Using Wireless Sensor Networks to Save Lives from Pollution Terrorism

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***Abstract*—Today, pollution is a significant consideration in public health due to the immense burning of fossil fuels and other chemicals for industries, power generation, vehicles and a multitude of other uses. This is especially the case in urbanized areas where people and sources of pollutants are densely concentrated. In this paper, we cover several works on wireless sensor networks and pollution monitoring. We focus on a prominent work on pollution monitoring that involves a wireless sensor network with mobile and static node that is able to process and deliver information in real-time. We also cover other relevant and vital papers established in this area of technology, including different architectures and different deployment schemes (e.g. public transportation, personal mobile devices, and static nodes). We close our survey with a discussion of the state-of-the-art technologies in pollution monitoring wireless sensor networks, including both solved and existing problems, and our expectations of its future direction based on current developments and opportunities.**

***Index Terms*—Wireless Sensor Networks, Air Pollution**

I. Introduction

Industrialization, increased energy use, traffic, and growing urban centers, among other factors have caused air pollution to be a serious issue in many countries not just for the environment, but public health. In the United States, 79% of Americans live in urban areas [1] and are subjected to a dramatically increased degree of air pollution than would exist outside urban and industrial centers. The US Environmental Protection Agency identified the six most common air pollutants as particulate matter, carbon monoxide, sulfur oxides, nitrogen oxides, ozone, and lead [2]. In the United States, COPD, asthma, and other respiratory diseases plague millions of people. COPD is the third leading cause of death in the country [3] and 26 million Americans suffer from asthma. Air pollution is prominent in worsening symptoms and effects of these fatal diseases [4]. Studies have demonstrated results showing how destructive the effects of air pollution can be, particularly on those afflicted by respiratory illnesses in polluted metropolitan areas like Los Angeles [5].

Wireless sensor networks (WSNs) enable gathering data wirelessly from a large number of nodes in almost real-time. In a world of air pollution harming the environment and human health, there does not exist a strategy to thoroughly monitor air pollution over a wide area and in different urban settings. To contrast, current methods of pollution monitoring via expensive equipment at fixed locations or laboratory analysis are inefficient in providing an accurate image of air pollution across a broad range of environments even within a single city. The granularity is extremely coarse and available data points are limited and data collection times are spaced out. These methods' primary disadvantages lie in the facts that they cannot usually be achieved in real-time and they involve extrapolating models that give a very imprecise, unreliable of pollution outside of the immediate area of where pollution data was collected. In addition, this data, as limited as it is, is also limited in its accessibility. However, WSNs allow for data at many points within a given area, real-time data collection and dissemination, and an effective scheme to monitor air pollution and formulate an accurate image of its proliferation and concentration. WSNs provide a high-granularity, real-time system that can gather high quantities of data in a dense area, which is necessary for effective awareness of air pollutants and their effect on health issues.

In this paper, we present a survey on different strategies in which WSNs are used for pollution monitoring. We discuss the various advantages and challenges involved in a wireless sensor network. This includes the architecture of wireless sensor networks and how it can produce a successful solution for effective pollution monitoring. We highlight various deployment schemes to demonstrate the effectiveness and feasibility of pollution monitoring WSNs. Our focus will be on analyzing the different solutions and strategies that have been proposed, and additionally on evaluating their benefits in solving the pollution monitoring problem. Critical emphasis will be placed on mobile, portable solutions that can be employed on public transportation or individual users, as these appear to be the most promising strategies.

II. Key Paper

The paper "Air Pollution Monitoring and Mining Based on Sensor Grid in London" [6] provides a very comprehensive and detailed work on a wireless sensor network for air pollution monitoring. The goal is to develop low-cost, pervasive sensor networks to gather real-time air pollution data from roadways over a large area. This work is motivated by the high levels of air pollution as a result of road traffic, which contributes 97% of CO and 75% of NOX emissions in the city, along with lead, ozone, benzene, and particulate matter. All of these have a seriously detrimental effect on the environment and human health. In addition, existing monitoring stations are often only at pollution hotspots, may be several kilometers apart from each other, and the data is processed offline, which limit such a system's effectiveness in thoroughly monitoring air pollution. The data gaps in pollution monitoring have produced three major barriers: the lack of validation of traffic and pollution models, inability to determine individual exposure to pollutants, and a lack of integrated traffic and environmental control. These concerns can be addressed by generating new types of useful data and more data at both the temporal and spatial levels. The work proposes the Mobile Discovery Net (MoDisNet), a low-cost mobile monitoring system to develop a grid structure to improve monitoring of harmful environmental gases.

The MoDisNet air pollution monitoring system has an infrastructure based on the use of vehicles as a platform for environment sensors along with static sensors placed at roadside locations in a grid setting. More specifically, the system has a two-layer network architecture with one layer being the Mobile Sensor Nodes (MSN) and the other being the Static Sensor Nodes (SSN). The data collected by MSNs is sent to SSNs for data processing, storage, receiving, and uploading. This is shown in the figure [6].

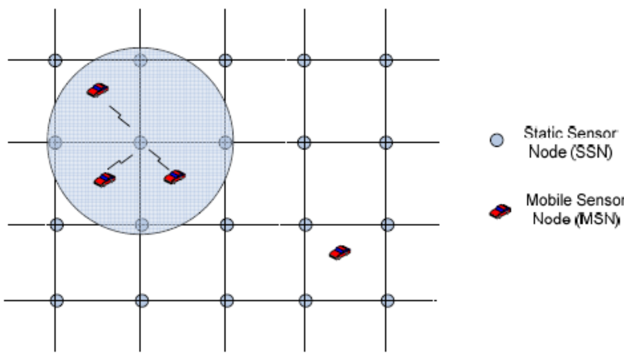

Figure 1. MoDisNet network architecture

The GUSTO (Generic Ultraviolet Sensor Technologies and Observations) sensors designed and used in this system are capable of simultaneous detection of multiple pollutants, real-time data collection, low cost per unit, data robustness, and high accuracy of pollution concentrations. When a vehicle passes a sensor, the detected pollutants (SO2, NOx, O3, etc.) exhausted from the vehicle are detected by the GUSTO sensor and the data is processed to determine the concentration. The nodes in the wireless sensor network communicate each other as a P2P (peer-to-peer) network. Due to the gigabit magnitude of data transferred per sensor each day, the sensors must store and communication the information, which is filtered and processed before being stored in a backend repository. The GUSTO sensors connect to the MoDisNet grid through Sensor Gateways (SGs) according to different wireless protocols (Wi-Fi, Zigbee [7], etc.). The sensors send their data to the gateways across the network, in a multi-hop manner across sensors if necessary. Meanwhile, the SGs are responsible for handling the data between the sensors and the backend data warehouse and for load balancing of the data traffic. The backend warehouse stores the data from the sensors along with other data such as traffic, weather, and health information, which can be used by the grid to create air pollution and traffic models. In addition, it can provide real-time information to end users about the current environmental conditions. Figure 2 [6] shows the whole MoDisNet sensor network architecture.

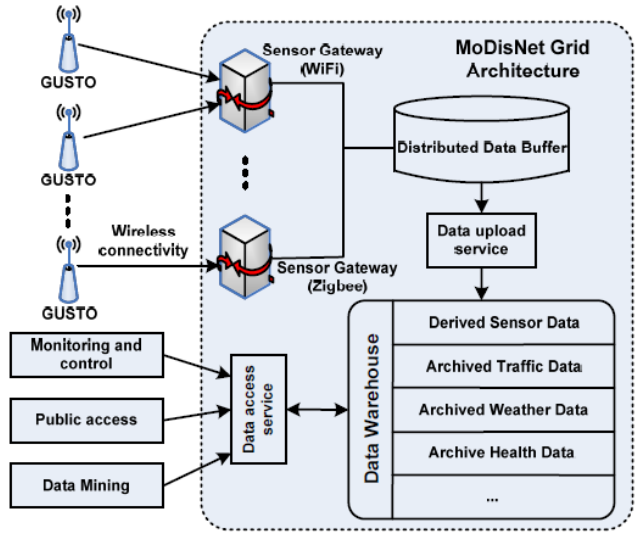

Figure 2. MoDisNet sensor grid architecture

Data mining techniques are critical to the research and study of the relationship between the environment and road transportation. Often, end users will have to query data from the backend data storage to understand the current environmental setting. In this area, centralized data mining is implemented in the backend with the purpose of discovering long-term pollution and traffic patterns and finding the relationship between specific traffic and pollution events. P2P-based distributed data mining is implemented in the sensors, as it depends on data collected and stored by each sensor in real-time. By mining this real-time data straight from the sensors, a quick analysis can be made on the pollution concentration and as a result, on the traffic situation as well. However, the results may be simple and not as thorough and accurate as the centralized mining results. There is also integrated data mining, where the distributed mining results match a pattern retrieved from the centralized mining leading to the assumption that some event will happen, or there is a new result that leads to an updated, more accurate model in the centralized mining area. Data mining in sensor networks faces challenges such as the resource constraints on the sensors (battery, communication bandwidth, etc.), the mobility of sensor nodes which adds complexity to data collection and analysis, and sensor data is transferred in real-time over the network which cannot make use of traditional backend schemes. Distributed data mining can address these problems by using distributed resources in an optimal manner, with focuses on intelligent data collection schemes to reduce volume, optimized node organization schemes to increase homogeneity of the data, and efficient mining algorithms to reduce computing complexity.

MoDisNet has a simulation platform which allows it to give an evaluation of the hardware and software design. It focuses on simulating the wireless communication processing, the sensor units, upper and lower layer algorithms and programs, and the cooperation between the MSN and SSN types of sensors. The simulation can be visualized to demonstrate the effectiveness of the configuration of the system and performance of the routing protocols and data transfer. The authors simulate an 18 sensor node (12 SSNs and 6 MSNs) which can send data bidirectionally to sensors within range. Air pollution data for four pollutants is taken at every minute in an urban setting, showing that the system can receive and send messages from node to node with minimal collision and packets lost. Another evaluation demonstrates the ability of MoDisNet in a real-time pollution data monitoring scenario, based on actual data collected from a sensor grid. The evaluation is not only able to determine where there is high pollution, but which gases contribute to the pollution as well, which can be organized into pollution clouds. Figure 3 [6] shows the map with the pollution clouds at different times of the day, while Table 1 [6] exhibits what each of the clouds mean. For example, the results show that at 9:00, the pollution is greatest near schools (circles) and main roads, at 15:30 by the schools and factory (square), and at 17:00 by the hospitals (ovals), factory, and main roads.

Table I
POLLUTION PATTERNS

Time	Clouds	Analysis			
		NO	NO_2	O_3	SO_2
9:00	Red	High	Middle	Low	High
	Blue	High	Low	Low	Low
	Yellow	Low	Middle	Low	Middle
15:30	Red	Low	Middle	Middle	Middle
	Blue	Low	High	High	Middle
	Yellow	Low	Low	Low	High
17:00	Red	Middle	High	High	Middle
	Blue	Low	Low	Middle	Middle
	Yellow	Low	Middle	Middle	High

III. ADDITIONAL PAPERS

In this section, we will address specific additions that the key paper does not cover but are an area of interest as research can be furthered in these directions to improve WSN systems as a whole. Firstly, MoDisNet does not focus on different deployment mediums. There are numerous types as will be mentioned later in this survey, but we focus on a mobile phones for the next part. However, there are pros and cons from deviating from the traditional state of the art system. Secondly, we evaluate a newer routing protocol presented in another paper that outperforms current WSNs in respect to energy efficiency. Lastly, we examine an improved clustering algorithm that also focuses on reducing energy consumption.

A. *Deployment via Mobile Phones*

In "Wireless Sensor Network Deployment in Mobile Phones Assisted Environment" [8], the idea behind using mobile phones as a deployment medium sheds a new light from the current state of the art, which uses vehicles. As in the key paper, it tries to leverage mobility. The benefits of using mobile phones include reducing the number of WSN units deployed, which also corresponds to the decrease costs in equipment

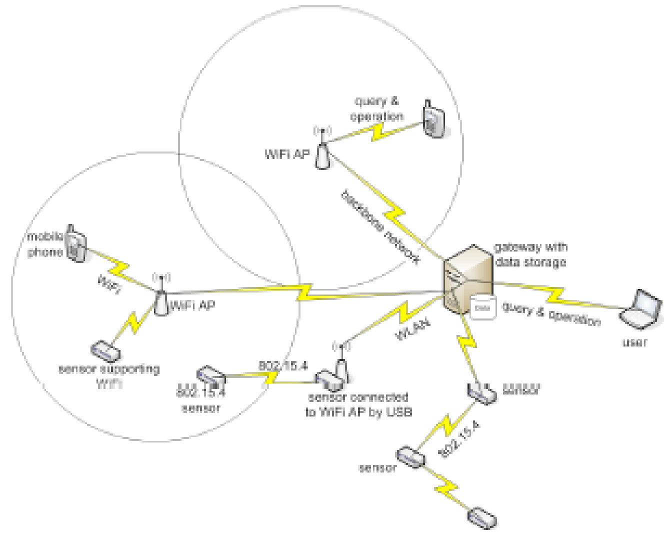

Figure 4. System architecture

and maintenance of the units. Rather than replacement of WSNs, the paper suggests that mobile phones can serve as a complement to existing WSN units and integration through their framework seamlessly. In order to prevent quality loss of areas not covered, the paper proposes a cost-effective sensor deployment algorithm that covers the necessary areas to meet application needs. This greedy algorithm determines where a mobile sensor should be placed on the grid based on the missing coverage probability and sensing quality. It focuses on areas where coverage is least effective and iterates through the list of grid points until all points are covered or an upper bound of sensors is met. In order to evaluation the effectiveness of the system, the paper introduces a sensing quality evaluation model and a mobility prediction model.

Building off the model presented by the current state of the art, this paper reflects the network structure presented in the key paper except where mobile phones replace the need for sensors in certain areas as shown in Figure 4 [9]. By reducing the overall cost of the system, the use of mobile phones introduce an array of sensor quality issues due to trustworthiness of users and data quality on phones for instance. This paper proposes an ambitious deployment scheme for deploying nodes in a WSN, which can be easily employed for pollution monitoring. It enables the users to actively provide air quality data in an unobtrusive manner, through the use of their mobile phones and a small, attached sensor device. Since nodes at static locations is not sufficient to acquire a thorough view of air pollution, the use of mobile phones for this purpose can enable data acquisition over a much greater area, rather than at specific points.

B. *Improvement on Routing Protocols*

A major networking issue in all WSNs is the unexpected downtime for a node, so WSN systems rely on an underlying routing protocols tailored to delay-sensitive networks. An interesting approach to load balance the system while providing

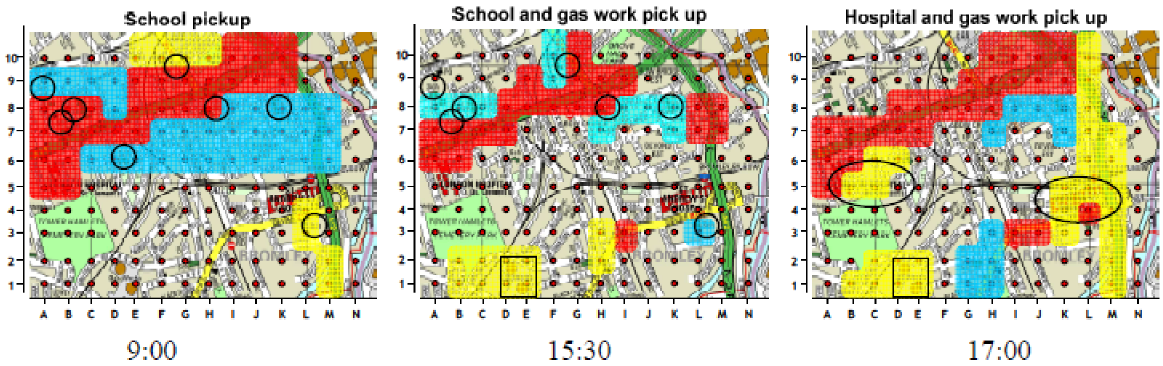

Figure 3. Pattern recognition for high air pollution level areas

fault tolerance is to use the knowledge of neighboring nodes to determine the next course of action. In “QoS-aware distributed adaptive cooperative routing in wireless sensor networks” [9], the authors propose a distributed adaptive cooperative routing protocol (DACR) to answer the issue of cooperative routing in WSNs. The main idea is to leverage cooperative communication and exploit knowledge of delay- and energy-aware routes in order to make trade-offs between reliability and delay. If a node in the system is not reliable for whatever reason, the underlying network protocol must be able to continue the operations of the whole system and transmit the necessary sensor data despite a node failure. In order to maintain a reliable system, DACR effectively determines, at each hop, which transmission mode, direct or relay, to pick in order for the system to continue running smoothly.

Compared to state of the art protocols in current WSN systems, DACR operates better in energy-distribution and load balancing using its network traffic prediction approach than MoDisNet SGs’ handler. DACR, like AODV, uses proactive relay selection, which is shown to improve QoS performance compared to using reactive selection. The paper highlights how the use of cooperative relay nodes reduce computation cost, leading to higher energy cost performance. In detail, the number of route reconstructions and packet retransmissions is minimized by the dynamic decisions made at each node. This work is quite important in regards to pollution monitoring WSNs because a network of this large of a scale requires minimal delay to ensure real-time data transmission and the ability to ensure data is transmitted in case of a node failure. It also allows for load balancing using its traffic prediction scheme, so that congestion does not occur when data must hop multiple nodes to its destination in an ad hoc network. However, if this approach mispredicts the expected traffic, it could lose large amounts of critical air pollution data due to network congestion.

C. Zone Partitioning in WSNs

The paper, “Power-Efficient Zoning Clustering Algorithm for Wireless Sensor Networks” [10], presents a clustering routing algorithm, called PEZCA, to improve on the energy-efficiency of WSNs. It works on the principles of Low-Energy Adaptive Clustering Hierarchy (LEACH) and Power-Efficient Gathering in Sensor Information System (PEGASIS) and builds off on current state of the art routing protocols. LEACH randomly selects cluster head nodes and rotates the responsibility in order to allow for even energy dissipation. As an improvement of LEACH, PEGASIS allows for chaining and data aggregation. PEZCA, which takes ideas from both, can be thought of as partitioning the nodes into fan-shaped regions. Clusters of nodes that lie closer to the base station are smaller, whereas those farther away are larger. The idea is to reduce inter-cluster relay traffic, which in turn lowers energy consumption.

Reduced energy consumption using PEZCA compares better against current state of the art clustering algorithms, which share typically longer chains among cluster heads. By allowing different cluster sizes and forming a fan-shaped configuration as shown in Figure 5 [10] originating from the base station, energy consumption is balanced amongst the system. This paper proposes an invaluable scheme for effectively managing energy usage across an air pollution WSN. Since energy-efficiency is a critical constraint in operating WSNs, PEZCA can help nodes across the grid last longer on a battery charge and can reduce congestion by reducing inter-cluster traffic. However, it does not appear to take into account traffic and congestion at the level of each individual cluster, and larger clusters with more nodes may find it difficult to handle data traffic to the cluster head node.

IV. State of the Art

Current WSN architectures for air pollution monitoring systems have static or mobile energy-efficient sensors that are connected to a backend infrastructure. These nodes upload their collected sensor information and operate only when needed in order to save energy. Generally, there are three configurations for when a WSN node should upload: time-driven, event-driven, and query-driven. Time-driven uploads occur over a set interval. Whereas, event-driven uploads happen in response as an alert to a particular event, and query-driven is when the sink requests for the data. Although a given node can only record pollution information for its own respective zone, together these nodes can collaborate to generate a map that covers a wide scale area. Applications then retrieve a summary of the processed data from the backend servers for the users.

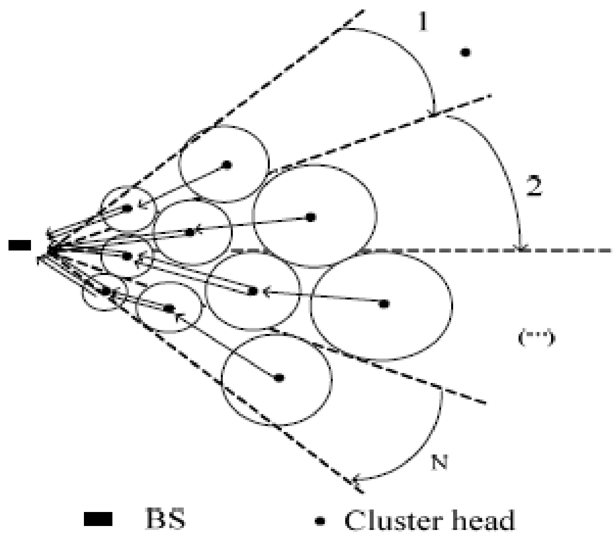

Figure 5. Overview of PEZCA

Within a WSN unit, which can be mounted on a sensing station as shown in Figure 6 [11], the core components include a power source, a radio receiver, and a sensor board. In most cases, there are usually two batteries attached to the sensor unit.

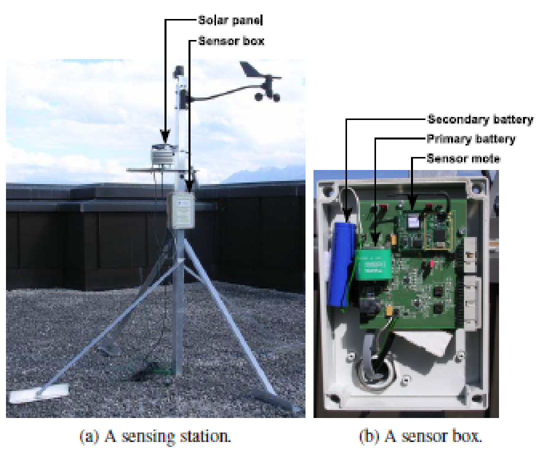

Figure 6. Sensing station

A. Problems Unsolved

The most common issues that arise with any WSN system (not just specific to the application of air pollution) and remain unsolved include communication bandwidth and scalability.

1) Communication Bandwidth: Communication bandwidth becomes an issue if the system prefers quality data where a high frequency of sensor information updates need to be perpetually sent between WSN nodes and the servers or if a sink node has too many incoming connections. As a result, a buildup of data packets at network bottlenecks will slow down system operations and provide delayed analysis for the end users. This challenge was deal with by the use of various routing algorithms [9] that have built in congestion control mechanisms that alleviate hot spot traffic by rerouting traffic to less impacted data paths.

2) Scalability: As WSNs can grow large in size, the challenge of scalability arises. Some solutions that are offered include clustering algorithms such that geographically close nodes form a cluster and routing algorithms that focus on load balancing the system. In order to efficiently communicate data to the sink, cluster heads are identified within the network structure to propagate sensor information collected by the nodes that they are responsible for. If a cluster head goes down, the system can even elect a new replacement cluster head to represent the group of nodes. There is currently a large list of clustering algorithms [12], which differ on how clusters are formed, how cluster heads are selected, and how nodes propagate data within clusters. Depending on the application needs, one algorithm may be selected over another.

B. Challenges

Many challenges still remain problematic for the state of the art architecture for WSNs, in which the main issues are power, robustness, and storage space. Although the state of the art architecture tries to approach these problems through alternative means, these challenges remain fundamental in WSN systems and solid solutions for the underlying problems are still sought after.

1) Power: Energy is the fundamental constraint in any WSN system. A node uses energy every time it collects data and transmits it, so unless the WSN unit is connected to a reliable battery source, the device should only be powered on when it needs to. In order to provide quality sensor data, the state of the art WSN nodes must transmit frequently or perform a tradeoff with power. If a static node runs out of power, the battery must be physically replaced in order for the unit to remain operational. As for mobile nodes, the battery should not interfere with other operations of the integrated device. Attempts have been made to solve the efficient-energy coverage (EEC) problem by designing better routing, clustering, and scheduling [13] algorithms.

2) Robustness: Because WSN nodes can fail without reason, the system needs to properly accommodate for these occurrences. If a node that is responsible for relaying data from a group of other nodes fails, these other nodes need to propagate their data through other network paths. The node would then need to be physically replaced by a functional unit in order to continue recording information for that area.

3) Storage Space: Because current state of the art nodes are resource-limited devices, storing large amounts of data becomes an issue. Due to power constraints, uploading sensor information frequently is inadvisable, so a unit must be able to maximize its storage per push to sink nodes. An alternative approach to handle the storage space issue is to distribute the data to local nodes through a cooperative storage mechanism [14].

V. Future Direction

As far as research goes on WSNs for pollution applications, improvements in deployment medium, network protocols, data processing, and hardware technologies contribute to developing a better system for monitoring the air quality in our environment.

A. Deployment Mediums

Moving away from the traditional deployment of static nodes, mobilizing the nodes becomes a step forward for the research community. In specific, the idea of integrating sensors on bikes [15], on buses [16], in cars [17], [18], and with phones [19] is becoming a greater interest as it tackles the problem of monitoring air pollution in another light. By personalizing the technology, people [20] are able to become more aware of their health as a result of knowing the air quality around them. However, this focus does not take away the important operations current pollution monitoring systems perform. Valuable sensor information will continue to be sent to backend servers for data analysis.

B. Network Protocols

For WSNs to be efficient, new network protocols must be tailor made to fit the specific needs and limitations of a system. The location of nodes and their estimated time spent online influence how and where data packets should be processed, which becomes a study into routing algorithms. In specific, researchers have begun looking into new clustering [21] and scheduling algorithms for how groups of related nodes should be identified and how often nodes should propagate their data to the next node.

C. Data Processing

In order to manage the large amount of incoming data to sink servers, the system must be able to efficiently process all this sensor information. Because storage space within WSN units is an issue, the unit should identify critical sensor inputs and filter out data impurities [22]. Future research work should focus on techniques for identifying outliers versus actual change in air quality in order to improve the accuracy in data processing. On a similar note, the unit should only activate to capture as often as the application sees fit. Therefore, improvements in scheduling algorithms will help manage how much outgoing data will be processed.

D. Hardware Technologies

The most recent major improvement in hardware technology for our study was the use of MEMS (micro electromagnetic systems). Due to their robustness and small size, they can produce a two-fold advantage over existing gas sensors: more accurate air pollutant measurements and a much smaller size. Due to this, it makes further miniaturization of these pollution sensors possible. This is particularly helpful for personal, mobile, and non-obstructive sensors that can even be toted with end users without creating any impediment. Overall, MEMS-based gas sensors can revolutionize pollution monitoring wireless sensor networks.

E. Public Policy

As pollution monitoring becomes increasingly more effectives, thorough, and convincing, it will become more difficult to ignore the harmful effects of air pollution, not only at the social level, but at the policymaking level as well. If public policymakers are presented with irrefutable and large-scale evidence of the correlation between air pollution and respiratory disease, then it will become more likely for them to support policies that would lead to technologies, systems, and practices that could improve air quality and reduces its harm on people at risk of or suffering from respiratory disease. In this manner, there will be a much stronger push for greener approaches in regards to air and environmental quality.

VI. WSN in Computer Science

The application of wireless sensor networks in computer science is not limited to air pollution, which is the specific focus in our paper; its usefulness expands to early warning detection in military defense, monitoring and resolving traffic congestion, identification of occupied parking spots, and much more. In every case, data must be efficiently routed back to the end user. As a result, efficient network routing becomes an important focus in research, especially since pollution monitoring WSNs, for example, may exist over a city-sized grid with thousands of nodes. In specific, the research of ad hoc networks in computer science pertains to this survey as the network architecture must properly reconfigure as nodes are added and removed from the system. Therefore, the deployment of WSNs must ensure node connectivity in order to handle robustness and scalability. In the field of computer science, WSNs share similar issues that cloud computing has to overcome. Aside from network routing, the study of better clustering algorithms in networks helps improve WSN performance. Also, the servers handling these clusters of nodes must be able to process a large amount of data and extract quality data from it, so techniques for data management and data fusion are necessary in reducing network overhead.

VII. Our Perspective

We believe that research on WSNs should be focused more at an individual level in the light of consumer-friendly devices enabling non-intrusive portability and providing quality updates to local nodes. Before, industry and research made improvements in this field to provide a general overview for the air pollution within a large area, in which users must query a specific area to find out its respective pollution information. This approach is good in the respect that these systems provide an encapsulating knowledge of pollution for large areas. However, we feel that the general user would be more interested in the quality information of the immediately surrounding area. That said, the users should be able to fine-tune pollution detection settings in order to have more updated and accurate data rather than to receive an averaged representative value for an area of interest. After all, by the end of the day, it is the end users that should be well informed of the pollution levels surrounding them.

VIII. Conclusions

In the modern era, pollution is becoming extremely harmful to human health. Despite its importance, we lacked a reasonably effective technology to monitor air quality until the introduction of pollution monitoring wireless sensor networks. Our survey discussed prominent works in this emerging technology. We place particular detail on the work describing the Mobile Discovery Net, which employs mobile and static nodes in a sensor network to collect air quality data and process it. We also covered other works on pollution monitoring in order to exhibit other schemes and strategies that exist in this area, such as deployment via mobile phones. In addition, we discussed the state-of-the-art in this field, with its various innovations and existing challenges. We also wrote on the future direction for this exciting technology in terms of usage and future innovation. Overall, the future is bright for this technology and hopefully it will continue to broaden our understanding of air pollution and reduce the effects of poor air quality on human health.

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