Urban Air Quality Monitoring through Large Scale Wireless Sensor Networks

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***Abstract*—We have developed a wireless sensor platform, named ENVIROMOTE, that addresses the issue of pollution monitoring at a large scale. It is based on TI's MSP430 microcontroller core with off the shelf sensors to detect gases like CO_2, CO, NO_2, SO_2 and humidity in the ambient air. It takes advantage of deep penetration of the cellular network and supports a GSM wireless link. It also provides a low cost Zigbee wireless link. With this latter link, we can scale up to a wireless ad-hoc sensor network formed with Zigbee links, with only one controller node providing the GSM connectivity to the external world. Power consumption, a major concern for remotely deployed wireless sensors is also addressed in the design. Prototype version of the platform is realized and tested.**

***Index Terms*—Pollution monitoring, MSP430, GSM, Zigbee**

I. Introduction

Air pollution has become a major challenge in India's towns and cities due to the rapid urbanization and growth of vehicular traffic. There are serious long term health effects to people inhaling this toxic air and hence there is an urgent need to attack this problem at various levels of urban planning, policies, regulations and enforcement. A critical ingredient for enabling this will be the continuous measurement and recording of pollutant concentrations at various points in a town/city. Such data will be invaluable to study the scope of the pollution problem and the efficacy of various solutions in tackling it. Currently air quality monitors do exist, but only in a few locations. We believe this is not sufficient for large cities like Bengaluru. We would like to obtain data at a much finer level of spatial and temporal resolution, ideally from every traffic intersection, once very few minutes. This calls for a low cost pollution monitoring device, with wireless connectivity, whose data is eventually available real-time on the internet to a wider audience. Such a device should be battery operated and easy to deploy and maintain.

Table I lists some of the existing air monitoring systems. Solutions from RAE systems have multi-gas sensing capability and are battery powered, but costly.This can be a limitation in their large scale deployment. Similarly the solution from Recordum requires higher power. Also the form factor and weight of the device hinders its large scale and ease of deployment.

CamMobSens [1] was developed as part of MESSAGE project, a collaboration between Cambridge University, Imperial College London, Leeds University, Newcastle University and Southampton University. This system monitors vehicle occupancy, position, movement, temperature, humidity, noise, CO and NO_2. It has a low cost, low power zigbee transceiver and a data logger on board. It collects data through a gateway to a central server.

TABLE I: Existing Air quality monitoring solutions

Model/Make	Salient Features
RAE Systems [2]	
1) QRAE Plus	1)1-4 gas detector 2)Li-ion/alkaline battery 3)20 hours continuous operation 4)$1223 per unit
2) ToxRAE	1)Single gas (H_2S) monitor 2)Li-ion battery powered 3)$185 per unit
3) MiniRAE3000	1)Handheld VOC detector 2)RF modem for real time data transmition 3)Transmission range upto 500ft 4)$3940 per unit
Recordum [3]	
1) AirPointer	1)Upto 7 ambient gas analyzers 2)Access to data over internet 3)Supply:230VAC/50Hz, 500W 4)Dimensions:740x352x831mm 5)Weight: 65.8 kgs
Cambridge Mobile Urban Sensing [4]	
1)CamMobSens	1)Handheld and fixed devices 2)Data transfered over Bluetooth/GPRS

We have developed a wireless sensor platform, called ENVIROMOTE, that detects gases like CO_2, CO, NO_2, SO_2 as well as humidity in the ambient air. It is based on TI's MSP430 micro controller core with off-the-shelf sensors. It supports a wider reach GSM network in addition to a low cost Zigbee wireless link. With this latter link, we will experiment with using a wireless ad-hoc sensor network formed with Zigbee links, with only one controller node providing GSM connectivity to the external world. This GSM link will be used to transfer the data form all the sensors in the network to an external server on the internet.

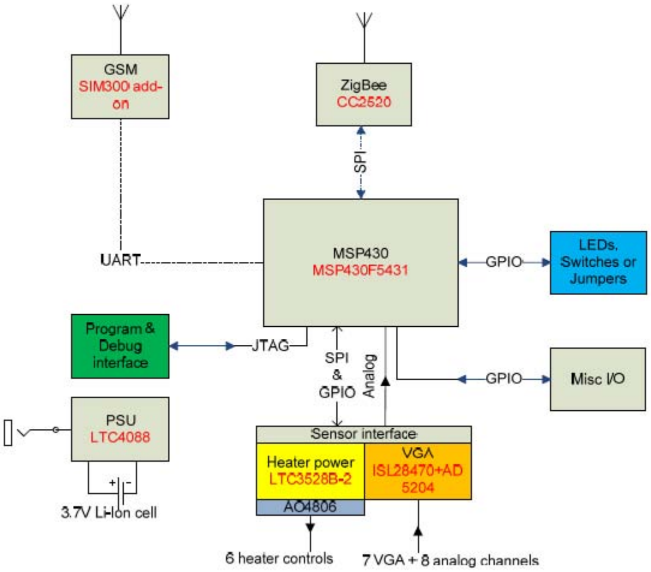

Fig. 1: Block Diagram

Power consumption is a major concern for remotely deployed wireless sensors. The key power saving technique of shutting down sub systems, is widely employed in our design. Thus the power hungry sensors and the radio are turned on briefly only when required and remain shut off for rest of the time. The first generation design includes a high density rechargeble battery. However in future revisions, we will investigate using cheaper batteries as well as energy harvesting techniques to recharge the batteries.

Our design envisions a scalable deployment with one single mobile unit at one end of the spectrum to a city wide deployment at thousands of locations.

The paper discusses the hardware and software design of the wireless platform. Section II details the implementation of the design in hardware and software. In Section III we have tried to estimate the power consumption of individual blocks and hence there effect on the total power consumption of the mote. An approximate cost estimation is also made in this section. Section IV discusses the salient features of the design. Experimental results are presented in Section V. Finally Section VI discusses the opportunities for future modifications and additions to this design.

II. Implementation

A. Hardware Description

The wireless platform is developed on MSP430 micro controller at the core with onboard provisions for GSM and Zigbee. The platform is essentially battery operated and can be recharged by a simple 5V wall charger. The platform is compatible with a broad range of sensors for humidity, temperature and various other types of gas sensors (Electrochemical, metal oxide) etc. Figure 1 shows the block diagram of the design. The basic sub-modules of the platform are detailed below:

1) Motherboard: The Motherboard, houses a microcontroller, a Zigbee module, the power management unit, sensor signal conditioning circuitry, a battery and associated charging circuitry and provision for connecting to different daughter cards.

a) Microcontroller: The MSP430-F-5435 microcontroller [5](Texas Instruments) communicates with different modules and generates the necessary signals including I/O and control signals for Zigbee radio and GSM module and the sensors, control signals for battery charger and regulated supplies.

b) ZigBee: The Zigbee radio CC2520 (Texas Instruments) [6] uses a 2.4 GHz IEEE 802.15.4 Radio. It was incorporated in the design of the mote for low power short range communication. In order to reduce the power consumption, the radio is operated at 2.7V. The processor-radio interface is through SPI and GPIO pins. The balanced RF output of the radio is matched to 50 Ohm antenna (internal chip antenna or an external whip antenna).

c) Power Management Unit: This section has a 3.7V Li-Ion cell and generates various supply voltages. It has a Li-Ion battery charger (LTC4088) [7] and two DC-DC converters to generate 5V (LTC3528B) [8] and 2.7V (LTC3405) [9]. In order to have reasonable life time for the system, an 8000mAh cell was used with a charging current of 250mA. LTC4088 provides a regulated 3.3V supply which is used to power up the processor and sensor signal conditioning circuits. If the load current requirement is more than inrush current limit (during GSM activity), then power is sourced from the battery.

d) Sensor Interface: : The sensor outputs have to be scaled before connecting to the ADC in MSP430. This is achieved by a variable gain amplifier implemented using a fixed gain stage (AD8504) [10] and a digitally controlled resistor (AD5204) [11]. Seven variable gain channels with a maximum gain of 10x are provided. Signal conditioning specific to a sensor is implemented on the sensor daughter board. The sensors need to be heated up prior to taking a measurement. The DC-DC converters are enabled to generate 5V (using LTC3528B) for CO_2 sensor and 2.7V (using LTC3405) for CO and NO_2 sensors. The heaters are switched on with MOSFET switches (AO4806) [12].

2) GSM Module: SIM300 GSM module [13] is used for establishing GSM connectivity and for communication of the data. Module is interfaced with MSP430 over UART. The power management for GSM is done by GPIO connected to PWRKEY pin of SIM300. To switch on the GSM module, the PWRKEY pin is pulled down for a period larger than 1500ms and then pulled back high. To turn OFF the GSM, PWRKEY pin is pulled down for less than 1000ms and then pulled HIGH for 2 to 5 sec.The GSM daughter card houses the SIM-300 GSM module and a SIM card holder.

3) Sensor Daughter Board: Sensor daughter board houses the sensors mentioned in Table II. The board gets 5V and 2.7V from the motherboard. Signal conditioning specific to the sensor is implemented in this section. The CO_2 sensor has high output impedance and needs to be buffered. The buffer is implemented by AD8504. The potentio-static circuit [14] needed for the electro-chemical sensor (SO_2 sensor) are also

TABLE II: Selected Sensor Details

Measurand	Sensor Make	Range	Power Specification
CO_2	TGS-4161, Figaro	300-10^4ppm	5V/50mA
CO	MiCS-4514, e2v	1-10^3ppm	2.4V/32mA
NO_2	MiCS-4514, e2v	upto 5ppm	2.4V/32mA
SO_2	EC4-20-SO2,e2v	0-20ppm	Electrochemical sensor, no heating power required
$Humidity$	HoneyWell	0-100% RH	5V/200μA

Fig. 2: ENVIROMOTE

implemented on this board. The circuit is based on AD8504 op-amp. Humidity, CO and NO_2 sensors give a voltage output which is directly fed to the motherboard.

a) Sensor Selection: Off the shelf sensors from different manufacturers [15]–[17]are used to provide the required gas sensing capabilities. The selected list of sensors is tabulated in Table II.

4) Packaging: The developed PCB and packaged system is shown in Fig 2. In this design the battery decided the size of the enclosure. The motherboard and GSM module are stacked vertically. Because of larger available space, the sensor module is kept separate from the motherboard. The enclosure is cut open to expose the sensors. The enclosure is to be mounted with sensors facing down (opposite to that shown in Fig 3) so that moisture and dust will not directly fall into the enclosure. To provide additional protection, a moisture repellent conformal coating is applied on the PCBs.

B. Software Description

Microcontroller code schedules the turn ON and turn OFF of various modules in the design through an Interrupt Service Routine. Figure 4 shows the flowchart implemented by the software code. The technique used to minimize power consumption is to use different components only when needed. Hence the GSM module, sensors and the ADC core are

Fig. 3: Inner Assembly

powered up only when a measurement is needed. After power ON for the first time, basic checks for the GSM connectivity are done after which the GSM module is powered OFF. As metal oxide sensors need a heating time, the sensors are turned ON for a minimal period (2min).

The periodicity of powering up the sensors and the GSM module are user programmable and are a compromise between the battery life, frequency of data samples and the RAM memory space in the processor. CCR0 interrupt of TIMER-B manages and updates a software real time clock. Similarly CCR0 interrupt of TIMER-A initiates the sensors every 15min. Dedicated GPIOs in MSP430 control AO4806 transistor switches which in turn control the power supply to the sensor heaters. DCR chip AD5204 is programmed over SPI link and its output goes to a fixed gain amplifier (implemented using AD8504 opamp) which is set to a gain of 10. GSM module interfaces with the MSP430 over Rx-Tx UART link. Functional operation of the GSM module is managed by a set of AT commands (as specified for the SIM300 GSM module) that are sent over UART from the controller. The GSM module is turned OFF most of the time and turned ON only when data transmission is required. The present revision of the software manages the sensors power supply, signal conditioning through programmable DCR and fixed gain amplifier, data sampling using ADC and finally data transmission over TCP/IP link to a fixed IP or over SMS to a fixed mobile number.

III. Power and Cost Estimate

A. Power estimation

As the wireless mote is a battery powered device and is intended to be deployed in different locations, the estimation of total power consumption is an important task. The break-up of power requirement of different submodules is tabulated in Table III. It is observed that the sensors are the most power hungary components followed by the GSM module and they together amount to more than 50% of total power consumption. Hence a strategy to intermittently power up these components is very important. Assuming the mentioned power figures,the total energy consumed for making a measurement is around 28J. Assuming a 10% loss in DC-DC converter, 31J is needed for one measurement. If measurements are taken every 15 minutes, the sensors consume 124J in an hour. So every day, the sensor consumption alone is 2.976kJ. SIM300 consumes 333J a day assuming 3min operation every day. The

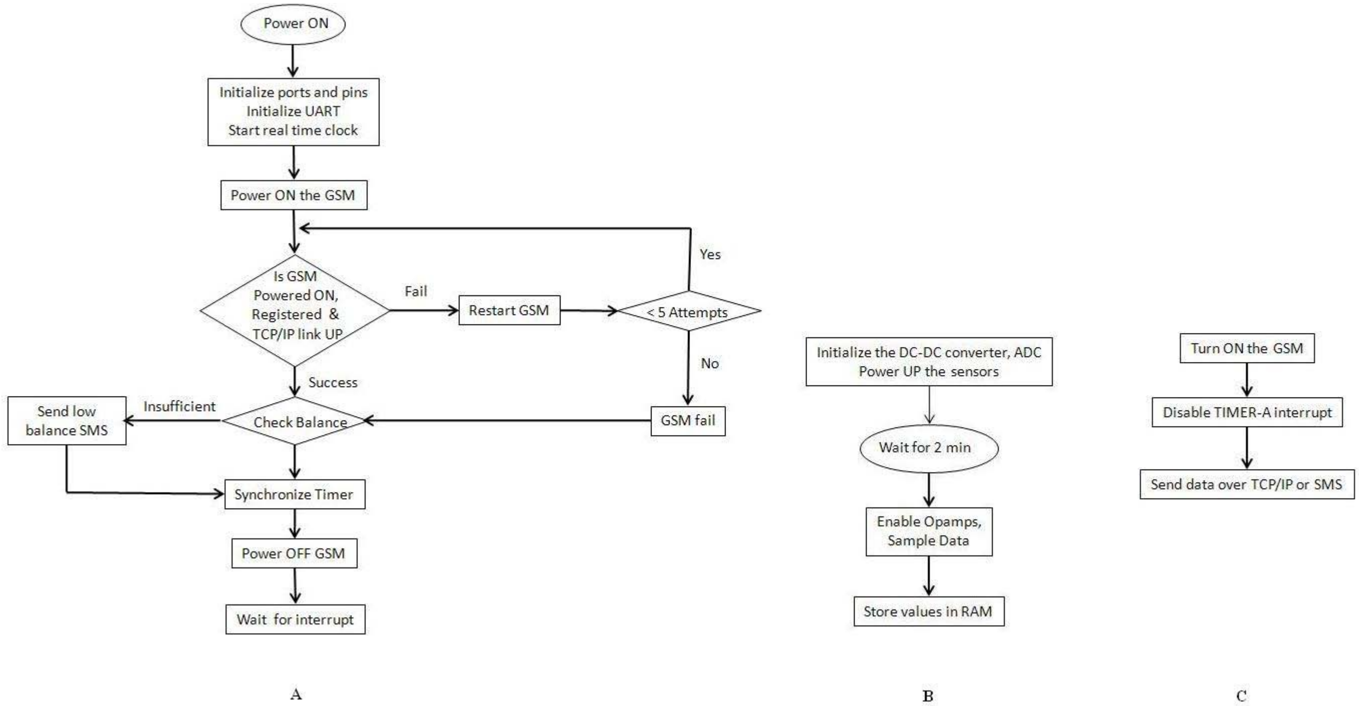

Fig. 4: Flowchart (A)Power ON (B) Sensor module (C)GSM module

battery capacity is 8000mAh. Neglecting power consumption of other peripherals we get a battery lifetime of 32days.

TABLE III: Power Consumption Break up

Component	Power/Energy
Sensors	
CO2	275mW
NO2 + CO	178mW
Humidity	1.1mW
Temperature	275μW
Motherboard	
MSP430	3.7mW
Zigbee	81mW
VGA + DCR	231μW
GSM Module	
Power ON	3.045W

B. Cost estimation

A cost estimation was also performed to conclude the final approximate price of one wireless platform. The cost breakup of different modules is listed in Table IV. It is worth noting that the figure of INR 23000/- is a prototyping cost and is primarily due to the higher unit cost of sensors, PCB manufacturing, battery etc when procured in low volumes. This figure is expected to reduce to approximately INR 15000/- or less for bulk production.

IV. Salient Features of the Design

1) The wireless platform is generic with ability to handle upto 16 analog sensors
2) The motherboard provides regulated power supply and basic signal conditioning

TABLE IV: Cost Break up

Component	**Unit Cost (INR)**	**Lot Size**
Sensors		
CO_2	2250	10
$NO_2 + CO$	1500	10
SO_2	7250	6
Humidity	700	1
Temperature	200	1
Motherboard		
MSP430	600	5
Zigbee	350	5
Sensor Interface	500	5
Power Management Unit	700	5
GSM Module		
SIM300	2200	5
SIM card holder	50	5
Battery	4200	5
Passive Components	500	-
PCB fabrication	2000	5
Enclosure	400	5
Total Cost	23000	5

3) Communication ports (SPI & UART) are brought out so that digital output sensors can be interfaced.
4) The platform runs from a rechargeable Li-Ion cell. The integrated charger can charge up to 10000mAh cell from 5V wall charger.
5) The 8300mAh cell used gives an expected life time of 32 days.
6) GSM and Zigbee connectivity are provided in one single platform
7) The platform is designed in a way that the motherboard is an independent entity and all the requirements specific to the sensors are placed on a different PCB. Hence, the

same wireless platform can also be used with different sensors also with no changes required in the mother-board hardware as well as the software.
8) The system offers a low cost solution for pollution monitoring. The cost estimate are provided in Section III

V. Results and Discussion

The sensor mote was placed in a room and tested continuously for a period of 24 hours. The data was acquired through SMS. Figure 5 and 6 shows the plot of data acquired by the mote for NO_2, CO_2 and SO_2 sensors respectiviely. The concentration levels correspond approximately to the ambient environment. There are some deviations in the observed results and this is because of lack of extended calibration data for the sensors. Extensive calibration of the sensors is required in order to accurately predict the gas concentrations. However, the results are promising in terms of proving the performance and capability of ENVIROMOTE as a pollution monitoring device. ENVIROMOTE is definitely in line with existing solutions and promises to be better in terms of cost, performance and form factor.

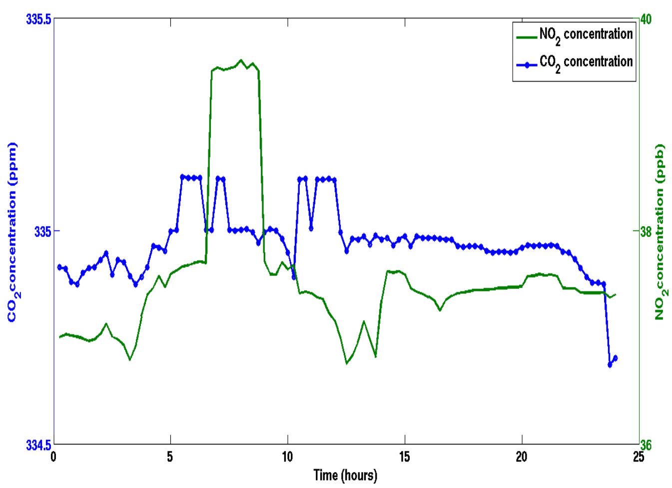

Fig. 5: Acquired data for NO_2 and CO_2 sensors

VI. Conclusion

The wireless platform has been tested and GSM channel is used for data transfer. The mote was able to measure ambient gas concentration levels. The first version of both hardware and software have been proven to work as per the requirements. Most of the power and cost budget of the wireless platform is devoted to the sensors alone. Hence there is a definite requirement to have low cost and low power sensors. We envision indigenously developed sensors being deployed in the future versions of the platform. The present form factor of the mote is limited by the battery hence using compact high density batteries and also harnessing solar energy is being considered.

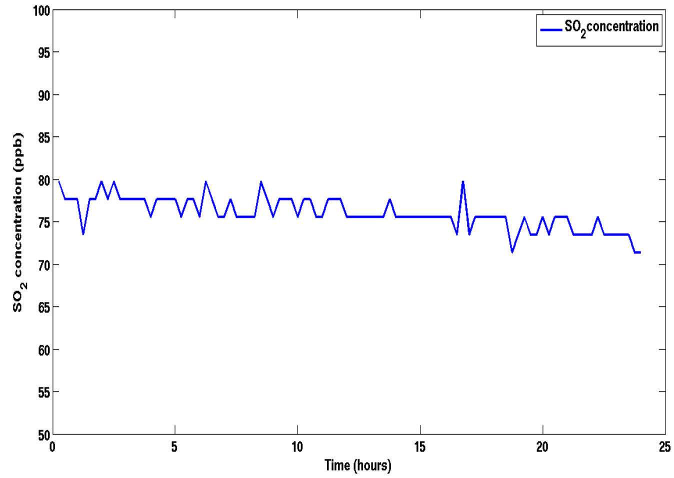

Fig. 6: Acquired data for SO_2 sensor

VII. Acknowledgement

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