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An IoT–GIS Integrated Architecture for Real-Time Urban Noise Monitoring and Intelligent Management

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Abstract

Urban noise pollution, exacerbated by traffic, construction, and high population density, seriously threatens public health and quality of life. While effective on a small scale, traditional noise monitoring methods fail to provide the real-time data needed for widespread urban applications. This paper explores the potential of the Internet of Things (IoT) technology for noise monitoring in urban environments, examining an IoT architecture that integrates Wireless Sensor Networks (WSNs), cloud computing, and machine learning to provide comprehensive noise data collection and analysis. Key case studies from Barcelona, New York, and Delhi highlight real-world applications, and challenges such as data privacy, sensor calibration, and scalability are examined with proposed solutions. By adopting IoT-enabled noise monitoring, cities can implement data-driven noise management policies that improve public health and urban living conditions.

Keywords: Internet of things, Noise monitoring, Urban management, Wireless sensor networks, Smart cities, Environmental pollution.

1 | Introduction

As urban populations expand, noise pollution has emerged as a critical environmental and public health issue, directly impacting human health and overall quality of life. Noise is linked to various health problems, including stress, cardiovascular issues, sleep disturbances, and hearing impairments. Traditionally, noise levels are monitored using sound level meters placed in fixed locations. However, these methods provide limited spatial coverage and lack real-time data capabilities [1–3].

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The Internet of Things (IoT) offers a new paradigm for noise monitoring in urban areas. By employing wireless sensor networks, IoT-based systems enable the continuous collection and analysis of environmental noise data. IoT systems can collect real-time data from multiple locations across urban environments, thus overcoming the geographical limitations of traditional methods. These systems transmit data to centralized servers, where advanced analytics can identify trends, detect anomalies, and inform policy decisions [4].

This paper examines the architecture and operation of IoT-enabled noise monitoring systems, focusing on deploying sensors, communication networks, data processing methods, and noise mitigation strategies. We also analyze case studies where IoT has been successfully deployed to manage noise pollution, exploring challenges such as data privacy, sensor accuracy, and maintenance. The insights provided by these systems are essential for developing sustainable urban noise management solutions [5].

2 | Literature Review

Noise pollution has been extensively studied in various contexts. WHO guidelines highlight the need to maintain acceptable noise levels to preserve human health. Traditional noise monitoring methods, however, are often impractical for large urban areas due to their costs and labor requirements. Early efforts involved manual data collection from sound level meters, which were later aggregated for analysis. While these methods provided valuable insights, they were limited by the lack of real-time data and geographical constraints.

Recent advancements in IoT have led to innovative noise-monitoring solutions. Such systems enable large-scale monitoring by using IoT-enabled sensors to gather real-time data, which is then analyzed in cloud environments. Kumar et al. (2021) expanded on this approach by implementing IoT systems that integrate data from various environmental factors like humidity and temperature to improve noise data accuracy.

2.1 | Traditional Noise Monitoring Techniques

Early approaches to noise monitoring involved placing sound level meters at fixed points and manually collecting data. This method, though reliable, is labor-intensive and provides limited spatial and temporal coverage. Traditional methods can also not adapt to the dynamic nature of urban noise pollution, where noise levels vary significantly between locations and times of day. This lack of real-time data limits the ability of urban planners to make informed, timely decisions about noise management [6].

2.2 | IoT Advancements in Environmental Monitoring

IoT technology has transformed environmental monitoring across various domains, including air quality, water quality, and noise pollution. In noise monitoring, IoT enables the deployment of distributed, low-cost sensors across urban areas, allowing for continuous data collection. Studies have shown that IoT-based Wireless Sensor Networks (WSNs) can provide more comprehensive noise data than traditional methods. By connecting these sensors to a centralized platform, cities can monitor noise pollution in real-time, analyze trends, and implement policies to address high-noise areas [7].

2.3 | Case Studies in IoT-Based Noise Monitoring

Cities worldwide have begun adopting IoT for noise monitoring as part of their smart city initiatives. For instance, Barcelona, Spain, has integrated IoT-enabled noise sensors into its urban infrastructure to monitor traffic and construction noise. In New York City, the Department of Environmental Protection uses IoT sensors to enforce noise regulations, while Delhi's pilot program focuses on tracking traffic noise in high-density areas. These case studies demonstrate the effectiveness of IoT in providing detailed noise data, enabling policymakers to take action against noise pollution [8].

2.4|Technology Components in IoT Noise Monitoring

IoT-based noise monitoring systems incorporate several key technologies, including WSNs, Low-Power Wide-Area Network (LPWAN), cloud computing, and machine learning. WSNs enable the deployment of sensors across vast urban areas, while LPWAN protocols like LoRaWAN and Sigfox provide reliable, long-range data transmission. Cloud computing offers scalable storage and processing capabilities, and machine learning algorithms are used to analyze noise patterns, detect anomalies, and predict future noise levels. Each of these technologies plays a crucial role in the effectiveness of IoT noise monitoring systems [8].

3|Background

According to the ministry of environment, forest & climate change, mechanical energy released by any medium source creates molecules' vibrations. The molecules start vibrating in the oscillatory mode, and the energy travels through the medium in the form of vibrations. If the oscillations in the medium are in the range of 20 Hz to 20 kHz, they are audible by human ears and are classified as sound.

3.1|Ambient Noise

Ambient noise is often referred to as environmental noise. It is noise that one hears in daily life and does not include workplace noise. Various sources of noise are industries, road traffic, rail traffic, air traffic, construction sites and public works, indoor sources (air conditioners, air coolers, radio, television, and other home appliances), etc [9].

3.2|Air Quality Standards

The Central Pollution Control Board constituted a Committee on Noise Pollution Control and recommended noise standards for ambient air and for automobiles, construction equipment, and domestic appliances, which were later notified in Environment (Protection) Rules,1986, as given below [10]:

Silence zones are areas under 100 meters around premises such as hospitals, educational institutions, and courts. The competent Authority must declare these zones. Vehicle horns, crackers, and loudspeakers shall be banned in these zones [10].

Most monitoring stations recorded with high noise levels were located on busy and congested roads, where vehicles were the most significant contributors, with constant honking aggravating the problem. The ambient noise levels in residential and commercial areas indicate that the average daytime noise levels in the metros are higher than the national standard of 55dB for residential areas and 65dB for commercial areas. The data is available in real time, so governments can devise traffic plans for real-time intervention.

4|IoT Architecture for Noise Monitoring Background

4.1|Sensor Network Design

An IoT-enabled noise monitoring system begins with a network of noise sensors deployed across strategic locations in an urban area. These sensors measure sound pressure levels and transmit the data wirelessly. Key considerations in sensor design include durability, accuracy, and energy efficiency. Sensors must be capable of withstanding environmental conditions like temperature changes and humidity, which can affect noise levels [8].

4.2|Communication Protocols

The communication layer in an IoT system determines how data is transmitted from sensors to a central server. Wireless communication protocols such as Wi-Fi, LoRa, and Zigbee are commonly used in urban noise monitoring. Each protocol has unique advantages; for example, LoRa offers low power consumption and wide-area coverage, making it ideal for large-scale deployments. However, Wi-Fi or cellular networks may be preferable in densely populated areas due to their higher data transmission speeds [11].

4.3 | Data Processing and Storage Layer

Data processing is crucial for extracting meaningful insights from noisy data. Cloud computing provides the necessary storage and computational power, while machine learning algorithms analyze noise trends, detect unusual patterns, and generate predictions. By integrating machine learning, cities can implement proactive noise management strategies, such as setting alerts when noise levels reach critical thresholds [3].

4.4 | Security and Privacy Framework

Security is a key concern in IoT-based systems, as sensors continuously transmit data that may be sensitive. Encryption protocols and secure access controls are implemented to ensure data integrity and privacy. Data anonymization techniques also prevent identifying individuals in noise-sensitive areas, adhering to privacy regulations [12].

5 | Methodology

Competent authorities, such as the Union Ministry of Environment and Forest, make the existing sensor network in metro cities available, but it has limited coverage. Crowd-sourcing makes the sensor network much wider, flexible, and economical. As people participate actively due to crowdsourcing, it becomes easy to monitor high fluctuations in the noise level during festivities. Also, it makes it easier for people to avoid visiting areas that contribute to very high noise levels [13].

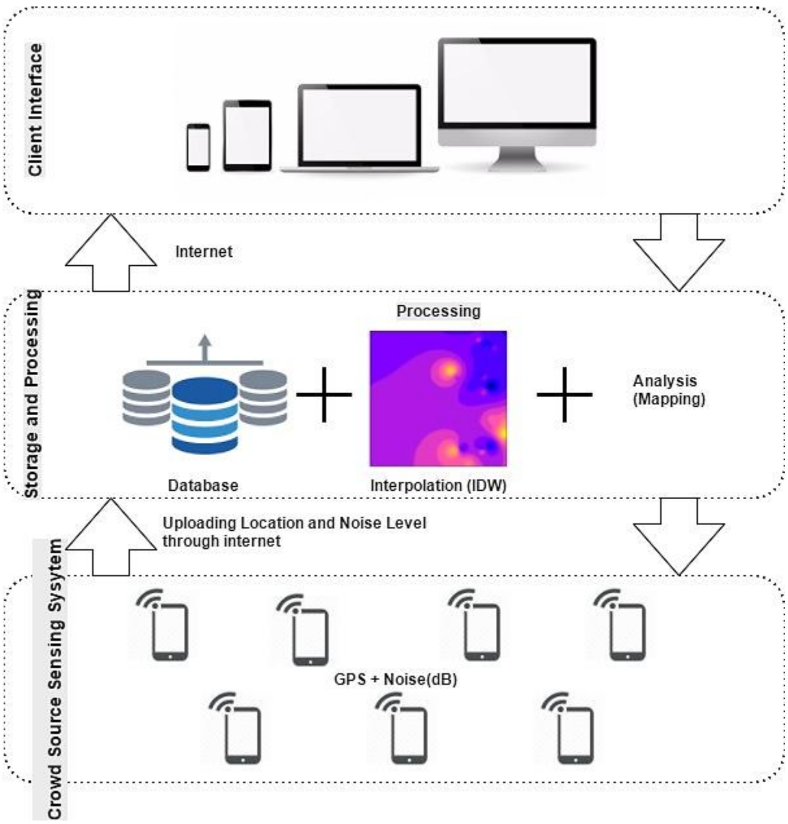

Fig. 1. Flowchart of noise detection and mapping.

5.1 | Noise Detection

Instead of laying a network of sensors at prominent locations to collect the noise data, a mobile phone's microphone is used as a sensor. An Android application(Noisetrack) has been developed to collect noise data using a mobile phone's microphone. This app can be used as a two-way communication tool, i.e., it can collect the noise data and show the noise data analysis on the user's end. By adopting this technique, more samples can be collected while reducing overall expenses significantly. The sensor collects the noise data regarding sound pressure Level(SPL) in Pascal, which is then converted into decibel scale (dB) using the formula [14].

Where,

P = Sound pressure we are measuring.

Pref = Sound pressure humans can hear (2.0×10-5 Pa).

$$\text{SPL} = 20\log_{10}\left(\frac{\text{p}}{\text{p}_{\text{ref}}}\right)\text{dB}.$$

The noise level measured by the App is uploaded to the server (ESRI server) using an HTTP post request. The noise level gets stored on the server along with the sampling site coordinates, date, and time of sampling. For multiple sampling at the same point at the same instance, the average value of the noise data will be considered during data analysis. This averaging helps eliminate ambiguity created by local disturbances near the sensor. The data stored on the server is then used for spatial analysis of noise levels, which is then used to map the noise levels.

5.2 | GIS Noise Mapping

This work aims to develop a mobile application to continuously monitor the noise in various city zones and provide real-time analytics to the user. To achieve this, the following approach is adopted:

Step 1. Mapping of GPS collected data along with noise levels, taking the average noise level values.

Step 2. Designing a Spatial feature layer on a server (ESRI server).

Step 3. Spatial modeling and application of advanced interpolation techniques in GIS to obtain an accurate picture of the acoustic situation based on a limited number of sample points [15].

5.3 | Spatial Database Development

A spatial database has to be created to support recorded noise levels with geographical information. For the database, the Feature layer was created on the ESRI server. Each point contains the following attribute data:

I. Geographical coordinates (Latitude and Longitude).

II. Date and time of collection.

III. Average noise level.

5.4 | Spatial Interpolation via IDW

Inverse Distance Weighting (IDW) estimates the output grid cell values by averaging the values of nearby sample points using the linear weighted combination. The weight is a function of the inverse of the distance of sample points; the closer the points, the more weight is given.

6 | Data Collection and Transmission

6.1 | Data Collection Techniques

The accuracy of noise monitoring systems depends on the precision of data collected by sensors. Noise sensors are calibrated to measure sound pressure levels and environmental variables such as temperature and wind speed. Accurate calibration helps minimize errors in noise measurements, ensuring reliable data for analysis [16].

6.2 | Transmission Protocols

Effective data transmission is essential for the success of IoT-based noise monitoring. LPWAN protocols like LoRaWAN and Sigfox enable long-range communication with minimal power consumption, making them ideal for urban deployments. Wi-Fi or cellular networks are often preferred in high-density areas where interference may affect transmission quality [11].

6.3 | Data Processing on the Edge vs. Cloud

Edge computing reduces the amount of data transmitted to the cloud by processing some information at the sensor level. This approach minimizes latency and bandwidth usage, enabling real-time noise monitoring even in areas with limited connectivity. For instance, initial noise analysis can be conducted locally, with only critical alerts sent to the central server [17].

6.4 | Data Storage Solutions

Data storage is critical for managing the large volumes of noise data generated by IoT sensors. Cloud storage solutions, such as Amazon Web Services (AWS) and Microsoft Azure IoT, provide scalable storage options and allow data to be accessed from anywhere. Storage optimization techniques, including data compression, enhance system efficiency by reducing storage costs [18].

7 | Case Studies in Urban Areas

7.1 | Barcelona, Spain

Barcelona's Smart City initiative includes an extensive IoT-based noise monitoring system. Sensors are strategically placed near major roads, schools, and hospitals to monitor traffic noise and identify noise pollution hotspots. Real-time data from the sensors informs policies, such as restricting heavy vehicle traffic in residential areas during peak hours.

7.2 | New York City, USA

New York City has implemented IoT noise monitoring to enforce local noise ordinances. The system uses sensors to detect noise levels that exceed legal limits, allowing officials to respond promptly to complaints. This approach has reduced the number of noise-related complaints and improved public satisfaction [8].

7.3 | Delhi, India

Delhi's pilot noise monitoring system manages traffic noise in congested areas. Data from IoT sensors is used to create noise maps, helping urban planners identify noise-sensitive zones and implement noise mitigation measures. For example, quieter zones are established near hospitals, schools, and residential areas to protect public health.

8|Challenges and Solutions

8.1|Sensor Accuracy and Calibration

Environmental factors such as wind and temperature affect the accuracy of noise sensors. To maintain data reliability, sensors are regularly calibrated, and machine learning models are used to account for environmental variables [19].

8.2|Data Privacy and Security

Privacy concerns arise when collecting noise data in residential areas. To address these concerns, data is anonymized, and secure encryption protocols are implemented to protect sensitive information. Compliance with regulations, such as the General Data Protection Regulation (GDPR), ensures that privacy is maintained [20].

8.3|Scalability and Maintenance

Deploying and maintaining a large network of IoT sensors can be costly. Modular sensor designs and automated maintenance alerts help reduce costs by simplifying sensor replacements and repairs. Additionally, partnerships with private companies can provide funding for system expansion [21].

8.4|Integration with Other Urban Systems

IoT noise monitoring systems are often integrated with other urban systems, such as traffic management and air quality monitoring, to provide a comprehensive view of urban health. This integration allows for coordinated responses to environmental challenges, enhancing urban resilience [22].

9|Future Directions and Emerging Technologies

9.1|AI and Predictive Analytics

Machine learning and AI enable predictive analytics in noise monitoring, allowing cities to anticipate high-noise events and take preventative measures. For instance, predictive models can forecast noise levels based on historical data, enabling proactive noise management [23].

9.2|Blockchain for Secure Data Handling

Blockchain technology offers a decentralized, secure method for handling IoT data. By creating an immutable record of data transactions, blockchain enhances data integrity and security, addressing privacy concerns in IoT-enabled noise monitoring [24].

9.3|5G Connectivity

5G networks offer faster data transmission, making them ideal for large IoT networks in urban areas. By reducing latency, 5G improves real-time monitoring and supports the integration of more sensors, enhancing the granularity of noise data [25].

9.4|Cross-Functional Applications in Smart Cities

IoT noise monitoring systems can be integrated with other smart city applications, such as traffic control and environmental monitoring, creating a unified response to urban challenges. This cross-functional approach enables more effective, data-driven urban management [26].

10 | Conclusion

IoT-enabled noise monitoring systems present a transformative approach to managing urban noise pollution. By deploying wireless sensor networks, cloud computing, and data analytics, cities can achieve real-time, large-scale noise monitoring, facilitating data-driven decision-making and effective noise management.

Despite challenges such as sensor accuracy, data privacy, and costs, advancements in IoT technology, particularly in machine learning and data encryption, promise to overcome these issues. As urban areas grow, IoT-based noise monitoring will be essential in creating quieter, healthier cities.

The examples and challenges discussed provide a roadmap for cities to develop their noise monitoring strategies, leveraging IoT to enhance urban living conditions and minimize the impact of noise pollution on public health.

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Data Availability

The data used and analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest regarding the publication of this paper.

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