Feasibility Analysis onIntegrated Recharging and Data Collection in Pollution Sensor Networks

Pooja Gupta[a], KaushikKandakatla[b], Swades De [b], and Soumya Jana [c]
[a]Bharti School of Telecom Technology and Management, IIT Delhi, New Delhi
[b]Electrical Engineering Department, IIT Delhi, New Delhi
[c]Electrical Engineering Department, IIT Hyderabad, Hyderabad

Abstract – **Uninterrupted network operation in field sensing activities such as pollution monitoring is a big challenge, as the pollution sensors could be quite power hungry. One way to keep the network functioning is to recharge the nodes periodically via radio frequency energy transfer, which can be achieved by using a mobile robot that acts as an energy source and a data sink. Given a set of sensors deployed in a geographic area, a mobile robot is required to visit all the sensors in a way so as to avoid a node's energy drainage and its buffer overflow. Before optimum path planning strategies depending on a set of given sensing and physical environmental constraints, a critical task is to investigate the components of energy consumed by a node on different activities. To this end, this work does an extensive study on the energy consumptions with a few chosen pollution sensor examples. Based on the energy consumption and rectification parameters, the required recharging periodicity is derived. This analysis forms the basis of constrained mobility and path planning of the mobile robot.**

I. INTRODUCTION

The demand for cost-efficient deployment and operation of the wireless sensor networks in critical applications, such as pollution monitoring, disaster management, surveillance, structural health monitoring [1, 2, 3, 4],has promoted significant research on energy efficient communication protocols. To achieve uninterrupted network operation, periodically recharging the nodes from various ambient sources, such assolar energy, radio frequency (RF) energy, vibrations, etc. have been proposed in the literature. Most of the researchliterature on sensor networks considersthat the major energy consumption of the sensor nodes is attributed to the communication activity, while the sensing related activities were considered to consume significantly less energy. However, in case of pollution monitoring, the pollution sensors are generally energy hungry, as they consume significant energy in sensing, processing, as well as the sensor's idling stages. In fact, in such sensors, the energy consumption in sensing could be comparable or even higher than that in communication activities. This contrasting fact of lesser consumption in communication is also a function of the networking protocols involved. In this context, there is a need to develop novel strategies to achieve continuous network operation. Although various energy harvesting techniques can be used to recharge the field nodes, we suggest RF energy harvesting, as it has advantages of on-demand energy availability and also has minimal effect of weather/time of day.

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Generally there are two approaches to disseminate the sensor node data to the base station: (1) multi-hop forwarding; (2) using a data MULE (Mobile Ubiquitous LAN Extension). When the sensor nodes are densely deployed, the sensor data can be forwarded from one sensor to other in a multi-hop fashion till it reaches the base station. However, multi-hop forwarding makes somenodes more loaded than the others. This is because, the nodes closer to the base station tend to die out early compared to the other nodes in the network as they need to relay the sensed/forwarded data from the peripheral nodes to the base station. Such traffic flow imbalance leads to the formation of dead spots in the network. On the other hand, using a data MULE (which does the single-hop communication) in the proximity to sensor node to collect the data significantly increases the node lifetime, as it can save the energy that would have been otherwise used as contention and forwarding overheads.

In this work, we approach the problem of uninterrupted network operation by integrating the tasks of data collection and recharging by the use of a mobile robot, which we call Integrated Data and Energy MULE (IDEM) [5]. The IDEM visits the nodes periodically and positions itself appropriately to recharge them by radiating RF energy as well as collects their data by sending a wakeup signal [6] to the node. The field node then sends its data to the IDEM. In order to find the optimum path, it is of prime importance to find out the energy consumptions of a node on different functionalities. To this end, the contributions in this paper are two-fold: (a) wefirst investigate the energy consumption of a field sensor node on various functionalities, such as sensing, data processing, sleeping, and data communication. (b) To study the feasibility of uninterrupted operation of the field nodes by recharging via RF energy transfer, we investigate the recharging constraints and compute the stoppage time required at a field node under various conditions, such as sampling rate, sensing type, and recharging interval.

The remainder of the paper is organized as follows. In Section II, we discuss various energy consumption models in the literature. Section III presents our problem setting. An insight of Mica2 components is given in Section IV. The analysis of energy consumption of pollution sensor nodes is presented in Section V. Section VI concludes the paper.

II. RELATED WORK

As alluded in Section I, to develop an efficient strategy for path planning, it is important to know the sensor nodes' remaining lifetime, which can be determined if the energy discharging rate of the nodes is known. Also, to estimate lifetime of the sensor node accurately, we require an energy consumption model. Several different approaches can be taken to model the energy consumption of microelectronic devices.

Highly accurate estimates can be obtained by simulation of a microelectronic circuit on transistor level or on even lower abstraction levels, for example with SPICE. It covers all the effects including leakage, switching energy, etc. But these simulations are very time consuming and require in-depth knowledge of the hardware.

Relatively accurate energy simulations can be obtained using Atemu [7] and PowerTOSSIM [8] by measuring the synthetic bench-marks. These contain loops that execute only one kind of instruction, so that the energy consumption of every single instruction can be calculated from the measurements. Though these models allow relatively accurate energy simulations,they require a lot less knowledge of the hardware circuit and have improved simulation runtime, the cost of model creation is relatively high and the resulting model is still too complex.

Simple approximations of overall power usage can be derived from the estimates of the node peripherals' duty cyclesand theirpower consumptions. There have been various attempts to model sensor node energy consumption using this method. Heinzelman et al. [9] proposed a model that considers micro-controller processing, radio transmission, and receiving only. Their model does not consider other important sources of energy consumption, such as transient energy, field sensing, data logging. The model proposed by Millie and Vaidya [11] did not consider energy consumption due to sensing and data logging. Zhu and Papavassiliou's model [13] did not consider energy consumption of transients and sensor data logging.In Table I, we compare these energy models to use in our analysis.

Table I: Comparison of energy models

Energy sources	**[9]**	**[10]**	**[11]**	**[12]**	**[13]**	**[14]**
Processing	√	√	√	√	√	√
Communication	√	√	√	√	√	√
Sensing	-	-	-	√	√	√
Logging	-	-	√	-	-	√
Transient	-	-	-	√	-	√
Wake-up	-	-	-	√	-	√

We take the approach followed by Halgamue et al. [14], which considers the consumptions due to all the sources responsible for functioning of the node.

III. PROBLEM SETTING

We consider the energy-hungry pollution sensor nodes are sparsely deployed along some physical road or path. Apart from the basic sensing, processing, and communication capabilities, the nodes are equipped with an additional component for RF. A RF harvesting unit consists of a RF-DC conversion circuitry. With an objective to save more energy,we use wake-up radio concept instead of duty cycling approach[15]to minimize idle listening to detect the arrival of the IDEM in its vicinity. A field node's sensor module performsperiodic sensing until it receives a wake-up signal from the IDEM. The components not associated with field sensing remain in sleep mode in absence of a wake-up signal and its related activities.

IDEM, with a constraint to move on a fixed trajectory, visits the node having the minimum operating time and positions itself appropriately in the close proximity of the node. On reaching near a field node, it sends a wake-up signal and the node transits from sleep to active mode. On receiving ID of the IDEM, the field node responds by sending information about itsremaining energy and number of data samples to transmit. From this information,IDEM calculates the energy consumption and time taken for the communication and accordingly charges the nodes. After the connection is established, the node sends all the data to IDEM and then the IDEM transmits RF energy using a high gain directional antenna for charging the node.

With the predetermined sensing functionalities and periodicity, the IDEM is considered to have the nodal energy and bufferavailability map in the network, from which the nodal visit sequence is determined. The remaining energy and buffer space of a node depends on the time elapsed from the previous visit of the IDEM, sampling rate, and power consumption values. More specifically,

$$T_{\text{buffer overflow}} \propto \frac{1}{\text{sampling rate}};$$

$$T_{\text{battery life}} \propto \frac{1}{\text{power consumption}}.$$

The IDEM revisit time is the summation of time required in travelling, stopping for communication and charging other nodes. The problem formulated as: Design an optimum path so that the IDEM is able to visit a node and recharge it before the node's energy depletion and/or the buffer is full. That is, the interval of revisiting a node j is governed by:

$$T_{\text{revisit},j} < \underset{j}{\operatorname{argmin}}\{T_{\text{buffer overflow},j}, T_{\text{battery life},j}\}.$$

We need to analyse the nodal powerconsumption in different states and the choice of various parametersthat affect the nodal lifetime and its charging time. Before doing so, in the subsequent section we provide an insight of some example gas sensors and Mica2.

IV. PLATFORM DESCRIPTION

A sensor node consists of modules for sensing, processing, data storage, communication, energy harvesting, and also has a passive wake-up radio module.The Mica2 mote does the job of processing, storage and communication through an interface of the sensor board. The remainder of the section describes each in detail.

A. *Gas Sensors*

It is important to know when dangerous concentration of various harmful gases like chlorine, carbon monoxide, hydrogen sulphide, etc., arise, as these have adverse effect on living elements when being exposed over certain time. The National Institute for Occupational Safety and Health (NIOSH) and the American Conference of Government Industrial Hygienists (ACGIH) have established short- and long-term exposure limits for many toxic industrial gases. Table II shows limits for a few common gases.

Table II: Exposure limits for toxic gases

Toxic Gas	**Long term exposure limit (ppm)**	**Short term exposure limit (ppm)**	**Immediate danger to life limit (ppm)**
CO	50	200	1,200
Cl_2	0.5	1	10
H_2S	10	20	100
SO_2	5	20	150
NO_2	3	5	20

We have considered Alphasense toxic gas sensors which are electrochemical cells that operate in the amperometric mode[16]. That is, they generate a current that is linearly proportional to the fractional volume of the toxic gas. The specifications of different sensors considered for the analysis having ranges defined in Table II are listed in Table III.

Table III: Specifications of sensors

Toxic Gas	**Sensor**	**Range(ppm)**	**Response Time(s)**	**Sensitivity (µA/ppm)**
CO	CO-AI	0-2000	30	50 -100
Cl_2	Cl_2-AI	0-20	60	-350- -750
H_2S	H_2S-BI	0-200	40	300-450
SO_2	SO_2-BF	0-100	40	300-480
NO_2	NO_2-AI	0-20	50	-400- -750

On exposure to gas, the sensor generates current, which is governed by thefollowing equation.

$$\text{gas concentration (ppm)} \times \text{sensitivity}(\mu\text{A/ppm}) = \text{current } (\mu\text{A})$$

To determine the concentration of gas, the output is electronically conditioned followed by analog-digital conversion (ADC) for logging in flash memory. The circuit used for conditioning is Analog Devices CN0234[17] which is a low power circuit and consists of trans-impedance amplifier, ADC, regulator and operates in 2.5-5.5V, suitable for mica2 motes. The currentconsumption of the circuit depends on the concentration of gas. In typical low power systems, the measurement circuitry powers up to make a measurement, then shuts down for a long standby period. In this application, however, the measurement circuit must remain continuously powered due to the electrochemical sensor's long time constants. Thus, it consumes 110µA current in inactive mode. Table IV lists the current consumption for the above sensors using CN0234 evaluation board.

Table IV: Current consumption of sensors using CN0234

Sensors	**Current consumption (μA)**
CO	657
Cl_2	472
H_2S	547
SO_2	505
NO_2	472

B.Mica2 mote

The Mica2 Mote is a third generation mote module used in low-power wireless sensor networks. It is powered by 2AA batteries and has operating voltage between 2.7V – 3.3V[18]. The main components are Atmega128L(processor), AT45DB041B (flash memory) and CC1000 (transceiver radio)[18]. Dynamic power management ensures that these components are usually in sleep mode and activated when required, as the power consumption is of the same order of magnitude in the active and idle modes, and it is much less in the sleep mode[15]. The current/ energy consumption of these components in different modes are listed in Table V [8, 12, 19].

Table V: Energy consumption of mica2 mote

Components	**Current/ energy consumption**	
CPU		
Active	8.0 mA	
Power save	110 µA	
EEPROM access		
Read (1 byte)	0.24µJ	
Write (1 byte)	3.91µJ	
Erase	2.14µJ	
Sleep	2 µA	
Radio	**Current consumption (mA)**	**Time (ms)**
Initialize radio	6	350×10^{-3}
Turn on radio	1	1.5
Switch to Rx/Tx	15	250×10^{-3}
Time to sample radio	15	350×10^{-3}
Evaluate radio sample	6	100×10^{-3}
Receive 1 byte	15	416×10^{-3}
Transmit 1 byte	20	416×10^{-3}
Sleep	10^{-3}	

As the energy harvesting unit and passive wake-up radio module [6]operate by using the RF energy from the IDEM, we do not count them in calculating the total energy consumed by the field node.

V. ANALYSIS OF ENERGY CONSUMPTION OF POLLUTION SENSOR NODE

The states of operation of node are shown in Fig. 1. A fieldnodeconsists of a number of gas sensors (say n_i) having different response time (t_{ri}). A sensor node is considered to sensepollutants periodically, as shown in Fig. 2. So, the CPUis periodicallyactivated for logging data in the flash memory.When the IDEM arrives, it transmits a wake-up signal and on receiving it, the nodes' CPU transits from sleep to active mode and

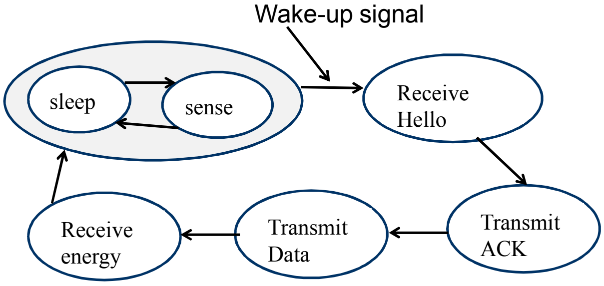

Fig. 1: A sensor node's operation states

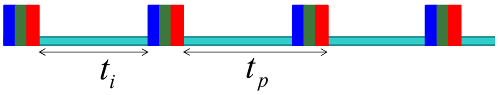

Fig. 2: Sampling rate of sensor

switches on its radio to receiving mode. On receiving an IDEM's signal, the node's radio switches to transmitting mode to transmit the information of remaining energy and number of samples to theIDEM. After completion of 2-way handshake, the data transmission starts, followed by energy reception. The sensor states of operation and corresponding mode of different component is shown in table 6.

Table 6: State of operations

State	Mode	CPU	Sensor	Memory	Radio
S0	Sensing	sleep	On	Off	Off
S1	Data logging	Active	Off	On	Off
S2	Receive Hello	Active	Off	Off	Tx
S3	Transmit ACK	Active	Off	Off	Rx
S4	Transmit Data	Active	Off	On	Tx
S5	Receive Energy	Sleep	Off	Off	Off

Let, the IDEM wakes up a node at interval$T$ (time unit) and the sensor's sampling period ist_p, So, thetotal number of samples in T time is: $n = T / t_p \times n_i$. If t_j is the response time of the jth sensor and t_i is the idle time of a sensor board, we have,

$$t_p = t_i + \sum_{j=1}^{n_i} t_j$$

Using the current consumption in different modes listed in Table V and finding out the time to be in that mode in different states using [20, 21, and 22], energy consumption is calculated. The energy consumed by a node consists of the operations of sensing, sleeping, receiving, transmitting, and data logging.

To aid the path planning, following parameters are identified and are quantified: (i) Number of sensors a node can have so as to have consumption supportable by RF charging; (ii) The sampling period of the sensor module; (iii) Arrival rate of IDEM; (iv) Distance at which IDEM has to stop for charging. These parameters are chosen in such a way so as to have optimum time of charging. To quantify the above parameters and to see their effectson the time of recharging, various plots have been obtained. Time of recharging is a crucial factor as it depends on all the above mentioned parameters. A higher time of charging is undesirable and smaller time of charging is not feasible using RF, though reliable, it involves energy wastage due to power loss owing to propagation loss. Therefore, RF charging is the least efficient compared to other harvesting techniques in terms of output power [23, 24].

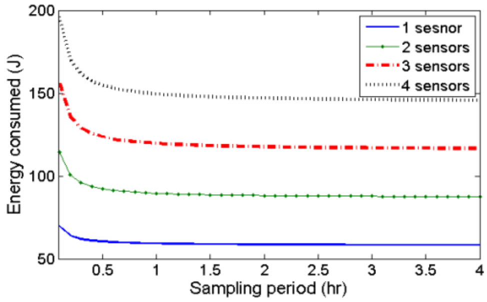

Fig.3: Energy consumption versus sampling period

From the Fig. 3, it can be observed that using 4 sensors per node, the energy consumption is drastically increased to nearly 150J compared to 70J for the single sensor case for the same sampling period making RF harvesting infeasible for charging. Even though the sensors are active in nature and are using low power circuitry for conditioning and power management schemes for other components, the major consumption is due to sleep mode of all the components. Therefore, it is advised to use a single gas sensor per field node.

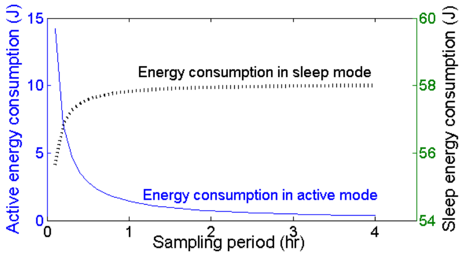

Fig. 4: Effect of duty cycle

The nature of Fig.3 can be best explained by the Fig. 4. From the Fig.4 it can be observed thatby reducing the sampling period, the energy consumption cannot be controlled by making components to sleep as major portion of the energy consumption is due to the sensing. And for our application of periodic sensing using gas sensors, the sampling period ischosen in such a way that we get an adequate number of samples while consuming less amount of energy. From Fig. 3, as the energy consumed is nearly constant after nearly 1 hour sampling period, we prefer the sampling period to be 1 hour.The sampling period of 1 hour is found to be practical as this is the sampling period used by Haryana State Pollution Control Board for ambient air quality measurement [25] and also mentioned in the Guidelines for Ambient Air Quality Monitoring [26] by National Air quality Monitoring Program (NAMP).

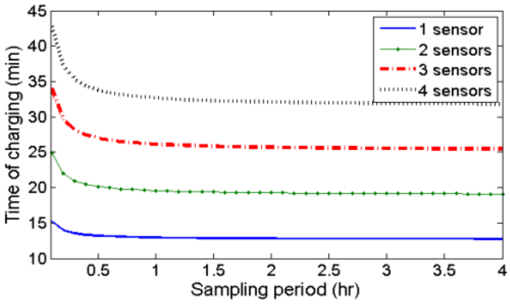

Fig. 5: Time of charging versus sampling period assuming IDEM arrives twice a day

Fig.5 shows the effect of sampling period on time of charging. It can be observed that higher sampling period does not have much effect on the charging time, assuming theIDEM's rate of arrival to be twice a day. This is because due to sleeping consumption of the node as discussed before.

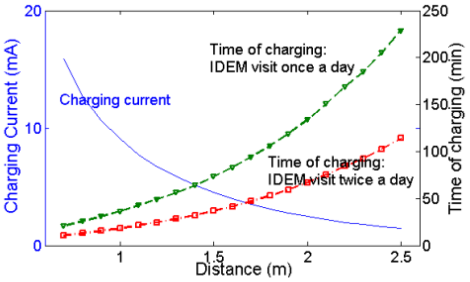

Fig. 6: Distance versus charging time

Having decided the nodes parameters, IDEM's parameters are deduced keeping in mind the nodes constraints. Fig.6 shows the distance of charging for IDEM versus the time of charging. Maximum charging distance is guided by the energy sensitivity, which is the minimum input power required by RF-DC conversion circuitry to obtain useful output dc power, resulting in higher time of charging. The minimum charging distance is governed by the antenna far-field distance and maximum input power of RF-DC conversion circuitry. Distance should be chosen so that time is required for charging is minimum otherwise itsignificantly increases the stoppage time of the IDEM thereby increasing the chance of interruptionfor the operation of other nodes in the network. 10-20 minutes of stoppage for charging is desirable for which the corresponding distance is in the range of 0.7-1.1meter and therefore a IDEM revisit rate should be twice a day.As the objective of the paper was to create a pollution map, the data collection by the IDEM after every 12 hours is justified.

VI. CONCLUDING REMARKS

In this paper we quantified the parameters which are required for path planning of the IDEM so as to provide uninterrupted operation of sensor nodes by integrating data collection and recharging. The problem was divided into two tasks: 1) estimation of node lifetime and stoppage time; 2)finding the optimum path. To ensure availability of energy on demand, the use of RF energy transfer was proposed for charging nodes, and wake-up radio concept was used at the nodes so that each node can remain in sleep state while not being visited by IDEM.

In this work, we have addressed the task 1. The detailed energy consumption components on different functions of a node were derived from the basic devices data sheets. Based on these values, MATLAB simulations were conducted to estimate the stoppage time of the IDEM and also other parameters such as distance from the sensor node for charging, sampling period were quantified.Though different energy efficient schemes were used, it was noted that the consumption is significant due to the sleepmode of the pollution sensors. Contrary to the views in prior research, our evaluation showed that, a longer sleep cycle of the currently available pollution sensors do not necessarily lead to a significant energy saving. The above observations will pave the way to the task 2. Our, future worksin this direction includeoptimum path planning of IDEM under different optimality criteria.

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