Wireless Sensor Network for Real-Time Air Pollution Monitoring

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***Abstract*—This paper presents an ambient real-time air quality monitoring system. The system consists of several distributed monitoring stations that communicate wirelessly with a backend server using machine-to-machine communication. Each station is equipped with gaseous and meteorological sensors as well as data logging and wireless communication capabilities. The backend server collects real time data from the stations and converts it into information delivered to users through web portals and mobile applications. The system is implemented in pilot phase and four solar-powered stations are deployed over an area of $1\ \mathrm{km}^2$. Data over four months has been collected and performance analysis and assessment are performed. As the historical data bank becomes richer, more sophisticated operations can be performed.**

***Index Terms*—Air quality monitoring, Machine-to-Machine communication, wireless sensor networks, data analysis.**

I. Introduction

The purpose of air quality monitoring is not merely to collect data but to provide the information required by scientists, policy-makers and planners to enable them to make informed decisions on managing and improving the environment, in addition to presenting useful information for public end-users. Monitoring fulfils a central role in this process, providing the necessary sound scientific basis for developing policies and strategies, setting objectives, assessing compliance with targets and planning enforcement action [1].

In fact, the effect of air pollution on human health is considered a major and serious problem globally, especially in countries where oil and gas industries are prevalent. Huge efforts are being done in order to improve air quality in both indoor and outdoor environments. According to the United States Environmental Protection Agency (US EPA) [2], the air quality is characterized by measuring specific gases that affect the health the most, out of which are: ground-level ozone (O_3), carbon monoxide (CO), and hydrogen sulfide (H_2S) [1]. Often, the temporal environmental data is reported within a time frame defined by the standard. For example, CO is reported either by 1-hour average or by 8-hour average; whereas O_3 and H_2S are reported by 8-hour average [2], [3].

The data received from the air quality monitoring system is in a format determined by the sensing modules used. This information should be extracted from the varying sensing modules and stored in a database using a common format in order to automate its extraction and analysis [4]. The measured data might contain missing, noisy, or erroneous values. Appropriate data integrity checks should be performed before storing the data for subsequent use. Afterwards, additional processing might be needed before presenting the data over a graphical user interface (GUI). For example, we might need to display summary graphs for daily, monthly, or yearly averages of a certain pollutant, whereas the data might be coming from the sensors on a second-by-second or minute-by-minute basis [1].

Traditionally, bulky air quality monitoring stations are used for collecting various gases concentrations. These stations include many reference analyzers where each analyzer measures one gas. Although these analyzers produce measurements with high level of accuracy, such stations require frequent calibration and maintenance and they need access to power socket mainly for air conditioning. This inevitably limits their use on large scale. Nowadays, and because of the recent advances in micro-electro-mechanical (MEMS) systems, research and industrial bodies are focusing on developing new generation of sensing stations with low cost, smaller size, and more mobility features [5]. Variations of such stations are being used in different indoor and outdoor environments for both residential and industrial applications. These senor stations are generally deployed as a wireless sensor network (WSN).

WSNs are attracting increasing research attention, due to their wide spectrum of applications, including military purposes for monitoring, tracking and surveillance of borders, intelligent transportation systems for monitoring traffic density and road conditions, and environmental applications to monitor, for example, atmospheric pollution, water quality, agriculture, etc. [6].

A WSN is composed of a number of sensing stations transmitting wirelessly the information they capture. A sensing station is generally composed of a power unit, processing unit, sensing unit, and communication unit. Power consumption is the main limiting factor of a sensing station. In fact, sensing stations are in general required to operate autonomously and independently for a large period of time in areas where power infrastructure may not be available. Thus, battery-powered sensing stations should be able to operate with very low power consumption. Some sensing stations have batteries rechargeable by solar power, thus ensuring longer autonomous operation. The processing unit is responsible to collect and process signals captured from sensors before transmitting them to the network. The sensing unit is a device that produces a measurable response to a change in a physical condition like temperature or pressure. The wireless communication unit is responsible for transferring the sensor measurements to the exterior world, e.g., to be stored on a server, where they can be distributed on the internet or accessed by specialized personnel. The wireless communication unit can also ensure a mechanism for ad-hoc communication between sensing stations forming a WSN [6]. In fact, in some scenarios, it might be more energy efficient to transmit a message via multihop communications over short distances instead of a single hop long distance transmission to the base station (BS).

In [7], a smart sensor network for air quality monitoring applications has been discussed. The authors have shown that using multi-input, single-output artificial neural networks (ANNs) can solve inherent problems of the used sensors, namely the dependency on both ambient temperature and relative humidity. Models for air pollution concentrations as a function of the emission distribution have been investigated in [8]. In [9], an auto-calibration method for a dynamic gas sensor network for air pollution monitoring is proposed. The simulation results show that using this method a high accuracy can be achieved. More related work can be found in [10], [11], [12], [13], and [14].

In this paper, a real-time air quality monitoring system is presented. This system is based on utilizing multi-gas (MG) monitoring stations that communicate with a platform by the means of M2M communication. Each MG monitoring station includes gaseous sensing elements, data logging component, and wireless communication board and it is powered by the solar energy. The platform is located on a backend server where data cleaning and filtering operations are carried out. In addition, this platform converts the received data to useful information that are delivered to users through web portal and mobile applications. To the best of the authors' knowledge, the novelty in this work is in describing a deployed and functional comprehensive end-to-end system. In addition, the system uses a high density of sensing stations per unit area in order to provide localized pollution information, as opposed to bulky analyzers, which are deployed in limited numbers. Furthermore, the presented system ensures real-time air quality monitoring using an M2M communication paradigm, and it can be accessed in real-time by authorized users via web and mobile applications.

This paper is organized as follows: in Section II, a description of the system is given. The measured data is presented and assessed in Section III. Conclusions are drawn in Section IV.

II. System Description

The system architecture for real-time air quality monitoring is shown in Fig. 1. The system corresponds to an actual deployment of four MG monitoring stations in Education City, Doha, State of Qatar. The MG monitoring stations have been deployed and started operation in March 2012. The current deployment is a pilot test and more stations are planned to be deployed in the future. At the time of writing this paper, the sensors have been operating accurately for four months in harsh weather conditions, with temperatures reaching 50°C and sand storms occurring regularly.

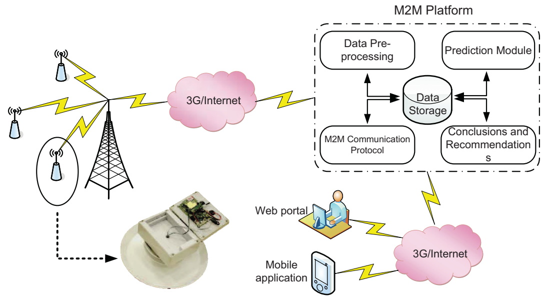

Fig. 1. Air Quality Monitoring System Architecture.

The end-to-end system consists of two main subsystems: 1) the MG monitoring stations, and 2) the platform at the back-end server. The MG monitoring stations communicate with the backend server via M2M communication. More detailed description of these subsystems is given in the following subsections.

A. Multi–Gas Monitoring Stations

An MG monitoring station consists of several gaseous and meteorological sensing elements, the data logging and wireless communication board, and the power supply system. the current system has four stations: Qatar 1, Qatar 2, Qatar 3, and Qatar 4. The first two stations are equipped with O_3, NO_2 and CO sensors, and the last two stations are only equipped with H_2S sensors. Each of the four MG monitoring station carries also two sensing elements for the ambient temperature and relative humidity.

The gaseous sensing elements are based on nanotechnology semiconductor concept where the gas concentration is evaluated by measuring the electrical conductivity of a thin metal-oxide layer. When a toxic gas touches this layer, it is absorbed and, consequently, its electrical conductivity changes. The gas concentration is a function of electrical conductivity variation. The measurement ranges and accuracy of the sensing elements are shown in Table I.

All the sensing elements are connected to the analog inputs of the data logging and communication board. The data logging and wireless communication board is based on Atmega 2560 microprocessor and houses an external MicroSD memory with 2 GB capacity. The main functions of this board are data acquiring, processing, logging, and transmitting. The board is equipped with a GPRS modem for wireless connectivity. The MG monitoring stations are configured to take a sample of all parameters every $1\,\mathrm{min}$ and then calculate and save the average of five readings. The station establishes a TCP/IP Internet connection through the GPRS modem with the M2M platform located at the backend server.

TABLE I
Sensor Ranges and Measurement Accuracies

Monitored Parameter	Range	Accuracy
Ozone O_3	0-200 ppb	$< 5\%$
Carbon Monoxide CO	0-100 ppm	$< 5\%$
Nitrogen Dioxide NO_2	0-200 ppb	$< 10\%$
Hydrogen Sulphide H_2S	0-10 ppm	± 0.5 ppm

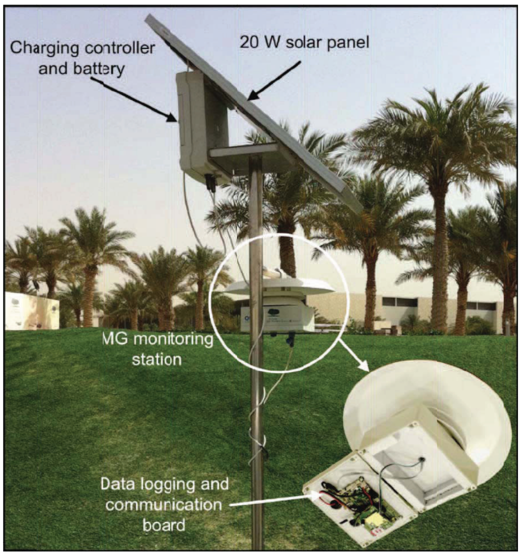

Fig. 2. MG monitoring station.

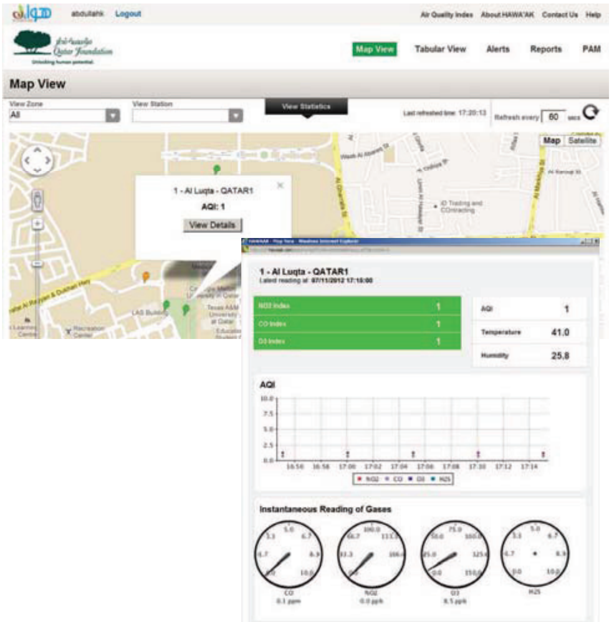

Fig. 3. Map View.

The monitoring stations are powered by solar energy. Consequently, this allows more flexibility in their deployment in areas where power from the main electricity grid might not be available. A picture of one of the deployed monitoring stations is shown in Fig. 2.

B. M2M Platform

The M2M platform is operating on a backend server. The main modules of this platform are: an M2M communication module, data integrity module, data processing module, data storage, and prediction module. The M2M communication protocol operates over GPRS or 3G network and is responsible for connecting to all MG monitoring stations for data transfer. The stations are configured to initiate a TCP/IP connection with the platform. The communication stays for 1 min during which the station sends the data. Once received, the data is sent to the data integrity module which is responsible for handling missing, erroneous, and noisy data. The output of this module will be stored in the database. The data processing module applies statistical operations on the data before presenting it to the user interface. The prediction module is used to perform prediction or estimation of pollution levels in the near future (e.g., average in the next 24 hours). This module is not fully operational yet since it requires a large amount of historical data in order to lead to accurate results, e.g., see [15].

C. Client-Side Applications

Dissemination of the measured information is performed via client-side applications running on computers or mobile devices, e.g. smart phones. These applications access the network via the server, which forwards the stored data received from the sensors. The applications could include a periodically updated web site with data summaries and statistics, data visualization with display of sensor locations on a map (along with the measurements at each station location), and data dissemination applications like SMS alerts relating to pollution levels in certain areas.

In the case of the deployed end-to-end system, named HAWA'AK (which means "your air" in Arabic), a web application is available on the link: http://qf.hawaak.com. The information is not currently public during the pilot phase, and only authorized users can access the website. The website allows displaying the positions of the MG monitoring stations on a map. Clicking a particular station enables a pop-up window that shows the most recent measurements at that location. An example is shown in Fig. 3. In addition to this map view, the website provides a tabular view where the measurements of all stations are listed. In addition, a report view provides detailed reports and statistics about the pollution levels of the different gases. When pollution reaches certain levels, alerts can be issued and sent via SMS to designated users, in addition to being displayed on the website. A mobile application providing similar functionality was also developed. In the next section, we present and analyze some historical data collected from March to June 2012 (four months).

III. Analysis of Measurement Results

In this section, we present and analyze historical data collected from March 1 to June 30, 2012. Measurements from MG monitoring stations Qatar 1 and Qatar 2 are presented. Fig. 4 shows the CO measurements of Qatar 2 whereas Fig. 5 shows the O_3 measurements of Qatar 1. The plots in Figs. 4 and 5 are generated using the "OpenAir" package of the open source *R* software system [16].

The figures plot the average measurements, with the shaded areas representing the range of the measurements obtained,

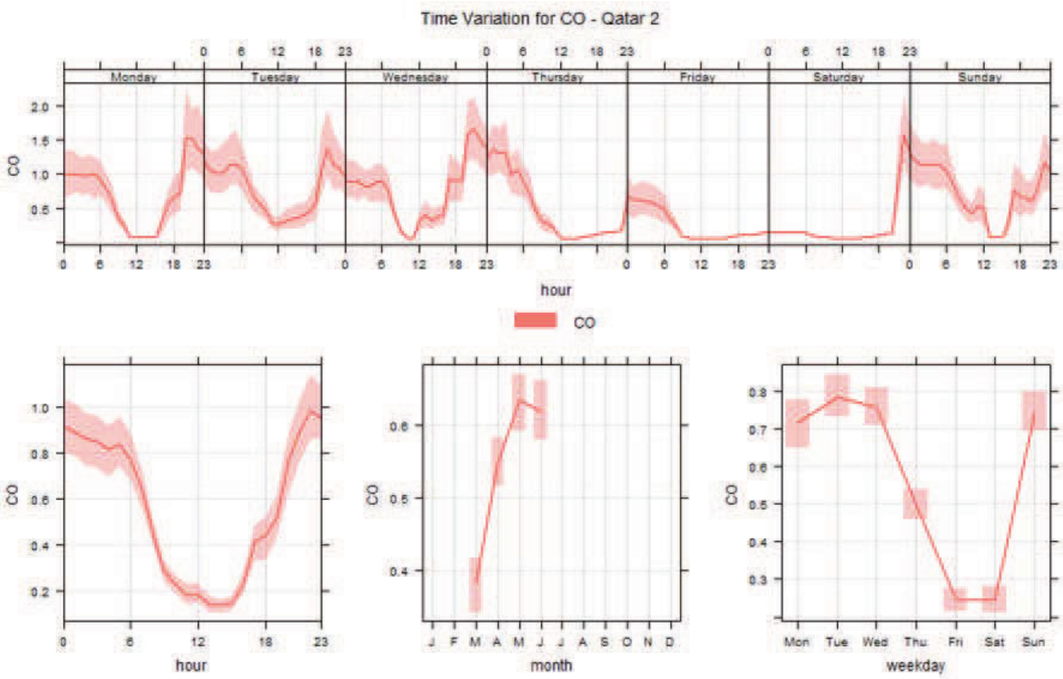

Fig. 4. Carbon monoxide (CO) measurements.

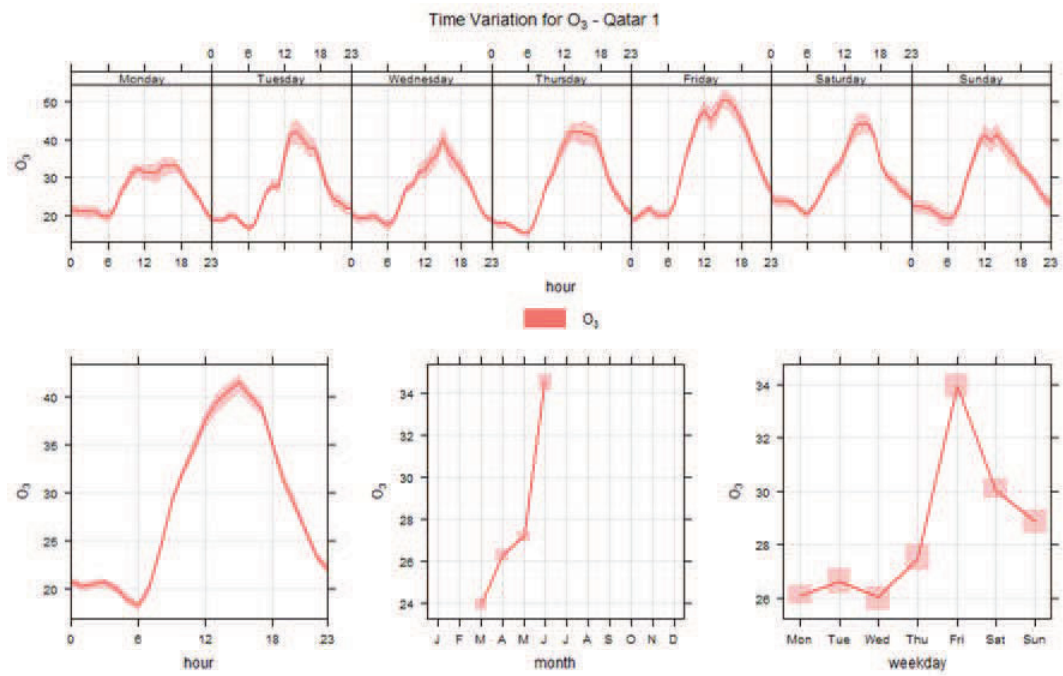

Fig. 5. Ground level ozone (O_3) measurements.

from the minimum measured concentration to the maximum measured concentration. For example, the bottom right subfigure of Fig. 4 indicates that during the measurements performed on Mondays during the specified four months, the concentration of CO varies between 0.65 and 0.78 ppm, with an average of 0.72 ppm.

Fig. 4 shows interesting patterns in CO concentration. The upper subfigure shows regular patterns for all week days except Friday and Saturday, where the concentration drops significantly. These results are also confirmed by the lower right subfigure. In fact, Friday and Saturday are the two weekend days in Qatar, and consequently there is no much traffic in Eduction City during those days. Since the main source of CO is the exhaust gases of vehicles, it is expected that the CO concentration would be significantly reduced during weekends in the Education City campus.

The bottom left subfigure of Fig. 4 shows the CO concentration versus the 24 hours of a day. As expected, these concentrations are reduced during working hours, where the number of moving vehicles is limited. In the morning and afternoon hours, the concentration increases due to the increase in the number of vehicles on the road.

Fig. 5 also shows interesting patterns for ground level Ozone concentration. It should be noted that ground level Ozone is not to be confused with the Ozone located at the upper regions of the atmosphere. Although both types have the same chemical composition (O_3), the upper atmospheric Ozone protects the earth from the sun's harmful rays, whereas ground level ozone is a pollutant [17].

Ozone concentration is known to increase in hot sunny days [17]. This is clearly reflected by the statistics of Fig. 5. In fact, the bottom left subfigure shows an increase in the concentration of O_3 during the most sunny hours of the day, and a reduced concentration in the hours of darkness. In addition, the bottom middle subfigure shows a sharp increase in the O_3 concentration as we move towards the hot, sunny summer months of Qatar. Clearly, the concentration rises quickly and steadily from March to June.

It should be noted that the upper subfigure of Fig. 5 shows a more regular behavior of O_3 during all weekdays, compared to CO in Fig. 4. In fact, since O_3 is not as dependent as CO on the exhaust gases of moving vehicles, its concentration trend during weekend days has the same shape as the normal week days, as seen in the upper subfigure of Fig. 5.

IV. Conclusions

In this paper, an end-to-end system for ambient real-time air quality monitoring and prediction is presented. The system has two main components, the multigas monitoring stations and the M2M platform. Four solar powered multigas monitoring stations have been deployed and the data of four months have been collected, cleaned, and analyzed. The monitoring stations communicate in an M2M fashion with a backend server using GPRS communications. Web and mobile applications have been developed to allow authorized personnel to access the data.

Additional techniques under current investigation include the use of prediction algorithms based on neural networks in order to estimate pollution information in the near future. In addition to this prediction in time, prediction in space is also an interesting research topic: given the pollution levels at the locations of the monitoring stations, it would be interesting and challenging to estimate the pollution levels over the whole area of interest. Another challenging research topic includes multihop communications among the monitoring stations. In fact, when the number of deployed stations increases as planned, separate GPRS communications with the server and each station individually are expected to lead to congestion when a single cellular base station is serving a large number of MG monitoring stations. Thus, cooperative, distributed, and energy-efficient communication protocols between the monitoring stations need to be devised in order to reduce the active number of simultaneous GPRS connections with the base station.

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