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IoT-Enabled Air Pollution Monitoring Systems: Technologies, Solutions, and Challenges

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Abstract. Air quality is a crucial aspect of the overall health of any ecosystem. Rapidly increasing urbanization and transportation have proven detrimental to the quality of the air we breathe. Nearly two-thirds of urban air pollution is caused due to vehicular emissions. The harmful pollutants released every day into the atmosphere are deteriorating the environmental and human health. Air pollution has been closely associated with climate change as well as some serious health issues. Hence there is an urgent need for consistent, large-scale air quality monitoring and mitigation strategies. In recent years, the Internet of Things, with its wide range of technologies and some distinct attributes like connectivity, sensing, analyzing and processing capabilities, scalability, and flexibility has provided the world with a dependable option to monitor air pollution in real-time. This paper discusses the key technologies which support IoT-enabled air pollution monitoring systems, proposed solutions, and the challenges faced in the deployment of real-time pollution monitoring systems.

Keywords. Air Pollution, Internet of Things, Cloud Computing, Edge-Computing, Sensor Technologies

1. Introduction

Air pollution is one of the biggest threats to human and environmental health in today's time. The increase in industrialization, transportation, urbanization, and even population density has resulted in alarming levels of ambient air pollution. Air pollution is ranked as the fifth-highest risk factor for the health of people and has been responsible for close to five million/year premature deaths worldwide[1]. On average, life expectancy is reduced by one year and eight months due to air pollution globally. One of the major contributors to air pollution is road transport. These vehicular emissions contain noxious pollutants which are detrimental to human health. Assessing and realizing the effects air pollution has on health and the burden of disease it inflicts on nations, World Health Organization (WHO) has issued air quality guidelines for monitoring air pollution[2]. However, still, nine out of ten people live in areas that have pollutant concentrations above the WHO guidelines[3]. This calls for aggressive monitoring of air quality so that remedial measures can be taken to control and lower pollutant concentrations. Consequently, the governments and pollution monitoring agencies have been actively

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employed to curb pollution levels. Air quality monitoring stations have been installed in cities with high population densities and concentrations of various dangerous pollutants are monitored at these stations[4]. However, due to size and cost constraints, there are only a limited number of such stations; as a result, alternative solutions are needed.

Advancements in the field of the Internet of Things (IoT), can be leveraged to monitor air pollution efficiently in real-time. IoT is a recently emerging technology that has gained a lot of momentum in the last decade as it finds applicability in almost every field[5,6]. Ever since its expansion IoT has been tightly coupled with the concept of Smart Cities as it offers a wide range of technologies that can be integrated to achieve desired objectives (like air and water pollution, traffic management, public safety, healthcare, etc.). Exploiting various IoT technologies like radio-frequency identification (RFID), wireless sensor networks (WSNs), and gas sensors, researchers have developed air quality frameworks providing low-cost and efficient systems which monitor air quality on large scale[7,8] which are discussed in this paper. The main objectives of this paper are:

- To discuss the role of the Internet of Things in ambient air pollution monitoring.
- To examine the prevalent technologies being utilized in IoT- based air pollution monitoring systems.
- To analyze the solutions offered by existing IoT-based systems.
- To investigate major challenges encountered and discuss plausible solutions for future implementation.

The rest of the paper has been organized in a section-wise manner. In section 2, a wide range of enabling technologies used for air pollution monitoring systems have been discussed. Section 3 highlights various proposed IoT-based solutions to monitor air pollution. Section 4 elucidates the challenges faced in the implementation of the proposed systems. Lastly, the conclusion along with some key points for future directions have been discussed in section 5.

2. Enabling Technologies

In the literature, several trends have been found concerning the various technologies utilized for IoT-enabled air pollution monitoring systems. Firstly, a lot of emphasis had been laid on the types of sensors used and the associated benefits such as lower costs, low power consumption, and data collection accuracy. The most widely used sensors have been categorized as electrochemical sensors, semiconductor sensors, non-dispersive infrared absorption (NDIR) sensors, photo-ionization detector (PID) sensors, and catalytic sensors[9]. The majority of systems have deployed semiconductor-based MQ-series sensors (such as MQ-2, MQ-7, MQ-135 and MQ-137), some have explored other options like electrochemical SEN-series sensors, NDIR, laser-based sensors, which have produced results with fairly good accuracy. Table 1 below enlists the most commonly used sensors along with the pollutants monitored by them.

Secondly, any IoT system's performance largely depends on the type of hardware used as it affects the overall functionality, efficiency, and scalability of the system. There is larger reliability on Arduino and Raspberry Pi boards (various versions of both) in the literature, as they offer a variety of features for the implementation of any IoT-based project. Arduino is a single-board microcontroller whereas Raspberry Pi is a small computer system with its processor and memory. Raspberry Pi boards come with in-built modules for Wi-Fi, Bluetooth, and ethernet connectivity; however, in some Arduino boards external ethernet shields and modules are required to be embedded. Arduino is more than capable of handling basic functionality; whereas Raspberry Pi can handle complex computations as well. Overall, both the boards have low power consumption and are a good fit for the prototyping of air pollution monitoring systems by researchers[10].

Table 1. Pollution Monitoring Sensors

Sensor Category	Sensor	Pollutants Monitored
Gas sensors (Semiconductor)	MQ-2	LPG, C_4H_{10}, C_3H_8, CH_4, CO
	MQ-3B	Alcohol
Life Expectancy: 10+ years	MQ-4	Natural gas, Methane
	MQ-5B	LPG, Natural gas, Coal gas
Power consumption: High	MQ-6	LPG, Propane
	MQ-7	Carbon Monoxide
	MQ131	Ozone
	MQ135	NH_3, Benzene, Alcohol, Smoke
	MQ136	Hydrogen
	MQ137	Ammonia
	MQ138	VOCs (Benzene, Aldehyde, Ketone, etc.)
Gas sensors (Electrochemical)	SEN0134	Carbon Monoxide, Combustible gas
	SEN0129	Methane, LNG, Natural gas
Life Expectancy: 1-2 years	SEN0219	Carbon Dioxide
	SEN0159	Carbon Dioxide
Power consumption: Very low	ME4-CO	Carbon Monoxide
	ME4-H2	Oxygen
	ME3-NH3	Ammonia
	ME3-SO2	Sulphur Dioxide
PM Sensors	SEN0233	PM2.5, formaldehyde, temperature, humidity
Life Expectancy: 2-5 years	DSM501A	PM1.0, PM2.5
	GP2Y1010	Dust Density
Power consumption: Low	SEN0177	PM2.5
	PMS7003	PM1.0, PM2.5, PM10
	PMS5003	PM1.0, PM2.5, PM10

3. IoT-based Solutions

Understanding the urgency to tackle air pollution, many distinct systems have been proposed that monitor any location's pollution levels as well as monitor individual vehicle emissions. Figure 1 represents a basic IoT-based architecture for pollution monitoring systems. Solutions such as the generation of automatic e-challan, halting of vehicle engines, continuous reporting of vehicle emissions to monitoring agencies, and suggesting alternate routes to drivers, have been proposed[11,12] leveraging the wide range of enabling technologies offered by IoT. Some of the systems have also included other aspects such as traffic management, avoidance of accidents, controlling noise pollution generated from vehicles, the contribution of vehicle's speed to pollution generated, effects on driving behavior due to pollution, etc. [13–16].

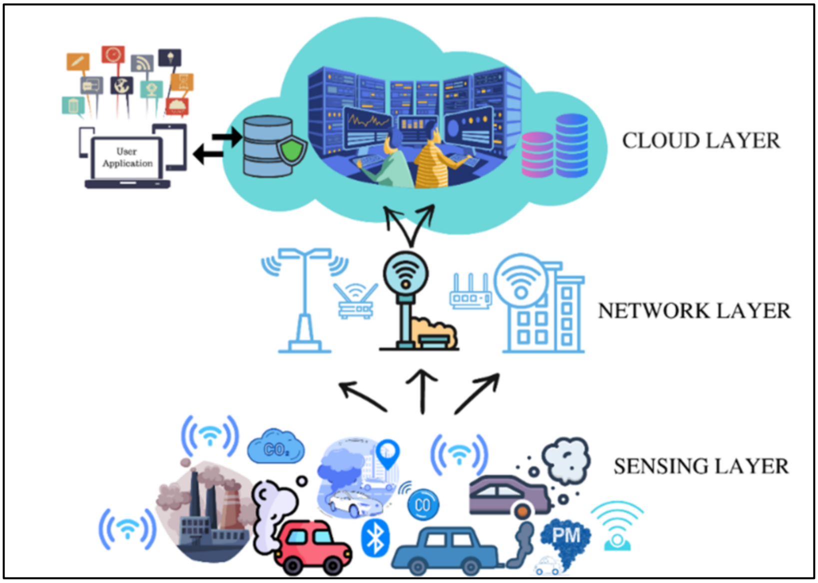

Figure 1. A basic IoT-enabled air pollution monitoring architecture

Another interesting trend is the use of the machine and deep learning algorithms. One such system has produced some promising results in predicting PM values using time series data and applying multilayer neural networks and support vector machine regression techniques[17]. Another system applied three deep learning models viz. long-short term memory, skip-generation adversarial network, and variation auto-encoder to identify anomalies in sensor readings; hence increasing the overall accuracy of the system[16]. Another important trend witnessed is the use of Radio Frequency Identification (RFID) technology which allows the identification of objects and is often regarded as the prerequisite of IoT[18]. RFID along with the wireless sensor network approach makes the identification of moving vehicles easier as the vehicles are equipped with tags and whenever they are within range of an RFID reader, the data can be obtained from anywhere [19].

Whether the systems are static or mobile, they have availed the services of the cloud as it offers large storage and complex computational services which the sensor nodes are not capable of handling. Also, since the amount of data produced by air pollution monitoring systems is gigantic; it becomes a necessity to exploit the cloud's services for deep analysis and further processing. In recent years, edge computing has also gained attention because of its ability to process data closer to the end devices, hence decreasing the overall network traffic and bringing down the power consumption and overall cost. Moreover, it offers much larger mobility support and context awareness which is quite useful in location-based data gathering [20,21].

4. Challenges

A variety of solutions incorporating multiple IoT technologies have been proposed; however, there still are some major challenges in collaborating these technologies due to their heterogeneous nature and individual complex intricacies. One of the major issues faced is regarding the selection of sensors and the accuracy of the data sensed. The sensors used have reasonable accuracy and sensitivity; however, they are unable to provide precision as high as conventional systems. Deployment of sensor nodes is another concern; the sensor node should be installed such that it has a continuous power supply and can sense pollution data accurately [22].

Further, IoT frameworks are a combination of heterogeneous devices and these devices capture huge amounts of data and simultaneously try to transfer data across the network to a local gateway or remote servers. First of all, constant internet connectivity is required for the transmission of data, which is often not available at all times. Secondly, the transfer and processing of such huge and heterogenous nature of data increases the overall cost and undermines the idea of energy conservation. Deep et al., suggest that this issue can be addressed by introducing the concept of edge-computing where individual sensor nodes are capable enough to carry out local processing and transfer only the necessary bit of data to the cloud servers[23]. Idrees et al. have reported a reduced computational burden of sensing nodes, up to 70%, and decreased power consumption by 23% in their system using edge computing[24].

5. Conclusion and Future Directions

The Internet of Things paradigm provides a suitable solution for real-time monitoring of air pollution and several systems have been proposed in recent years. The majority of systems have relied on the integration of IoT and cloud technologies, followed by wireless sensor network-based approaches. WSNs have been mainly utilized for sensing purposes wherein low-cost sensor nodes have been deployed to achieve greater spatial coverage, and relatively considerable energy and cost-efficiency. Analysis of the proposed systems depicts that real-time IoT-assisted air pollution monitoring is still in its infancy; numerous technical challenges need to be addressed to fully realize the suggested systems. The first major challenge is to validate the credibility of the data gathered by the suggested low-cost sensors; the type of sensors used and their placement, and maintenance, in the long run, need to be addressed. Secondly, there is high dependability on cloud platforms for storage and computational purposes; here edge can be introduced for optimized bandwidth and reduced latency[25]. Thirdly, common communication standards should be agreed upon to resolve interoperability issues, which in turn will make data acquisition and processing easier. Fourth, there is both short-range and long-range communication among the end devices and their communication with gateways and clouds; hence it is necessary to facilitate secure communication and maintain the authenticity of the data [12]. Thus, addressing these issues in future systems can greatly affect the performance of the systems improving the overall efficiency and accuracy.

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