Energy Harvesting-enabled 5G Advanced Air Pollution Monitoring Device

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***Abstract*—We have designed a 5G-capable environmental sensing network (ESN) node prototype, called Advanced Air Pollution Monitoring Device (AAPMD). The developed prototype system measures concentrations of NO_2, Ozone, carbon monoxide, and sulphur dioxide using semiconductor sensors. Further, the system gathers other environmental parameters like temperature, humidity, PM_1, $PM_{2.5}$, and PM_{10}. The prototype is equipped with a GPS sub-system for accurate geo-tagging. The board communicates through Wi-Fi and NB-IoT. AAPMD is also implemented with energy harvesting power management, and is powered through solar energy and battery backup. Compared to the conventional designs with Wi-Fi-based connectivity, the developed system consumes 10-times less energy while using 5G NB-IoT communication module, which makes it a very competitive candidate for massive deployment in highly polluted metro cities like Delhi and Kolkata, in India. The system can update pollutant levels on controllable time granularity.**

***Index Terms*—Air pollution monitoring device, energy harvesting, 5G, NB-IoT, energy efficiency**

I. Introduction

Air pollution occurs when toxic chemicals, pollutants or contaminants interface with the air that we breathe. Some of the major causes of air pollution in large cities are human-initiated activities such as factories, vehicle tail-pipe emissions, power plants, and chemical effluents. Gasses like sulphur dioxide (SO_2), carbon monoxide (CO), oxides of nitrogen (NO, NO_2), ozone (O_3) and dust particulates (PM_1, $PM_{2.5}$, PM_{10}) are hazardous to the population, and have a perilous long-term impact on the environment. As per the report of the World Health Organisation, every year 2.4 million people die from causes directly related to air pollution [1].

Gas chromatography is used at conventional air quality monitoring stations, and has limitations with respect to cost, time-consuming deployment, and extensive requirements at the installation sites. Opsis , Codel, Urac, and TAS-Air [1] are some available pollutant monitoring systems, which are typically expensive and have installation limitations. Large-scale, fine-granular, and near-real-time pollution sensing and pollution localization are some important requirements for urban and industrial deployments. However, such objectives cannot be fulfilled with the conventional pollution stations due to cost and feasibility. Thus, there is a need for a cost-efficient and energy-sustainable pollution sensing network for near real-time sensing. Given the large-scale demand and environmental diversity in India, indigenous pollution monitoring solutions are required to be developed with energy harvesting capability, which are able to operate unattended at deployment locations.

Towards low-cost and energy-efficient large-scale sensing, in this work we have designed a 5G-capable environmental sensing network (ESN) node for air pollution monitoring. The ESN node is equipped with temperature, humidity, gas sensors, and particulate monitoring. The designed prototype is an indigenous 5G platform, completely powered by a solar energy harvester.

A. State of the Art

Besides the conventional big pollution monitoring stations, such as the ones maintained and operated by Central and State Pollution Control Boards in India, numerous air pollution monitoring systems have been developed by researchers in recent years.

1) On Development of Sensing Prototypes: [1] introduced an industrial air pollution monitoring system which is integrated with GSM (Global System for Mobile communication) and used ZigBee as its communication protocol. This system can be deployed to the industries to monitor CO, SO_2, and dust concentration. Their proposed Wireless Sensor Network (WSN) air pollution monitoring system implemented a data aggregation algorithm named Recursive Converging Quartiles. For better power management they used a hierarchical routing protocol which causes the nodes to sleep during idle time.

[2] developed a mobile air quality monitoring network that uses sensor nodes equipped moving vehicles to monitor air quality in a large area. The nodes consist of GPS (global positioning system), a microcontroller, and a set of sensors which detect the concentration of O_3, CO, and NO_2. For sending the data they proposed to use Bluetooth connectivity.

[3] introduced a sensor network called Indoor Air Quality monitoring system. The system is equipped with a power management approach for reducing sensors energy consumption.

Implementation of a small and portable air pollution measurement system, called ArduAir, was demonstrated in [4]. ArduAir integrates low-cost sensors and microcontroller which could be used by a number of people. [5] presented an Internet of Things (IoT) device which is equipped with Arduino IDE, gas sensors and a Wi-Fi module. Arduino IDE captures the gas sensor data and forwards the same to the cloud using Wi-Fi. An android application named IoT-Mobair was developed for availing the data from cloud to the users.

[6] proposed a vehicular mobile approach to measure fine-grained air quality in real-time. Using Libelium Waspmote

and Wi-Fi/GPRS they collected data from different sensors and showed the Air Quality Index.

The system introduced by Al-Ali et al. [7] consists of GPRS sensors array, Mobile data acquisition unit (Mobile-DAQ) and a fixed Internet-Enabled Pollution Monitoring Server (Pollution-Server). The system gives a real-time air pollutant level along with the location. Mongoose operating systems based monitoring system to monitor the harmful pollutants' concentration continuously. The prototype was designed using cost effective low power ESP32 development board and appropriate sensors to monitor CO, CO_2, NH_3, smoke particulates ($PM_{2.5}$) and O_3. The values of pollutants (in parts per million or PPM) captured by this prototype can be sent through message brokers to the cloud server set up using Losant IoT platform, by configuring it as a Wi-Fi access point. PPM values of pollutants are then displayed on the Losant device logs through a light-weight messaging protocol, called MQTT. Losant device ID, API access tokens play a key role in providing access to the users on Losant. The proposed prototype is powered using standard power bank as part of implementation of design. Some IoT indoor measurement system perform real-time monitoring of the particulate matters such as PM_1, $PM_{2.5}$, and PM_{10}, temperature, and humidity. The system also allows Bluetooth connectivity.

The work in [8] represents a prototype of wearable air quality monitoring sensor node that collect samples of different air pollution monitoring parameters and transmit the data via Bluetooth to a smartphone. The sensor node consists of a micro-controller and some air quality monitoring sensors such as CO, NO_2, O_3, temperature, pressure, and humidity. The node is powered by a rechargeable energy unit connected to it. Data is pre-processed in the node itself using a micro-controller before transmission to reduce the communication energy. The users can check the data in their cell phones and share with their friends. A 7200 mWh Li-ion battery takes 5.23 days to discharge while the node is continuously sampling and transmitting at every 5 seconds.

A gas sensing system in [9] is based on the feedback control of air-to-fuel ratio. This automotive exhaust gas system is used in the vehicles to control the combustion of fuel by feeding the amount of gases generated by the fuel combustion. The gas constituents are CO, hydrocarbons and oxides of nitrogen (NO).This kind of feedback system helps to improve vehicle performance and decreases emission levels as well. The work in [10] represents a prototype design of air pollution monitoring sensor board which consists of 5G communication system. The sensor node consists of a micro-controller to collect data from off-the-shelf sensors and store in memory built into the board, BC66 NB-IoT chip for data transmission to the cloud. The sensing parameters are temperature, humidity, PM_1, PM_{10}, $PM_{2.5}$, NO_2, O_3, CO, SO_2, etc. The node is powered by a solar energy harvester (consists of Li-ion battery and BQ25506 solar energy harvester IC). In [11] the authors confined emission of Volatile Organic Compounds as target pollutants and proposed a method to estimate source location and emission rate estimation via AERMOD tool.

All these works did not focus on the network/systems level energy consumption and energy replenishment aspects.

2) On Energy Efficiency and Sustainability: There have been a series of systems-level studies in recent years on energy efficient sensing and data collection strategies as well as automated powering strategies for energy sustainability.

In wireless sensor networks, traditional battery operated nodes die after a short time as the battery is depleted. Therefore, we need renewable energy harvesting-based communication to resolve this problem [12]. In order to improve the energy efficiency of radio frequency (RF) energy operated wireless sensor networks, a two-tier network was contemplated in [13] for sensing data collection of the field sensors. In the first tier more energy-hungry and potentially solar-powered router nodes take part in communication, while in the second tier the miniature field sensors nodes gather RF energy from the ongoing communications in first tier nodes in their vicinity. In densely deployed sensor networks, mobile robots were proposed to be used for data collection from the sensor nodes and recharging them using RF energy transfer [14], [15]. The work also outlined mobility and path planning of a mobile robot for uninterrupted operation of the field sensor nodes for power-hungry air pollution monitoring applications. The work in [14] also proposed a basic study on the gain associated with multi-hop RF energy transfer for online recharging of the field nodes.

Sustainability of solar-powered WSN nodes was studied in [16], where air pollution monitoring was particularly considered. It was demonstrated that, with appropriate panel size and storage capacity, sustainable operation of field nodes can be achieved. WSNs are useful in various application contexts, such as in industries, smart homes, health-care, etc. To this end, a network-level data-driven green sensing framework has been recently proposed in [17]. Data driven frameworks are found to be promising in design optimization of WSNs.

While these works have introduced novel network systems-level concepts for energy efficiency and energy sustainability, implementation of energy sustainability at the network-connected node-level and exploiting the interrelationship of sensed multi-stream data were not the focus.

B. Motivation

Air quality monitoring requires a large number of sensors distributed spatially over a wide geographical region. Operating each of these sensors with a battery is problematic; frequent battery replacement is difficult. Battery operated WSNs are taking operating power from the battery which needs to re-energize very often and thus makes the prototype an unsuitable candidate for outdoor use case. Some studies considered that the device is powered through a power bank which is not feasible in remote applications. Typical communication protocols for these outdoor wide area sensor networks require a large power budget that will deplete the battery rapidly. Energizing these batteries through solar or other renewable sources is not feasible because of the large power requirements of the node, primarily due to the communication protocol. The

communication protocol used in most of these applications are either ZigBee [1], Bluetooth [2], or Wi-Fi [5]. These are power-intensive protocols, while they provide a short range.

C. Key Contributions

In our work we have designed an advanced air pollution monitoring device (AAPMD) with a solar energy harvester. The communication protocol we are using to transmit data over cloud is NB-IoT, a 5G eMTC (enhanced Massive Machine Type Communication) protocol. It provides high range communication and consumes reasonably low power as compared to conventional Wi-Fi, ZigBee and Bluetooth. The particulate matter (PM) monitoring sensor is one of the highest power consuming sensors which needs to be sampled smartly to enhance the battery life of the entire board. In order to optimally reduce the energy consumption of the air pollution monitoring board, the sampling periods of the sensors are dynamically adjusted for prevailing conditions. Based on the energy consumed by the various sensors used in the AAPMD, their sampling periods are fixed, which is further used to explore the advantages of using NB-IoT over Wi-Fi in the modern WSNs.

II. Proposed Node Architecture

A block diagram of the node prototype is presented in Fig. 1, and the designed node prototype board is shown in Fig. 2. Fig. 3 shows the multiple sensing elements (sensors)

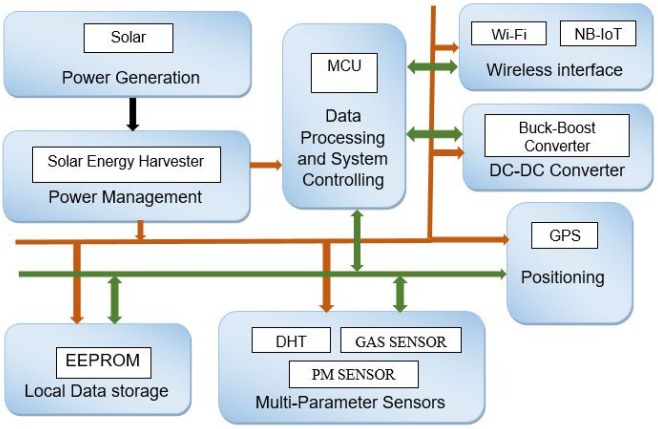

Fig. 1. Block diagram of the AAPMD

to be mounted on the board. The proposed monitoring device consists of solar energy harvester as a renewable source of energy. The communication protocol employed is NB-IoT (5G eMTC) and/or Wi-Fi. The device is capable of collecting nine air pollution parameters which include three PM sensing parameters, namely, PM_1, $PM_{2.5}$, PM_{10}, four gas concentration measuring parameters: SO_2, NO_2, O_3, CO, along with temperature and humidity. The board is also incorporated with a 512 KB EEPROM to store all the data samples in it for up to 32 hours. In 1 hour the sensors collect a total 504 samples based on a fixed sampling rate given in section-III and each

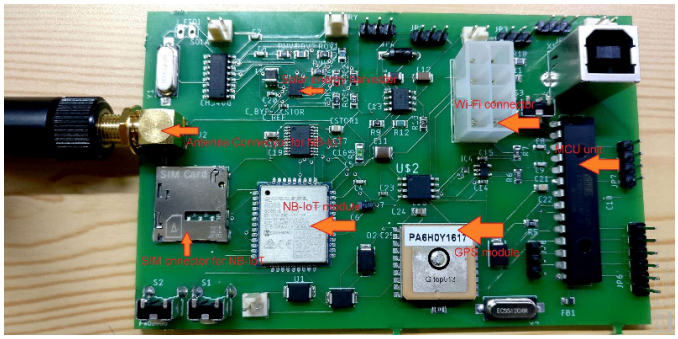

Fig. 2. 5G-enabled design prototype

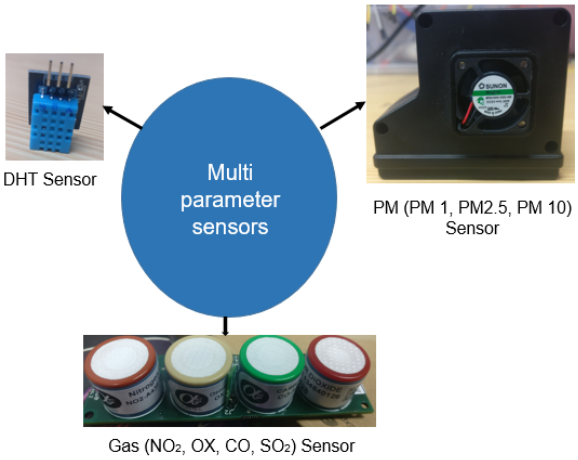

Fig. 3. Multi-parameter sensor

sample takes 4 bytes in the memory, that can be retrieved at any time. Other than this, real-time data is updated in a cloud database using the ThingSpeak cloud platform.

A. Air quality monitoring sensors

1) Alphasense OPC-N3: We have used Alphasense OPC-N3 to measure PM_1, $PM_{2.5}$ and PM_{10}. The sensor is taking 187 mA current in sensing mode and less than 50 mA during standby mode while operating from a 5 V power supply.

2) 3 Way AFE A4 4-Electrode AFE Gas sensor: This AFE enables us to measure NO_2, SO_2, O_3 and CO_2. This sensor board takes 3 mA current from a 5 V supply while sensing all the four parameters.

3) DHT11: Temperature and humidity are being sensed by using DHT11 sensor. It is taking 1 mA current during measurement while operating from a 3.3 V power supply.

B. Communication protocols

1) Wi-Fi: ESP8266Ex module is used in the proposed AAPMD, which completely works Wi-Fi networking protocol 802.11-b/g/n. The frequency range for communication is 2.4 GHz-2.5 GHz at a maximum of 20 dBm transmit power. The device can be operated at 3.0-3.6 V. It draws 65 mA current from a 3.3 V supply, while transmitting at 20 dBm [18].

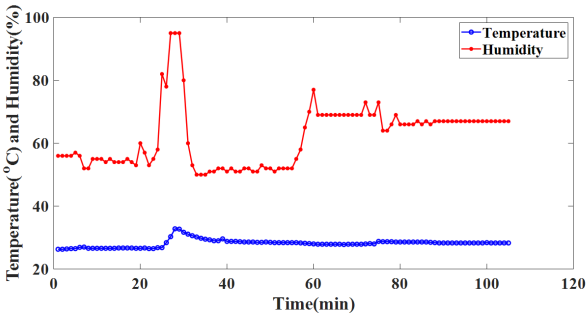

Fig. 4. Temperature and humidity graph data collected from cloud

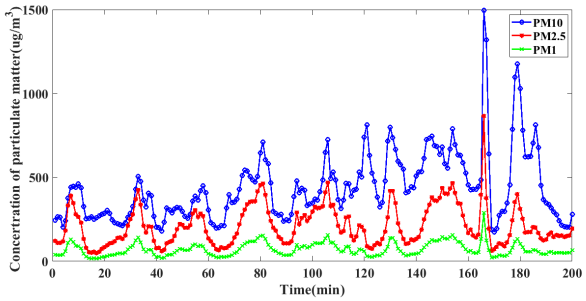

Fig. 6. PM sensor data collected from cloud

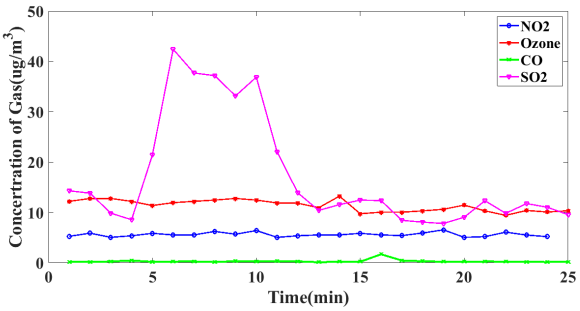

Fig. 5. Concentration of gas parameters collected from cloud

2) NB-IoT: BC66 module is used as a NB-IoT module in the AAPMD. It can work on multi-band NB-IoT and consumes extremely low power in sleep mode and idle mode. The device can operate at 2.1 V-3.63 V. During transmission it takes 110 mA current from a 3.3 V supply at 23 dBm output power. Typical data rate of BC66 is 100 kbps [19]

III. Results

In this section the experimental results of the prototype have been presented, and the sampling interval of each sensors based on their energy requirements is decided, followed by the comparison of energy requirements of the two protocols used in this study.

The sensors given in Fig. 3 are used to sample nine air pollution monitoring parameters using the AAPMD and stored in ThingSpeak cloud platform. Fig. 4 to Fig. 6 present some of the plots drawn from the data saved in cloud.

A. Experimental Analysis

Current drawn by the sensors at various operating conditions such as turn on (heat up), sensing signal, sleep mode are listed in Table 1. In Table 2, the experimental measurements of Wi-Fi and NB-IoT are listed.

Table-1: Specifications of sensors

Sensors	DHT11 (Temperature and Humidity)	AFE Alphasense A4 (4 gas sensors)	Alphasense OPC N3
Operating voltage (V)	3.3	5	5
Heat up time (sec)	2.5	1	30
Sensing time (sec)	0.5	0.2	1
Minimum sensing interval (sec)	1.5	0.5	1
Heat up current (mA)	1	5	187
Sensing current (mA)	1	3	50
sleep mode current (mA)	0.2	3	50

Table-2: Specifications of RF modules

Communication modules	Wi-Fi (ESP8266EX)	NB-IoT (BC66)
Operating voltage (V)	3.3	3.3
Turn on and connection setup time (sec)	10	0.5
Current drawn during setup period (mA)	105	0.0035
Data transmission rate (kbps)	100	11000
Transmission mode current (mA)	65	110
Sleep mode current (mA)	0.02	0.0035

B. Comparison of Energy Consumption between the sensors

Power consumption for different sensors are shown in Fig. 8. We took 900 sec time interval for this purpose and observe that the PM sensor as the highest power hungry sensor.

Energy consumed by the DHT sensor to sample two good data of temperature and humidity is 12.54mJ with a minimum

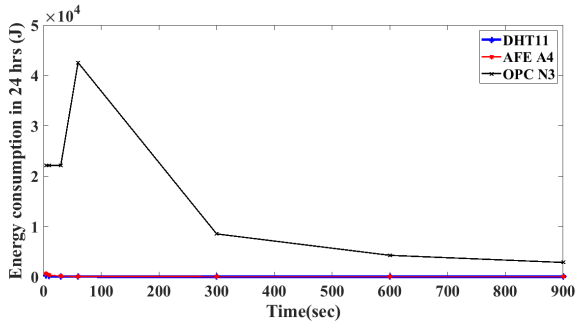

Fig. 7. Power consumption for all sensors in a fixed sampling interval

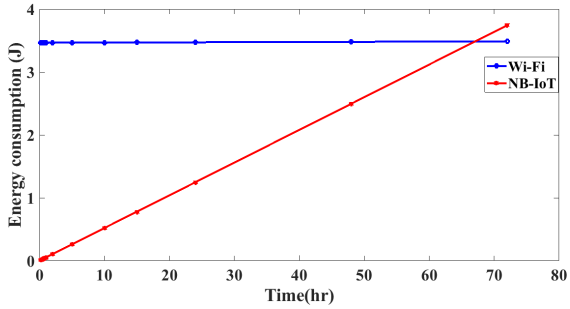

Fig. 9. Energy consumption of NB-IoT and WiFi in Case 2.

sensing interval. As, this sensor consumes very less energy, it is sampled at every 30 seconds.

Energy consumed by the gas sensor sensor to sample two good data for all the 4 parameters is 38.5 mJ with a minimum sensing interval. As, this sensor consumes more energy than DHT11 sensor, it is sampled at every 60 seconds.

Particulate matter sensor is the most energy hungry sensor among all the sensors that has been used in this case study. Energy consumed by this sensor to sample two good data for $PM1$, $PM2.5$, and $PM10$ (with a minimum sensing interval in between) is 29.55 J. As, this sensor is the most energy hungry sensor, it is sampled at every 300 seconds (5 min).

C. Comparison of Energy Consumption between two protocols: Wi-Fi and NBIoT

In between two data transmission interval the device can be either turn off or it can remain in sleep mode. Based on these two conditions the comparisons between the two protocols are shown in Fig. 8 and Fig. 9. If data reporting interval increases, data stored in the memory increases, hence more data needs to be transmitted at a time. Energy consumption in one transmission are plotted in Fig. 8 and Fig. 9, at various data reporting intervals.

- Case 1: Devices are in sleep mode between data transmission intervals (Fig. 8).

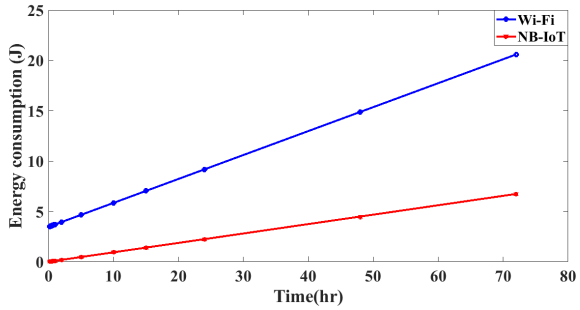

Fig. 8. Energy consumption of NB-IoT and Wi-Fi in Case 1.

- Case 2: Devices are off between data transmission intervals (Fig. 9).

As shown in table2, Wi-Fi consumes more energy in turn on, connection establishment and sleep mode compared to NB-IoT, hence in case1 NB-IoT always performs better than Wi-Fi. However, if the data reporting interval is large, the devices can be completely turn off to save energy. In case2, as the data rate of Wi-Fi is very large and transmission power is less compared to NB-IoT, it performs better than NB-IoT for large data reporting interval. On the other hand, due to low data rate NBIoT takes more time than Wi-Fi to transmit same amount data. Moreover, current drawn by NBIoT is more than Wi-Fi because of its long-range communication. Therefore, energy consumption for NBIoT increases with increases in data reporting interval at much faster than Wi-Fi in case2. In practical scenarios the data reporting interval of less than 24hrs is reasonable. Therefore, NB-IoT outperforms Wi-Fi in both the cases.

IV. Concluding Remarks

WSNs consist of small, cost-effective devices that can co-operate to gather and provide information by sensing various target parameters. ESNs are one of the use-cases of the WSNs. The developed AAPMD is an example of such an ESN node. AAPMD will aid in large-scale and fine-granular monitoring of the various critical air quality parameters, thereby facilitating attempts to improved environmental conditions for better livability. Geo-location tagged, fine-granular data from the AAPMDs is also expected to be useful in environmental law and order enforcement in developing nations with fast-paced urbanization and industrialization.

As demonstrated in this paper, by using NB-IoT based 5G communication feature in AAPMD improves energy efficiency and also increases communication range. AAPMD could be deployed with a very low energy budget which is both cost-effective and commercially sustainable. Further we are targeting to design different air quality monitoring sensors including particulate matter and focus will be on smart sensing techniques.

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