram applications for data communication and incorporates a solenoid valve to manage gas pressure, thereby enhancing worker safety. However, the work focuses mainly on application-layer integration without addressing communication efficiency or embedded processing optimization. Tangella S. P. et al. [3] developed an IoT-based solution for detecting open manholes, sewage overflow, and environmental variations. The system uses multiple sensors and GSM communication to notify municipal authorities, contributing to urban safety and cleanliness. Similarly, Andrews et al. [4] emphasized real-time monitoring of manhole lid positions to reduce accidents and manual inspection efforts, highlighting safety improvements through timely alerts rather than architectural innovation at the embedded level. Susithra N. et al. [5] introduced the Subterranean Access Point Surveillance System (SAPSS), which employs an ESP32 microcontroller to monitor gas emissions, water levels, and debris accumulation. The system uses GSM-based alerts and is designed to be scalable for urban deployments. While SAPSS demonstrates effective sensing and alerting, it relies on a single communication approach and does not explore hybrid communication strategies.

Vikram et al. [6] presented a cost-effective IoT-based smart manhole monitoring system that detects gas toxicity, tilt, and water levels. Alerts are transmitted via SMS, and data are updated on a web interface to assist municipal authorities. Singh and Kumar et al. [7] employed a Raspberry Pi-based controller with GSM and Wi-Fi connectivity to monitor parameters such as gas concentration, temperature, and water level. Although these systems improve real-time monitoring, they primarily depend on continuous data transmission and cloud processing. Mohanraj et al. [8] proposed a wireless sensor network–based manhole monitoring system integrated with cloud services to ensure real-time supervision of drainage conditions and improve the safety of manual scavengers. Ishrat [9] discussed broader smart city monitoring frameworks using sensor networks, highlighting the role of scalable and interoperable architectures for infrastructure health monitoring, including manholes. Vidhya Sree et al. [10] developed a LoRa-based manhole monitoring system using an ATmega328P microcontroller to detect hazardous gas levels and lid displacement. The use of LPWAN communication enhances range and energy efficiency, although embedded decision-making remains limited. Ariffin and Alias [11] focused on smart sensor–integrated manhole covers, emphasizing networking challenges and reliable connectivity for urban infrastructure management rather than embedded intelligence. Miriyala et al. [12] proposed an IoT-based system using multiple sensors and Wi-Fi communication to monitor manholes and alert municipal officers of hazardous conditions. Imran et al. [13] utilized a NodeMCU-based architecture integrated with GPS and the Blynk platform to monitor gas levels and water height, improving municipal maintenance efficiency. Roshan et al. [14] presented an Arduino UNO–based system with GSM communication for detecting blockages and gas leaks, highlighting cost-effectiveness and scalability.

Overall, existing studies demonstrate the feasibility of IoT-based manhole monitoring but largely emphasize sensing and cloud connectivity. Limited attention is given to embedded-level intelligence, communication efficiency, and hybrid communication architectures. These gaps motivate the proposed work, which focuses on event-driven embedded processing and reliable hybrid communication tailored for underground smart city infrastructure.

Table 1 shows Comparative Analysis of Existing IoT-Based Manhole Monitoring Systems.

Table 1. Comparative Analysis of Existing IoT-Based Manhole Monitoring Systems

Ref.	**Controller**	**Communication**	**Local Processing**	**Limitation**

[1]	Arduino	GSM	Limited	No latency or power analysis
[2]	MCU	Web / App	Minimal	No embedded decision logic
[3]	MCU	GSM	Limited	No power optimization
[5]	ESP32	GSM	Moderate	No hybrid communication
[6]	SBC	Wi-Fi	Limited	Higher power consumption
Proposed Work	Raspberry Pi Pico	Wi-Fi and GSM	Event-driven embedded logic	—

3. METHODOLOGY

The proposed methodology combines embedded sensing, local data processing, and wireless communication to support continuous monitoring of underground urban infrastructure. The system is designed with a strong focus on modularity, low power operation, reliable data transmission, and real-time alert generation, all of which are critical requirements for scalable smart city deployments. The overall architecture of the proposed system is illustrated in Figure 1, which presents the block diagram and highlights the interaction between sensing, processing, and communication modules.

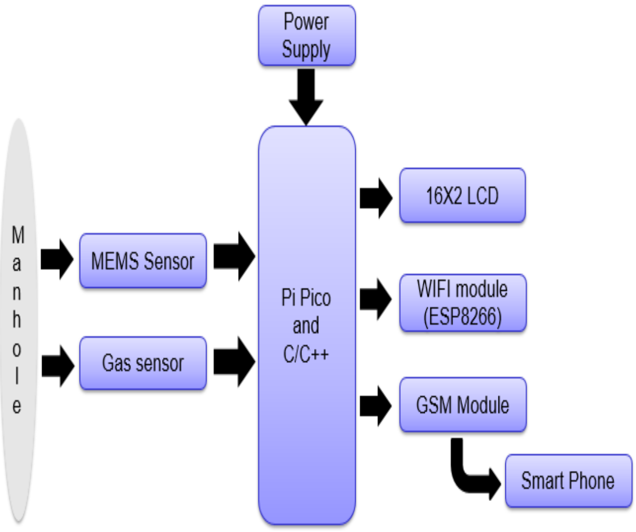


Figure 1. Block diagram of proposed system

3.1 System Architecture Overview

The proposed system adopts a layered IoT architecture composed of three main layers: the sensing layer, the embedded processing and communication layer, and the centralized monitoring layer. The sensing layer is responsible for collecting environmental and positional information from within the manhole, while the embedded processing layer carries out local computation, event-based decision-making, and wireless data transmission. The centralized monitoring layer manages data storage, visualization, and alert dissemination for system operators. This layered design promotes a clear separation of responsibilities across system components, which simplifies scalability and enhances fault tolerance. Each manhole is equipped with an autonomous sensor node capable of independent operation and direct communication with a central server. By performing preliminary data processing at the node level, the architecture supports real-time monitoring while reducing unnecessary data transmission and overall communication overhead.

3.2 Hardware Design and Sensor Integration

The Raspberry Pi Pico microcontroller serves as the core hardware component of the proposed system and is selected for its low power consumption, compact form factor, and dual-core processing capability. Acting as the central control unit, the microcontroller interfaces with multiple sensors and communication modules to manage data acquisition, local processing, and transmission. Its processing capability enables basic signal filtering and threshold-based decision-making at the node level, thereby reducing unnecessary data transmission and improving overall communication efficiency.

Hazardous gas detection is achieved using MQ-series gas sensors, which are commonly employed for monitoring gases such as methane and carbon monoxide in underground environments. These sensors generate analog voltage outputs proportional to gas concentration, which are sampled using the analog-to-digital converter (ADC) available on the microcontroller. Prior to deployment, the sensors are calibrated to ensure reliable and consistent detection across varying environmental conditions.

To identify unauthorized access or structural displacement of manhole covers, MEMS-based motion or tilt sensors are integrated into the system. These sensors continuously monitor changes in orientation or movement and communicate with the microcontroller through digital interfaces such as I^{2}C. This approach enables accurate motion detection while keeping wiring complexity and power consumption to a minimum.

All hardware components are housed within a weather-resistant and corrosion-resistant enclosure designed to withstand harsh underground conditions. The system is powered by rechargeable batteries supported by efficient power management circuitry, ensuring stable and continuous operation over extended deployment periods.

3.3 Embedded Software Implementation

The embedded software for the proposed system is developed using C/C++, enabling efficient execution on resource-constrained hardware platforms. The firmware is organized into modular tasks that handle sensor data acquisition, signal pre-processing, communication management, and alert generation. This modular structure not only simplifies debugging and maintenance but also allows for straightforward system upgrades and future feature expansion.

Sensor data acquisition routines periodically sample gas concentration and motion-related parameters from the connected sensors. To enhance measurement reliability, raw sensor readings are processed using simple averaging techniques to suppress noise and short-term fluctuations. Threshold values for each monitored parameter are established based on relevant safety guidelines and empirical testing. When sensor measurements exceed these predefined limits, the system identifies the condition as an abnormal event.

Decision-making is performed locally at the microcontroller level to reduce communication latency and improve responsiveness. Rather than transmitting continuous streams of raw sensor data, the system selectively sends event notifications and relevant summarized information to the central server. This strategy significantly lowers bandwidth consumption and power usage while ensuring that critical alerts are delivered in a timely manner.

3.4 Wireless Communication Strategy

Reliable wireless communication is a key requirement for effective real-time monitoring of underground infrastructure. To meet this need, the proposed system integrates Wi-Fi and GSM communication modules, each serving a distinct purpose. The Wi-Fi module is used for high-speed local data transmission, establishing a connection with a nearby access point to forward sensor data to the central monitoring server through lightweight communication protocols.

Sensor readings are organized into structured data packets and transmitted either at predefined intervals or immediately when abnormal conditions are detected. To improve robustness, the firmware incorporates retry and timeout mechanisms that help maintain reliable communication in environments where signal quality may vary due to underground constraints. These measures ensure consistent data delivery and reduce the likelihood of packet loss.

For critical situations requiring immediate attention, a GSM module is employed to send short message service (SMS) alerts directly to authorized personnel. This dual-communication strategy provides redundancy and enhances system responsiveness, particularly in scenarios where internet connectivity is unreliable or temporarily unavailable.

3.5 Centralized Monitoring and Data Management

The centralized monitoring layer is implemented through a server-based application designed to collect data from multiple distributed sensor nodes. Incoming data are processed at the server, time-stamped, and stored in a structured database to support historical analysis. This centralized data repository enables long-term trend evaluation and facilitates the development of predictive maintenance strategies for urban infrastructure.

A graphical user interface (GUI) is developed to present real-time sensor information, system status, and alert notifications in an intuitive manner. The interface provides operators with interactive dashboards that display gas concentration levels, manhole cover status, and node connectivity. Visual cues, including color-coded indicators and warning symbols, are used to clearly highlight abnormal conditions, allowing operators to make quick and informed decisions.

An integrated alert management subsystem ensures that critical events immediately trigger both on-screen notifications and short message service (SMS) alerts. By automating the alerting process, the system significantly reduces response time compared to conventional manual inspection practices and contributes to improved operational safety and maintenance efficiency.

3.6 Power Management and Energy Efficiency

Energy efficiency is a critical design consideration, particularly because underground sensor nodes are difficult to access for frequent maintenance or battery replacement. To address this challenge, the proposed system is designed to operate in low-power modes and uses optimized sensor sampling intervals to reduce overall energy consumption. During idle periods, the microcontroller transitions into low-power states and wakes only when sensor measurements or communication tasks are required.

In addition, the frequency of data transmission is dynamically adjusted according to system conditions. Under normal operating scenarios, sensor data are transmitted at predefined intervals, while the detection of abnormal events triggers immediate communication. This adaptive communication strategy effectively balances the need for timely responsiveness with long-term power conservation.

3.7 Experimental Validation Approach

To assess the performance of the proposed system, experimental evaluations are carried out under both controlled laboratory conditions and real-world deployment scenarios. Key performance metrics considered include sensor accuracy, communication latency, system response time, and power consumption. Gas sensing accuracy is evaluated by exposing the sensors to known gas concentrations, while motion detection performance is examined through controlled displacement tests of the manhole cover.

Communication reliability is analyzed by monitoring packet delivery success rates and measuring transmission delays under varying network conditions. In addition, power consumption measurements are used to estimate the expected operational lifetime of the system during typical usage. Together, these experiments confirm the effectiveness, reliability, and practical suitability of the proposed methodology for real-world deployment.

Figure 2. shows the flowchart of the process undertaken during the implementation.

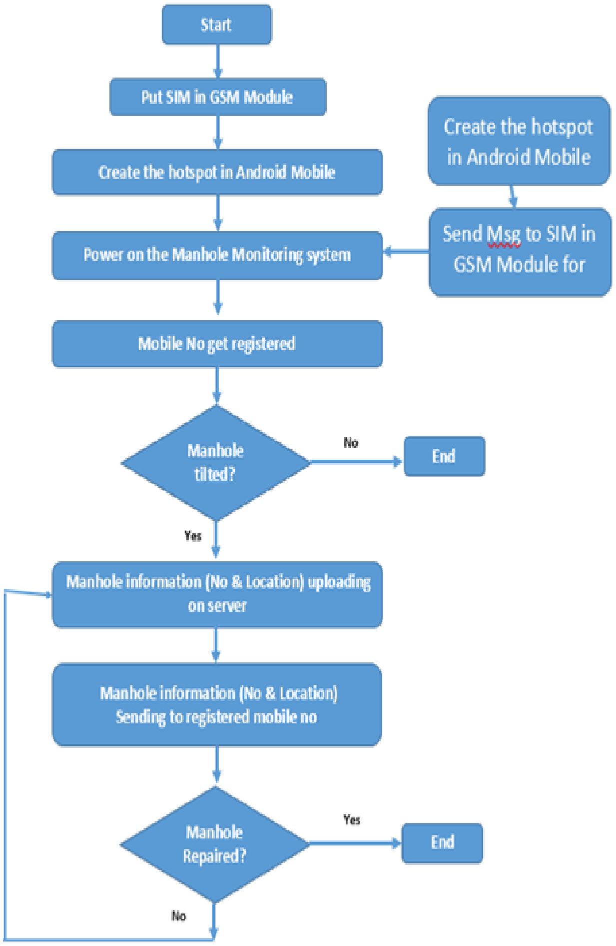


Figure 2. Flowchart of the process undertaken during the implementation

4. RESULTS AND DISCUSSION

This section presents the experimental results obtained from the implementation of the proposed IoT-enabled manhole monitoring system and discusses their significance in terms of system reliability, communication performance, and practical applicability in smart city environments. Figure 3 illustrates the experimental setup of the proposed manhole monitoring system.

The evaluation focuses on key performance indicators, including sensing accuracy, response time, communication stability, and energy efficiency, which are essential for effective real-time monitoring of underground infrastructure.

Figure 3. Experimental set – up of proposed Manhole monitoring system

The developed system was deployed in a controlled real-world environment to assess its ability to continuously monitor hazardous gas concentration and manhole cover displacement. The sensor nodes operated autonomously, acquiring environmental and positional data and transmitting processed information to the centralized monitoring platform. During normal operating conditions, the system successfully maintained periodic data updates without communication loss, demonstrating stable long-term operation.

The embedded processing strategy effectively filtered sensor noise and ensured that only relevant data were transmitted. This reduced unnecessary network traffic and contributed to efficient bandwidth utilization. The results confirm that local decision-making at the embedded node level is effective for underground monitoring scenarios, where communication reliability may be constrained.

To evaluate the effectiveness and reliability of the proposed IoT-based manhole monitoring system, a comprehensive performance assessment was conducted focusing on sensing accuracy, response time, power efficiency, and communication range. These metrics are critical for determining the system's suitability for real-time urban infrastructure monitoring and long-term deployment in smart city environments.

The accuracy of gas detection was assessed by exposing the sensing unit to controlled concentrations of methane under varying environmental conditions. The experimental results indicate that the gas sensing module achieves an average detection accuracy of approximately **95%**, demonstrating consistent and reliable identification of hazardous gas presence. This level of accuracy confirms the effectiveness of the sensor calibration and embedded pre-processing techniques used to minimize noise and false detections, which are essential for safety-critical applications.

System responsiveness was evaluated by measuring the time elapsed between the occurrence of an abnormal event—such as gas leakage or manhole cover movement and the generation of an alert at the monitoring platform. The results show that the system is capable of detecting and reporting events within an average response time of **500 milliseconds**, satisfying the real-time monitoring requirements of urban safety applications. The low latency is primarily attributed to local decision-making at the embedded node level and efficient wireless data transmission.

Power consumption analysis revealed that the system operates with an average current draw of approximately **200 mA** during active monitoring. This indicates that the proposed design is energy-efficient and well-suited for battery-powered operation over extended periods. Adaptive communication strategies further contribute to power savings by reducing unnecessary data transmission during normal operating conditions.

The communication range of the system was evaluated using the ESP8266 wireless module, which demonstrated stable data transmission over distances of up to **50 meters** in typical urban environments. This range is sufficient for most municipal monitoring scenarios and ensures reliable connectivity between underground sensor nodes and nearby access points.

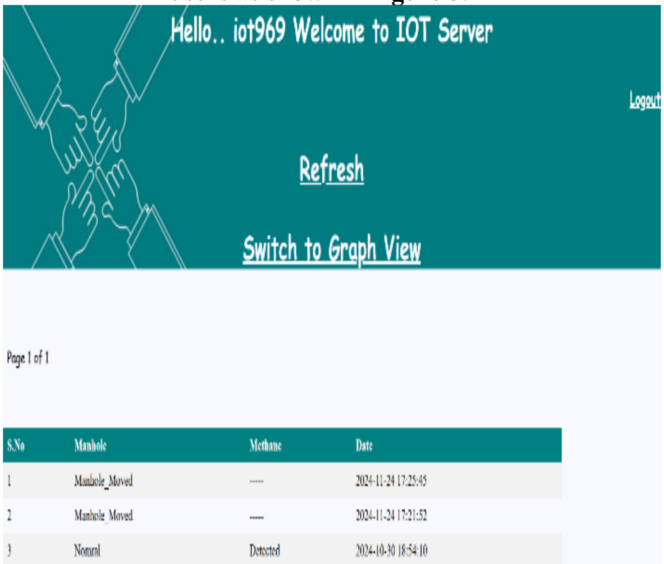
Overall, the performance evaluation confirms that the proposed wireless monitoring system is dependable, responsive, and energy-efficient. These characteristics make it a practical solution for enhancing public safety, reducing manual maintenance efforts, and enabling smarter, more responsive urban infrastructure management.

Table 2 shows the performance evaluation of the proposed Manhole monitoring system.

Table 2. Performance Evaluation of the Proposed Manhole Monitoring System

Performance Metric	**Parameter Evaluated**	**Observed Value**	**Discussion / Significance**
Gas Detection Accuracy	Methane detection accuracy	95%	Demonstrates reliable sensing capability for hazardous gas detection, confirming effective sensor calibration and noise reduction.
Response Time	Event detection to alert generation	500 ms	Indicates real-time system performance suitable for safety-critical urban monitoring applications.
Power Consumption	Average operating current	Approx. 200 mA	Confirms energy-efficient operation, enabling long-term battery-powered deployment in underground environments.
Communication Range	ESP8266 wireless coverage	Up to 50 m	Sufficient for most urban monitoring scenarios, ensuring stable data transmission to nearby access points.
Communication Reliability	Data delivery success rate	High (stable transmission)	Lightweight packets and retry mechanisms ensure dependable communication under variable signal conditions.

Figure 4 shows how real-time data logging on a secure server is achieved through this system. Also, it can send alert messages directly to mobile devices of registered users as shown in figure 5.



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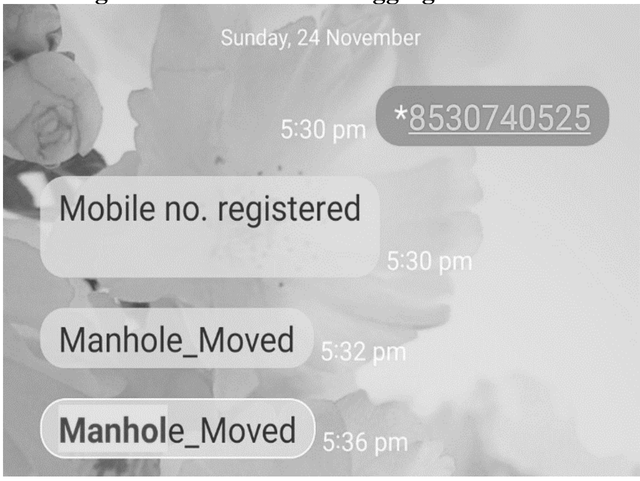
S.No	Manhole	Methane	Date
1	Manhole_Moved	-----	2024-11-24 17:25:45
2	Manhole_Moved	-----	2024-11-24 17:21:52
3	Nomral	Detected	2024-10-30 18:54:10

Figure 4. Real time data logging on a server



Sunday, 24 November

5:30 pm *8530740525

Mobile no. registered

5:30 pm

Manhole_Moved 5:32 pm

Manhole_Moved 5:36 pm

Figure 5. Real time manhole information message on registered mobile

4.1 Communication Efficiency and Scalability Discussion

Communication efficiency is a critical factor in underground IoT deployments, where signal attenuation, power limitations, and strict latency requirements pose significant challenges. In the proposed system, local embedded decision-making reduces the need for continuous data transmission by sending information only when significant events occur or at predefined intervals. This event-driven communication approach lowers bandwidth consumption and improves network stability, particularly when multiple sensor nodes operate simultaneously.

The hybrid communication architecture further enhances system robustness by integrating Wi-Fi for real-time data monitoring with GSM for emergency alert delivery. This dual-mode strategy ensures that critical notifications are reliably delivered even in situations involving partial network failure or limited internet connectivity. Experimental results demonstrate that the proposed communication design achieves sub-second latency while maintaining energy efficiency, making it well suited for scalable smart city infrastructure deployments involving large numbers of underground sensor nodes.

CONCLUSION

This paper presented the design, implementation, and experimental evaluation of an IoT-enabled real-time manhole monitoring system aimed at improving the safety, reliability, and efficiency of urban underground infrastructure. By integrating environmental sensing, motion detection, embedded processing, and wireless communication, the proposed system effectively overcomes the limitations of conventional manual inspection methods, which are often reactive, labour-intensive, and hazardous. The developed architecture demonstrates that low-cost, resource-constrained hardware can be efficiently utilized to support continuous monitoring and timely alert generation in smart city environments. Experimental results confirm the effectiveness of the proposed approach. The system achieved high gas detection accuracy, rapid response to abnormal events, stable wireless communication, and energy-efficient operation suitable for long-term deployment. Local decision-making at the embedded node level significantly reduced communication overhead and latency, while the hybrid Wi-Fi and GSM communication strategy ensured reliable delivery of critical alerts even under constrained network conditions. These results highlight the importance of combining embedded intelligence with efficient communication mechanisms for real-time urban infrastructure monitoring. Beyond technical performance, the proposed system contributes to smarter urban management by enabling proactive maintenance and reducing human exposure to hazardous underground environments. Centralized data logging and visualization provide valuable insights into infrastructure health, supporting informed decision-making and improved resource utilization. The modular design further enhances scalability, allowing additional sensors or functionalities to be incorporated without major architectural changes, thereby facilitating integration into broader smart city frameworks. Despite its promising performance, certain limitations remain, including potential communication variability in extreme underground conditions and dependence on battery capacity for long-term operation. Future work will focus on integrating low-power wide-area communication technologies, energy-harvesting solutions, and intelligent data analytics to support predictive maintenance. Overall, the proposed system offers a practical, scalable, and energy-efficient solution for enhancing urban infrastructure safety and represents a meaningful contribution to smart city research and real-world deployment.

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