Urban Air Pollution Monitoring Using Wireless Sensor Networks:
A Comprehensive Review

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Abstract: Air pollution is evolving as a severe environmental concern due to its enormous impact on the well being of the people, universal environment and also on the global economy. Conventional air pollution systems are not able to provide air pollution data of high spatiotemporal resolution due to non-scalability and limited data availability. With the advances in the areas of Micro Electro Mechanical Sensor (MEMS) and Wireless Sensor Network (WSN), the researchers proposed various state-of-the-art air pollution monitoring systems for measuring major air pollutants like CO_2, CO, O_3, SO_2, VOC and Particulate Matter (PM) with better results. A comprehensive review of continuous air pollution surveillance of both indoor and outdoor pollution by employing WSN is presented. It presents the various techniques and algorithms employed in the design of dedicated air pollution monitoring systems using WSN. A comprehensive and detailed review of the existing methods of Air Quality Monitoring systems using WSN is done along with their comparisons.

Keywords: Air Quality Monitoring, Wireless Sensor Network, Air Quality Index, Mobility, Temporal Resolution, Quality of Service (QoS), Routing Algorithms, Global System for Mobile (GSM).

1. Introduction

Air pollution is primary concern for the human kind, as it is degrading the environmental health and inhaling the pollutant air is dangerous for the health of the humankind. Due to these adverse effects of the air pollution on the human kind, the demand for the development of high-quality air monitoring systems has been in high demand and drawing the attention of researchers [1]. The air pollution monitoring systems detect the concentration levels of air pollutants and the analysis of the collected information is required for the policymakers to take necessary and proper steps to decrease the level of air pollution for the wellbeing of their citizens. For controlling air pollution first, we need to track Air Quality Index (AQI) which provides the levels of air pollution by using different sensors [2]. For the preservation of environment and health of the people measuring the air pollutants is a significant and a vital task.In the urban areas due to increase in the number of industries and automobile vehicles, emission of toxic gases like CO, NO_2 and CO_2 etc. are also increasing causing the severe impact on the health conditions of the general public like coughing, wheezing and asthma. Poor air quality may cause increased short-term health problems such as fatigue and nausea as well as chronic respiratory diseases, heart disease, and lung cancer. To monitor the indoor and outdoor air pollution, the

necessary steps involved in the design of the monitoring systems are data collection, analyzing the collected data and transmission of collected data. Wireless Sensor Networks (WSNs) are extensively used in the real-time applications to gather and examine the data smartly without the human involvement. In the present day, WSNs are widely employed in all the commercial, industrialized and military applications [2].Air pollution is monitored by conventional systems with stationary devices traditionally[1]. These monitoring stations are highly reliable, accurate and able to measure pollutants by employing the traditional analytical equipment, such as gas chromatograph-mass spectrometers. The drawbacks of the conventional monitoring devices are their large size, heavyweight and extraordinarily expensive. The locations of the monitoring stations need to be carefully placed to be useful as the concentration levels of air pollutants are sensitive to the human habitations and also depend on construction activities, movement of automobiles. Conventional air pollution systems are not able to provide air pollution data of high spatiotemporal resolution due to non-scalability and limited data availability

In the proposed paper, different air pollution monitoring methods using WSN is presented. It also brings the difference between conventional and WSN based air pollution monitoring systems [24].It describes the implementation, simulation methods to monitor Air pollution

2. Related work

Wei Ying Yi et al. 2015 [1] presented the concept of The Next Generation Air Pollution Monitoring System (TNGAPMS) with emphasis on the need for developing a real-time air pollution monitoring systems with low cost, energy efficient and high spatiotemporal resolution. The Next Generation Air Pollution Monitoring System (TNGAPMS) classified into three types of sensor networks based upon the carriers of the sensing elements are Sensors static Sensor Network (SSN), Community Sensor Network (CSN), Vehicle Sensor Networks (VSN). The working of these sensor networks was discussed along with the advantages, disadvantages, comparisons and limitations of present works

Liu, J.H. et al. 2011[3] proposed urban air quality monitoring system based on wireless sensor networks. Designed system architecture consists of sensor nodes comprising of a wide range of CO sensors powered by batteries; a gateway communication link includes a Global System for Mobile (GSM) and centralized control system provided by the Lab

view program. All the CO sensors on the sensor nodes integrate with Zigbee communications. Air pollutant data sensed by the sensor nodes were sent to the central system through the gateway. The designed system was implemented in the main roads of Taipei city which were able to collect finest air pollution information in real time scenario. The presented work is categorized under the static sensor networks.

Kadri, A et al. 2013 [4] developed a wireless sensor network for outdoor air pollution monitoring and tested the designed prototype on the real-time basis. In the designed system the sensors are used to collect the pollution data of O_3, NO_2, CO, H_2S and sensed information is send to the server through the GPRS. A solar panel was used for solving the power limitation of the stationary sensor nodes. Air pollution data captured by the sensor nodes can be made available to the public through the customized mobile and web Apps etc. after obtaining the authorization for the data dissemination. The presented work is categorized under the static sensor networks.

Mansour, S et al. 2014 [5] presented the outdoor air quality monitoring system based on wireless sensor networks for industrialized and urban areas. Designed system is capable of sensing O_3, CO and NO_2.These sensors are mounted on the sensor nodes Libelium's [43] Wasp mote. ZigBee communication link is used to upload the collected data by the gas sensors to the central server. Approved air pollution data is made available to the community through customized Web App, Emails or SMS. Designed system is simple, and it can be easily integrated with other applications. Clustering Protocol of Air Sensor (CPAS) was implemented in the designed system to improve the efficiencies in network lifetime, communication rate and network energy consumption in the simulation environment. In the proposed protocol, detection of failed sensor nodes and minimization of power consumption by the sensor nodes was achieved. The presented work is categorized under the static sensor networks in which the reliability, delay and accuracies of the system are also considered.

Khedo, K.K et al. 2010 [6] proposed a novel wireless sensor based system for air pollution monitoring (WAPMS).It consists of a communication system for collecting the air pollution information to the server from the array of sensor nodes. Air pollution data sensed by the sensor nodes sent to the server through the cluster heads autonomously. A Data aggregation algorithm Recursive Converging Quartiles (RCQ) was used to minimize the power consumption and to maximize the energy efficiency of the sensor nodes; a hierarchical routing protocol [33] was used. The designed system is implemented in the Mauritius city to monitor the outdoor air pollution. The presented work is categorized under the static sensor networks.

Jelicic, V et al. 2013 [7] proposed an indoor air pollution monitoring system based on WSN, which had addressed the issues related to the power consumption levels of the sensors, sensor nodes. In the proposed work, 36 sensor nodes were deployed on the first floor of the four-storied building to study the lifetime of the designed system. Various sensors are used on the sensor nodes for capturing the information related to temperature, humidity, carbon monoxide, VOC, accelerometers, motion sensors and obtained information is provided only to the researchers. The presented work is categorized under the static sensor networks

Hasenfratz, D et al. 2012 [9] proposed the mobile based outdoor air pollution monitoring system which is a low-cost sensing system consist of sensor nodes with small sensors for detecting the O_3 and a smartphone. Using the cellular network, location-based (GPS module built in smartphones) air pollutants information are uploaded to the server, and it is made available to the community with the customized mobile apps. In the proposed paper techniques are used to improve the quality of the data sensed by the sensors and it showed high spatial resolution. The presented work is categorized under the community sensor networks.

Mendez, D et al. 2011 [10] presented the participatory sensing technology for monitoring outdoor air pollution based on community sensor networks (P-Sense). Information sensed by the various sensors(CO, CO_2, VOCs, H_2, temperature and humidity) on the sensors nodes are sent to the smart phones through the Bluetooth link. Cellular networks are used to sense the information and then uploaded the gathered information to the server to make it available to the community with the customized mobile apps. Practical issues related to the deployment of the designed system are also discussed.

Lo Re, G et al. 2014 [20] proposed a low cost and portable Urban Air Quality Monitoring Using Vehicular Sensor Networks. The designed system consists of various sensors mounted on the public transportation vehicles like buses, a GPS module and Zigbee communication link. Sensors on the sensor nodes are used to collect the levels of temperature, relative humidity, NO_2, CO_2, CO andO_3 which are transmitted to the central server through the Zigbee communication link. By using the mobility of public transportation vehicles, it is possible to achieve broad area coverage resulting in high spatial resolution level of information even with few sensors. Air pollution information is shared only for the research purposes.

Devarakonda, S et al. 2013 [21] presented a real-time air quality monitoring through mobile sensing in metropolitan areas. In the proposed work, portable sensor nodes are used consisting of Mobile Sensing Box (MSB) and other individual sensing devices to collect the fine-grained air pollution information.CO and PM concentration levels are sensed by the sensors of the Mobile Sensing Box. MSB mounted on the dedicated car travels around the city for the data collection, and this information was transmitted to the cloud server through the cellular network. Air pollution data captured by the sensor nodes are made available to the public through the customized mobile and web Apps etc.

Sherin Abraham et al. 2014[22] presented a low-cost wireless sensor network based indoor air quality monitoring system Designed system consist of a micro gas sensor, Arduino board and XBee modules which are capable of measuring six air quality parameters simultaneously. Sensor calibration is performed using Least Square Estimation method (LSM). Designed system results are compared with the commercially available indoor air quality monitoring systems, and the system showed an appreciable performance. The overall architecture for the WSN based Indoor air quality monitoring system is shown in the figure 1.

James J.Q.YU et al. 2015 [23] proposed a vehicular sensor network based air pollution monitoring system. In the designed system public transport vehicles are chosen as carriers of the sensor nodes, and bus routes are selected for deploying these sensors called as Bus Sensor Deployment

Problem (BSDP). Chemical Reaction Optimization (CRO) is an optimization tool used to choose the buses to install the sensors. The project was implemented in the Hong Kong Island bus route and the real-time data acquired showed the CRO technique could solve optimization problems efficiently.
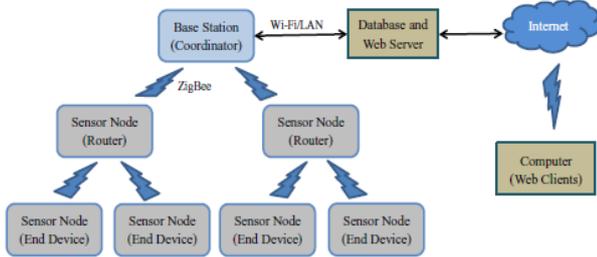

Figure 1. The architecture of WSN based Indoor Air Quality Monitoring System Figures are adapted from [24].

Elias Yaacoub et al. 2013[25] presented the wireless sensor network for monitoring and analyzing the air quality in Doha, Qatar. Multi-gas monitoring stations (MGMS) are used machine-to-machine (M2M) communications to communicate with a backend server. A smart platform was deployed on the server. The platform handles data cleaning filtering and data processing tasks. It presented the data presentation for environmental experts using dedicated software tools, e.g., the R software system and its OpenAir package. Analysis and assessment of real measurement data was also investigated. Air Quality Monitoring System Architecture is as shown in the figure
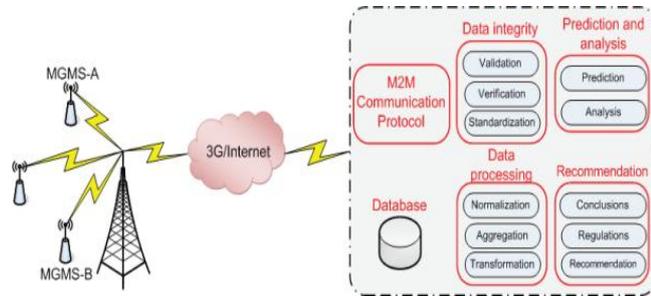

Figure 2. Air Quality Monitoring System Architecture Figures are adapted from [27].
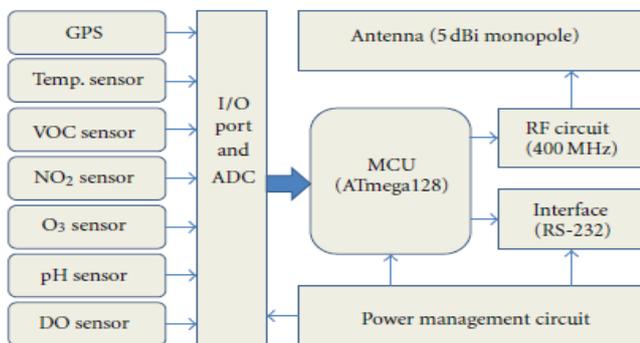

Figure 3. Block diagram of the RF sensor unit.Figures are adapted from [28].

Joonhee Kang et al. 2012 [26] proposed a low cost and portable RF based Sensor system to measure air pollution parameters like VOC, O_3, NO_2, and dust. Designed system was also used for measuring the pH and DO of water. It

consists of Sensor unit, GPS unit, a Central processing unit and RF unit. Performance and efficiency of the designed system was tested against the commercially available units for the O_3 and NO_2 gases, and it showed the accuracy was comparable with the standard commercial unit. Project was implemented for the air pollution monitoring in the city of Incheon in South Korea.

Tanuj Ahuja et al. 2016[27] presented a low-cost portable air pollution monitoring system by using the Internet of things (IoT) to create awareness to the public about the air quality enabling them to make better choices regarding traveling a route or purchasing of houses in the better area.

Ruiyun Yu et al. 2016[28] suggested a random forest method for finding the air quality (RAQ) for urban areas. Urban sensing systems collect the data regarding the meteorology, the historical air quality data, road information, point of Interest (POI) and real-time traffic pollution data. The algorithm was used for the data training and prediction, and it was evaluated with the city data. This algorithm showed a better prediction precision when compared with three algorithms Box model, Gaussian model, Lagrangian model.

Gyu-Sik Kim et al., 2016[29] presented the environmental sensors based air quality monitoring station to capture the information related to the temperature, humidity, PM_{10}, and CO_2. The proposed work was implemented at the Seoul Metro and Seoul Metropolitan Rapid Transit Corporation. In the subways [37], the accuracy and precision of the PM instrument to monitor the PM_{10} concentrations using the light scattering method was enhanced by the linear regression analysis technique. It was observed that use of ventilation fans experimentally in the subways could improve the air quality level and reduce the PM_{10} level

Movva Pavani et al. 2016 [30,31] presented a real-time pollution monitoring using wireless sensor networks (WSN).The sensors sense the concentration levels of carbon monoxide,carbon dioxide and oxygen gases deployed on sensor motes (Libelium Waspmote) which were calibrated correctly and the project was implemented in the industrial belt of Hyderabad city. A multihop data aggregation algorithm was employed, and air pollutant data collected from the designed test beds are made available onto the internet through the middleware and web interface. The developed system is capable of obtaining the fine grain pollution data on the real-time basis.

3. WSN applications in air pollution monitoring

With the technology development of the sensors, integrated circuits and wireless communications have paved the way for the fast growth of wireless sensor networks.WSNs are capable of detecting, measuring and gathering data from the real world (air quality, water quality, weather and traffic conditions, etc.) and transferring the information to end users. A sensor is a class of transducer which converts physical quantities like heat, light, motion, vibration, and sound into electrical signals. The primary unit in a sensor network is sensor node, which contains onboard sensors, processor, memory, transceiver and power supply. The sensor system consists of a vast number of sensor nodes deployed either inside or very close to the sensed phenomenon. Wireless sensors systems can be placed anywhere as the conventional wired network cannot be deployed, e.g., volatile places like high-temperature areas,

chemical and toxins prone areas. The capability of self-organization, ability to process concurrently, economical, limited energy resources, limited range of operation, fault-tolerance and rapid deployment characteristics of Wireless Sensor Networks make them resourceful for versatile applications like military, intelligence, control, monitoring, and surveillance of targeted areas.
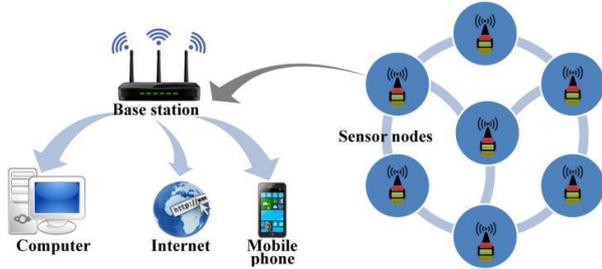

Figure 4. Wireless Sensor Network

The primary elements in air quality monitoring system using Wireless Sensor Networks are gas sensors (Fig. 5).

Figure 5. Various Gas Sensors

In Figure 6, the classification of gas sensors based on their working principles is shown.

The gas sensors of metal oxide semiconductor operate on the principle that the conductivity of the sensing element on the surface of the gas sensors will vary when they are exposed to the gas to be measured. Metallic oxide materials are used as sensing element. In polymer semiconductor gas sensors, the layer phtalocyanines are used as the sensitive element which has high thermal chemical stability. It works on the principle that the layer conductivity varies with the presence of gases. In the catalytic gas sensor, because of the catalytic reactions, there is a variation in the heat energy with the exposure to the gases.
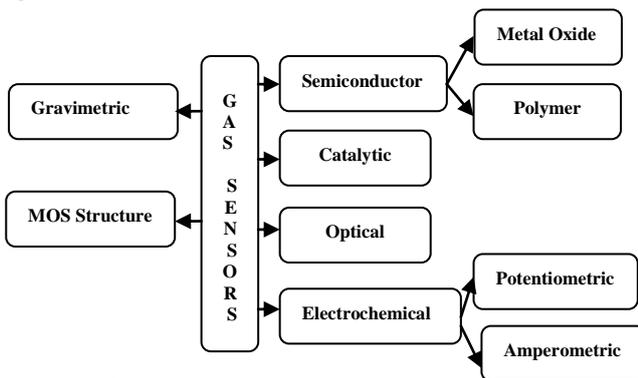

Figure 6. Classification of Gas Sensors

In the Electrochemical gas sensors, a chemical reaction takes place between the two electrodes which are made up of catalytic metals. These widely used gases sensors are classified further into potentiometric and amperometric gas sensors. The working principle involved in the optical gas sensors is the variation in the radiation characteristics like polarization, intensity when the surface is exposed to the gases. In the Gravimetric sensors, there is variation in the

mass due to the absorption of gas molecules leading to change in the mechanical properties. In Gas sensors based on MOS- structure, the characteristics of the transition metal electrodes vary with the exposure of gas. For developing the low-cost air quality monitoring systems, metal oxide gas sensors are preferred as they have high sensitivity and fast response time. The main drawbacks of these sensors are low selectivity and more sensitive to the temperature, humidity which makes identification of gases difficult. The characteristics of metal oxide gas sensors of the various companies are provided in Table 2.

Table 2. Characteristics of the Metal Oxide Sensors

Manufacturer	Sensor type	Gas Sensitivity	Gas Concentration [ppm]	Power consumption [mw]
Figaro	TGS2442	CO	50-1.000	14
	TGS2444	NH_3	10-100	56
	TGS825	H_2S	5-100	660
	TGS2611	CH_4	500-10.000	280
	TGS4161	CO_2	400-9.000	300
Synkera	705	NH3	25-10.000	975
	706	NO_X	0,5-10	500
	707	VOC_S	do 100	400
	714	H_2S	1-100	900
	711	CH_4, C_3H_8	90-10,000	900
Sgx Sensortech	MiCS-2714	NO_2	0.05-5	50
	MiCS-5524	CO	1-1.00	88
	MiCS-5914	NH_3	0,1-10	88
Sencera	HS134	CO	do 100	800
	HS811	CO_2CH_4, C_3	350-10.000	1,200
	HS131	H_8	1.000-5.000	800

4. Impact of air pollution on the health

Air Quality Index (AQI) is also referred as Pollutant Standard Index (PSI) or Air Pollution Index (API) gives the quality of the air in the range of 1 to 500 at a particular location.

Table 3. Air Quality Index (US Standards)

S.No	Air Quality Index (AQI) Values	Levels of Health Concern	Colors
	When the AQI is in this range:	…air quality conditions are:	….as symbolized by this colour
1	0 to 50	Good	Green
2	51 to 100	Moderate	Yellow
3	101 to 150	Unhealthy for Sensitive Groups	Orange
4	151 to 200	Unhealthy	Red
5	201 to 300	Very Unhealthy	Purple
6	301 to 500	Hazardous	Maroon

Higher the AQI value, higher the health risks. It is calculated for the primary air pollutants like Carbon monoxide, sulphur dioxide, particle matters and ozone.AQI value up to 50 is

considered to be good quality air and inhaling this air will not affect the public health. AQI value above 300 is deemed to be hazardous causing severe concerns on the public health. AQI value of 100 is set as a standard air quality by the Environmental Protection Agency (EPA). AQI value less than 100 is acceptable and above 100 is considered to be harmful to specific sensitive groups. AQI norms will differ for various countries and the AQI standards for the US is given in the table 3.

Table 4. Air Quality Index (Indian Standards) Sub-index

Colour Coding	AQI RANGE INDEX	O_3 8h Avg ppb	CO 8h Avg ppm	NO_2 24h Avg ppb	PM_{10} 24h Avg $\mu g/m^3$	$PM_{2.5}$ 24h Avg $\mu g/m^3$
Good	0-100	0-50	0-1.7	0-42	0-100	0-60
Moderate	101-200	51-98	1.8-10.3	43-94	101-150	61-90
Poor Unhealthy for sensitive group	201-300	99-118	10.4-14.7	95-295	151-350	91-210
Very Poor	301-400	119-392	14.8-30.2	296-667	351-420	211-252
Very Unhealthy	401-Above	393-Above	30.3-Above	668-Above	421-Above	253-Above

Air Quality Index, sub-categories proposed by IITM (MoES) for the Indian standards. Each group corresponds to the various levels of health risks.

- **Good:** Air quality is good and no health hazard when the AQI value is between 0 to 50
- **Moderate:** Air quality is acceptable and can cause respiratory problems to those who are sensitive to ozone or particle pollutants when the AQI value is in the range of 51-100.
- **Unhealthy:** Only Sensitive group will experience health effects when the AQI value is in the range of 101-150.
- **Unhealthy:** Every person will experience the risk of health concerns, and the sensitive group will have serious health issues when AQI is between 150 – 200.
- **Very Unhealthy**: Poses severe health problems to all when AQI value is in the range of 201 - 300.
- **Hazardous:** AQI values above 300 represent acute health effects; it's a health emergency condition.

Air pollution is a complex mix of various components like particulate matter (PM) , gaseous pollutants like ozone, nitrogen dioxide (NO_2), carbon monoxide (CO), sulphur dioxide (SO_2) and volatile organic compounds (including benzene). It is posing serious health concerns of respiratory diseases like asthma, chronic obstructive pulmonary disease, lung cancer and even cardiovascular diseases.Gaseous pollutant, Ozone will have a severe health impact on the

people suffering from lung disease, children and old people. Particle pollutants will have a serious health effect on the sections of people suffering from heart or lung diseases, older adults and children. It is suggested that the research should take place in this area to find the methods to reduce the air pollution levels to avoid cardiovascular diseases.

Table 5. The six standard pollutants and their health effects

S.No	Pollutant	Health Effects
1	Carbon Monoxide (CO)	Reducing oxygen in the blood cells leads to decreased oxygen delivery to the body's organs and tissues. The extremely high level can cause death.
2	Nitrogen Dioxide (NO_2)	The high-risk factor for emphysema, asthma and bronchitis diseases. Aggravate existing heart disease and increase premature death.
3	Ozone (O_3)	Trigger chest pain, throat irritation, coughing and congestion. Worsen bronchitis, emphysema and asthma
4	Sulphur Dioxide (SO_2)	The high-risk factor of bronchoconstriction can increase asthma symptoms.
5	Particulate Matter ($PM_{2.5}$ & PM_{10})	Cause premature death in people with heart and lung diseases. Aggravate asthma, decrease lung function and increase respiratory symptoms like coughing and difficulty breathing.
6	Lead (Pb)	Accumulate in bones and affect the nervous system, kidney function, immune system, reproductive systems, developmental systems and cardiovascular system. Affect oxygen capacity of blood cells.

5. Existing air pollution monitoring techniques using Sensor networks

Based upon the carriers of the sensor nodes, the present air pollution monitoring systems are classified broadly into three categories [1].

- Static Sensor Network (SSN)
- Community Sensor Network (CSN)
- Vehicle Sensor Network (VSN)

5.1 Static Sensor Network (SSN)

Low-cost sensors are deployed on fixed structures like traffic lights, street lights, walls or at meticulously planned areas as shown in Figure 4. The number of sensors used in Static Sensor Network can be increased by using low-cost sensors, and the density of the sensor nodes in Static Sensor Network is much larger than the conventional air pollution monitoring systems. Air pollution data captured by the sensor nodes can be made available to the public through various devices /platforms like internet pages, mobile and Web Apps, etc. after obtaining the authorization for the data dissemination.

Advantages of Static Sensor Networks

1. No constraint on energy consumption
2. No limitation on the size and weight of sensors
3. Multiple sensors can be placed per node
4. Accurate and reliable data
5. Network connectivity guaranteed
6. Well-calibrated and maintained sensors

Disadvantages of Static Sensor Networks

1. Need careful deployment of sensor nodes

2. Requires large number of sensor nodes
3. Resource wastage
4. Inconvenience in calibration and maintenance
5. Requirement of customised network

5.2 Community Sensor Network (CSN)

Low-cost portable sensors are used, and these nodes are carried by the public or the professional users usually environmental volunteers who are concerned about the quality of air as shown in Figure 5. Analysed air pollution data captured by the sensor nodes can be made available to the public through various devices /platforms like internet pages, mobile and web Apps, etc. after obtaining the authorization for the data dissemination.

Advantages of Community Sensor Networks

1. Cost efficiency
2. Public driven property
3. Mobility of sensor nodes

Disadvantages of Community Sensor Networks

1. Low data accuracy and reliability
2. Poorly calibrated and maintained sensors
3. Severe energy consumption constraints
4. Uncontrolled/semi-controlled mobility
5. Severe limitation on size and weight of sensors

5.3 Vehicle Sensor Network (VSN)

Low-cost portable sensors are used for acquiring the air pollution data in Vehicle Sensor Network (VSN) systems, typically carried by the public transportations like buses, trains, taxis as shown in Figure 6. By the mobility of vehicles, a large geographic area can be covered by the single sensor node which can achieve sufficient broad geographic coverage. Air pollution data captured by the sensor nodes can be made available to the public through various devices /platforms like internet pages, mobile and Web Apps, etc. after obtaining the authorization for the data dissemination.

Advantages of Vehicle Sensor Networks

1. Loose constraint on energy consumption
2. No limitation on size and weight of the sensors
3. Can place multiple sensors per node
4. Accurate and reliable data
5. High mobility of sensor nodes
6. Well-calibrated and maintained sensors
7. Feasibility in maintenance

Disadvantages of Vehicle Sensor Networks

1. Uncontrolled/semi-controlled mobility
2. Redundant sampling issues
3. Requirement of locating and communication devices equipment
4. Customised network requirement

Traditional and conventional air pollution monitoring systems use complex measurement techniques with sophisticated and high precision equipment with proper calibration techniques. To ensure the quality and data accuracy obtained from these systems, they are assisted by the build-in calibrator, air filtering equipment, temperature controller (cooler and heater) and relative humidity controllers. As a result, these equipment consume high power and they are in large volumes with heavyweight and cost. Due to significant size, power limitations, high maintenance cost and high initial investment traditional Air Quality Monitoring stations are used in the limited number. Wireless Sensor Network presents an attractive and alternate solution for the large conventional air monitoring stations as we could able to deploy the sensing stations with smaller size and low-cost sensors. The sensing stations are capable of collecting and transmitting the sensed information to the other sensing stations in the network. Comparison of methods and instruments employed in the existing air quality monitoring systems are given in Table 7.

Table 6. Comparison of SSN, CSN and VSN Networks

S.No	Type of Network	SSN	CSN	VSN
1	Mobility	Static	Very Good	Excellent
2	Temporal Resolution	Excellent	Good	Very Good
3	Cost Efficiency	Good	Excellent	Very Good
4	Maintenance	Very Good	Good	Excellent
5	Data Quality	Excellent	Good	Very Good

6. Research challenges and future directions

Critical issues that determine the performance and design of a wireless sensor network [34] for the air pollution monitoring are as follows:

Energy Efficiency: Designing the energy efficient [35] software algorithms, protocols [33] and developing the energy-efficient scalable hardware architectures are the critical challenges for the researchers in this domain. Sensors operate on the batteries and energy is consumed in data collection, data processing, and data communication and also in idle condition. Regularly batteries are needed to be replaced or recharged after they have been drained out. It is difficult sometimes to restore or replace the batteries because of demographic conditions.

Self Management: Wireless sensor networks should able to manage the network configuration, maintenance and repair by itself once deployed and function without any human intervention [36, 37].

Hardware and Software Issues: Hardware components in Sensor Networks consist of hundreds of thousands of nodes, Flash memories and FPGA-based microcontrollers which are to be inexpensive and practically economically viable. Software in WSN should be light and less energy consuming which is hardware independent [38, 39].

Operating System: Operating System for wireless sensor networks should support a simple programming environment [40]. Various Operating Systems developed for Sensor nodes include TinyOS, Mantis Operating System and Nano-Qplus.

Quality of Service (QoS): Air pollution monitoring systems using WSNs are used in real time, and it is mandatory for the network to provide an excellent level of service QoS to its users. Unbalanced traffic, constantly changing network topology and imprecise routing affects the QoS and these issues should be addressed for improving the QoS. WSNs QoS should not be affected by adding or removing the nodes in the network [41, 42].

Security: Security of data is a relatively challenging task in WSNs as it should provide the safety of data traveling between the sensor nodes of the network or between the sensors and the base station. The sensor networks should be designed adequately with each sensor node and the base station having the capability to verify the data received from the trusted sender. A false data can change the way a network could be predicted. The integrity of data has to be maintained without any change in the data, and accurate data must reach at the user end [44, 45].

Architecture: Properly designed sensor network architecture should be employed as they will support the durability and scalability of the system without affecting the QoS [46]

There is a significant need for research required in the design and development of air monitoring stations using the wireless sensor networks. Some of the future areas of research to be addressed are (i) Designing the energy efficient software protocols and developing the energy-efficient scalable hardware architectures (ii) Design of the self management systems (iii) Security and privacy (iv) Approaches for handling and utilization of the big data from numerous sensor deployed in the network. Hardware engineers should work towards designing the scalable architectures providing desirable QoS whereas software engineers should work towards developing efficient energy protocols. Wireless sensor networks present various practical issues which are needed to be addressed and feasible solutions should be evolved in building the future efficient and portable systems.

7. Conclusion

Air pollution is evolving as a severe environmental concern due to its enormous impact on the wellbeing of the people universal environment and also on the global economy. Conventional air pollution systems are not able to provide air pollution data of high spatiotemporal resolution due to non-scalability and limited data availability. Air pollution is majorly contributed by the industries and automobile vehicles. Hence there is a need to investigate and develop real-time, continuous air pollution monitoring systems of low cost and energy efficient. There is a need of proposing new methods in future to reduce Air pollution by introducing the proper controlling mechanisms.In the present review, various issues and challenges faced by the researchers during the implementation of the existing systems were presented.

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Table 1. Summary of Existing Air Pollution Monitoring Systems

S.No	Approach	WSN Type	Sensor Type	Operating Environment	Sensor Node & Algorithm Employed	Data Availability	Sensor Network Type
1	Murty R.N et al. 2008 [2]	WiFi 802.11a/b/g	Not mentioned	Outdoor	Linux based embedded PC (266 MHz/128 MB/1 GB)	Web Apps	SSN
2	Liu J.H. et al. 2011[3]	GSM and Zigbee	CO sensor	Outdoor	Octopus II (1 MHz/10 KB/1 MB) Lab view Program	Researchers only	SSN
3	Kadri A et al. 2013[4]	GPRS	O_3, NO_2, CO and H_2S	Outdoor	Arduino (16 MHz/8 KB/2 GB)	Web App, Mobile App	SSN
4	Mansour S et al. 2014[5]	ZigBee	Electrochemical (O_3, CO, NO_2)	Outdoor	Arduino (14 MHz/512 KB/2 GB) Clustering Protocol of Air Sensor	Email, SMS, Web App	SSN
5	Khedo K.K et al. 2010[6]	Not mentioned	Not mentioned	Outdoor	Not mentioned Recursive Converging Quartiles (RCQ)	Not mentioned	SSN
6	Jelicic V et al. 2013[7]	ZigBee	Solid-state (CO, VOCs)	Indoor	JN5168 (32MIPs/128KB/*)	None	SSN
7	Postolache O.A et al. 2009[8]	Wi-Fi (802.11 b/g)	Solid-state (CO, VOCs)	Indoor	IPu8930 (*/*/512KB)	Web page	SSN
8	Hasenfratz D et al. 2012[9]	Cellular network	Solid-state (O_3)	Outdoor	HTC HERO saxophone	Web App, Mobile App	CSN
9	Mendez D et.al 2011[10]	Cellular network	Solid-state (CO_2, VOCs), Catalytic (H_2), Electrochemical (CO)	Outdoor	PRO200 Sanyo cellphone	Web App, Mobile App	CSN
10	Jiang Y. et.al 2011[11]	Wi-Fi	NDIR (CO_2), Solid-state (CO, O_3)	Indoor	Arduino (16 MHz/2 KB/32 KB)	Web App, Mobile App	CSN
11	Honicky R et al. 2008[12]	Not mentioned	Not mentioned	Outdoor	LG VX980 smartphone	Not mentioned	CSN
12	Maisonneuve N et al. 2009 [13]	Cellular network	Microphone	Outdoor	NOKIA N95 cellphone	Web page, Mobile App	CSN
13	Tsow F et.al 2009[14]	Cellular network	QTF (VOCs)	Outdoor	Motorola Q phone	Web App, Mobile App	CSN
14	Volgyesi P et al. 2008[15]	Wi-Fi	Solid state (CO, NO_2, O_3)	Outdoor	8051 uC (*/4KB/2MB)	Web App	VSN
15	Ma Y et.al 2008[16]	Wi-Fi or ZigBee or Others	DUVAS (O_3, NO,NO_2, SO_2, VOCs)	Outdoor	Generic Ultra Violet Sensor Technologies (GUSTO) sensors	None	VSN
16	Hu S.C et.al 2009, 2011 [17 &18]	Cellular network (GSM)	NDIR (CO_2)	Outdoor	JN5139 (16 MHz/96 KB/192 KB)	Web App	VSN
17	Wong K.J et al. 2009 [19]	Wi-Fi or Cellular network (GPRS)	Optical analyser (PM), Solid-state (CO, NO_2, NO, VOCs)	Outdoor	Renesas H8S	Web App	VSN
18	Lo Re, G et al. 2014[20]	ZigBee	Solid-state (CO, NO_2,O_3, CO_2)	Outdoor	Arduino (16 MHz/8 KB)	None	VSN

19	Devarakonda S et.al 2013 [21]	Cellular network	Solid-state (CO), Optical analyzer (PM)	Outdoor	Arduino (16 MHz/8 KB/128 KB)	Web App	VSN
20	Sherin Abraham et al. 2014[22]	Zigbee/Wi-Fi	Heating semiconductor sensors - CO_2,O_3 VOC Chemical sensors- CO_2 Digital Sensors- Temperature and Humidity	Indoor	Arduino (16 MHz/8 KB/128 KB)	Web App	SSN
21	James J.Q.YU et al. 2012[23]	Not mentioned	Not mentioned	Outdoor	Not mentioned	Web App	VSN
22	Elias Yaacoub et.al 2013[25]	Internet	Solid state gas sensors	Outdoor	R software system	Web App	SSN
23	Joonhee Kang et al. 2012 [26]	RF	Solid state gas sensors	Outdoor	MCU ATmega 128	Web App	SSN
24	Tanuj Ahuja et al. 2016[27]	Zigbee/GSM/ GPRS/ Wi-Fi/ Blue Tooth	Solid state gas sensors	Outdoor	Microcontroller	Web App	SSN
25	Ruiyun Yu et al. 2016[28]	Not mentioned	Not mentioned	Outdoor	Random forest method for the air quality (RAQ)	Web App	SSN
26	Gyu-Sik Kim et al., 2016[29]	Internet	Temperature, humidity, PM_{10}, and CO_2	Outdoor	ATmega128	Web App	SSN
27	Movva Pavani et.al 2016[31]	Internet	Solid state gas sensors CO_2, O_2	Outdoor	Libelium Waspmote & multihop data aggregation algorithm	Web App	SSN

Table 7. Comparison of Methods and Instruments used in Existing Air Quality Monitoring Systems

Pollutant	Measurement Method	Advantages	Disadvantages	Accuracy
Carbon Monoxide (CO)	IR Absorption with Gas Filter Correlation Wheel	Accuracy, range and precision is excellent	Costly equipment is required.	±0.5% of reading
	Electrochemical Sensor	Lowest, very little power consumption Low maintenance, Response time < 50s	Life expectancy is 1-2 years	±0.5 ppm at 0–5 ppm ±10% at 5–25 ppm
Nitrogen Dioxide (NO$_2$)	Cavity Attenuated Phase Shift Spectroscopy	Accuracy, range and precision is excellent	Costly equipment is required.	±0.5% of reading
	Electrochemical Sensor	Lowest, very little power consumption Low maintenance, Response time < 50s	Life expectancy is 1-2 years	±0.02 ppm at 0–0.2 ppm or ±10% at 0.2–1 ppm
Ozone (O$_3$)	Chemiluminescence Detection	Accuracy, range and precision is excellent	Costly equipment is required.	±0.5% of reading
	Solid-State Sensor	Low Maintenance, Response time 20 s -90s, Life expectancy is 10+ years	High power consumption is, Require heating element	±5 ppb
	Electrochemical Sensor	Lowest, very little power consumption Low maintenance, Response time < 50s	Life Expectancy is 1-2 years	Not Provided
Sulfur Dioxide (SO$_2$)	UV Fluorescence	Accuracy, range and precision is excellent	Costly equipment is required.	±0.5% of reading
	Electrochemical Sensor	Lowest, very little power consumption Low maintenance, Response time < 50s	Life Expectancy is 1-2 years	±0.05 ppm at 0–0.5 ppm or ±10% at 0.5–10 ppm
	Solid-State Sensor	Low Maintenance, Response time 20 s - 90s, Life expectancy is 10+ years	Power consumption is Large, Require heating element.	Not provided
Particulate matter (PM)	Tapered Element Oscillating Microbalance analyzers	Provide real-time (<1 h) data with high precision	Large size, heavy weight and high cost. Require heating element	±0.5 µg/m^3
	β-attenuation analyzers (BAM)	Provide real-time (<1 h) data with High precision.	Large size, heavy weight and high cost. Require radioactive source for heating	±1.0 µg/m^3
	Black smoke method	Simple, robust and inexpensive. Low and Easy to maintain. Short sample time (in min).	Darkness-mass factor may Vary from time to time and location to location.	±2.0 µg/m^3 or higher
	Optical analyzers	Small, lightweight, battery operated. Short sample time, Measure different sizes of particles simultaneously	Particle characteristics differ from location to location and time to time	Not provided