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Energy Model for H_2S Monitoring Wireless Sensor Network

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Abstract— **Several applications have been proposed for Wireless sensor networks. These include habitat monitoring, structural health monitoring, pipeline (gas, water, and oil) monitoring, precision agriculture, active volcano monitoring, and many more. To demonstrate the feasibility of the proposals, researchers have developed prototypes and deployed them into real-world environments. Even though each prototype was developed for a specific sensing task, interestingly most of the networks share several characteristics in common. Some of these are: The need for time synchronisation, high sampling rate of short duration, multi-hop routing, periodical sampling and sleeping, and medium access control. Whereas there are a plethora of existing and proposed protocols to address these issues, each prototype chooses to address the issues in a proprietary manner. The lack of reuse practice poses a generalisation problem. In this paper we motivate toxic gas detection during oil exploration and refinery and demonstrate how existing or proposed protocols can be employed to establish a fully functional network. Moreover, we provide a comprehensive energy model to evaluate the feasibility of employing wireless sensor network for the monitoring task.**

I. Introduction

Several applications have been proposed for wireless sensor networks in the recent past. Mainwaring et al.[16] propose wireless sensor networks for habitat monitoring, to replace human presence during a scientific observation of the life and breeding habit of seabird colonies. The motivation of their proposal is that human presence can be a potential disturbance of behavioural patterns of some sensitive wild animals. It may even seriously reduce or destroy populations by increasing stress, eventually forcing the animals to shift to unsuitable habitat. The authors deployed several Mica sensors on Great Duck Island to monitor seabirds. The sensors used are humidity, temperature, barometric pressure, and surrounding light from which they determine breeding habits.

Xu et al.[26], Kim et al.[14] and Chintalapudi et al. [6] propose wireless sensor networks for structural health monitoring in which the structural integrity of bridges and buildings is inspected using accelerometer sensors. In structural health monitoring, inspection is usually categorzsed into local and global inspections. Local inspections aim to detect imperceptible fractures in a structure such as cracks, cavities, and inclusions (i.e., foreign materials) in a specimen. Global inspection aims to discover damages in a structure large enough to influence the properties of the entire structure or a large section thereof. A local inspection requires sophisticated, expensive and bulky equipments whereas global inspection is based on analysis of the response of a structure to an external excitation. The proposed wireless sensor networks are suitable for global inspection. Consequently, the networks are tasked to monitor the response of a bridge to an ambient excitation (heavy wind or passing vehicles) or a forced shake (using shakers or impact hammers).

The work of Xu et al. and Chintalapudi et al. include the Wisden platform employing Mica sensor nodes and 16-bit vibration cards. The sensor network itself was established and tested with 25 sensor nodes on three floors of a medium-sized office building and on a seismic test structure for conducting experiments. Kim et al. deployed 64 Mica sensor nodes on the San Francisco Golden Gate bridge to study the reaction of the bridge to strong wind and earthquake.

Likewise, Werner-Allan et al. [25] propose wireless sensor networks for active volcano monitoring. They deploy a linear network of 16 sensor nodes on Volcn Tungurahua, in central Ecuador to monitor seismic and infrasonic signals resulting from an active volcano. Each sensor node was equipped with a microphone and a seismometer. Interestingly, the sensor network could be able to capture 230 volcano events just over three weeks. Stoianov et al. propose the PipeNet wireless sensor network for monitoring large diameter, bulk-water transmission pipelines. The network collects hydraulic and acoustic/vibration data at high-sampling rate.

Other areas of applications of wireless sensor networks include precision agriculture [4], [3], healthcare [24], underground mining [17] and many more.

The above networks are optimised according to the sensing tasks for which they are deployed. On the other hand, they exhibit significant similarities in the types of sensor node hardware they use, the frequency band and bandwidth of communication, the runtime environment and some aspects of sensing, processing, and communication as well. Moreover, they all face a challenge common to all wireless sensor networks which comes from operating with exhaustible batteries, namely, limited life time. While we studied the implementation details of the applications, we observed that they all have the following concerns to address:

- Time synchronisation;
- High sampling rate for a short duration;
- High resolution of the sampled data;
- Multi-hop communication; and thereby the need for medium access and link control; and,
- Periodic sensing and periodic sleeping.

While this is the case, we also observed that each prototype develops its own protocol to address all or some of the above concerns and no two prototypes display similarity in any of the protocols they implemented. On the other hand, there are a myriad number of protocols and algorithms proposed by

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the research community, some even considerably referenced and recommended for their energy-efficient performance. The lack of protocol reuse practice is the motivation behind this paper. Inasmuch as off-the-shelf sensors and sensor boards, processors, memory and radio as well as runtime environments (TinyOS) are employed to assemble the sensor nodes used by the above applications, the research community should also begin reusing existing or proposed in-network processing algorithms and communication protocols to facilitate rapid prototyping and eventually producing commercially feasible wireless sensor networks. We begin this task by motivating a pipeline monitoring application, specifically monitoring the leakage of H_2S in an oil refinery (PetroChina). We identify existing self-organisation, medium access control and routing protocol and provide an extensive and comprehensive energy model to make the network fully functional. The energy model will enable us to evaluate the feasibility of wireless sensor networks for real-time gas, water and oil pipeline monitoring.

The rest of this paper is organised as follows: in section 2, we provide background as regards to gas pipeline monitoring; in section 3, we provide a network architecture for monitoring toxic gas with wireless sensor networks and define the sensing task; in section 4, we identify suitable protocols for establishing the network and give justification; in section 5, we provide an energy model and evaluate the network performance; finally, in section 6, we discuss our observation, share the experience learned, and raise open issues that merit future research.

II. Background

During oil exploration and refinery processes, many types of toxic gases are produced as product or by-product. These include Ammonia (NH_3), Hydrogen Sulfide (H_2S), and Sulfur Dioxide (SO_2). Among which H_2S is a useful and common by-product, but also a cause of health and corrosion problems. It is used to recover sulfur, which is commonly used for manufacturing sulfuric acid, medicine, cosmetics, fertilizers and rubber products. During oil extraction and refinery processes, H_2S is carefully transported in pipelines to workshops where further processing take place. The main concern at this stage is the potential of leakages that can have a severe impact on human beings as well as the environment. Leakage also mean putting a pipeline out of service for repair. The cause of leakages can be excessive deformations caused by earthquakes, corrosion, wear and tear, material flaws or even intentional damage.

A. The Sensing Aspect

Hydrogen sulphide is an extremely toxic, colorless, flammable gas that is heavier than air and soluble in water. It has a rotten egg odor, which is discernible at concentrations well below its very low exposure limit. Exposure to low levels of hydrogen sulphide will cause irritation, dizziness and headaches, while exposure to levels in excess of the prescribed limits will cause nervous system depression and, eventually, death [19]. Besides the harm to human beings, H_2S has also a negative impact on the ecological system. For instance, H_2S in water may change the PH value, which would eventually result in an ecological imbalance between the microbes and aquatic species in that habitat.

Subsequently, various parties are interested in monitoring H_2S release during oil exploration and refinery.

B. Existing Toxic Gas Detection System

Pipeline ownership entails considerable management challenges because of the long length, high value, high risk and often difficult access conditions of the pipelines. A pipeline inspection task involves both a stationary sensing system and portable sensors carried by maintenance workers. A stationary sensing system consists of sensors, power and signal cables and a control station in which the sensed data are processed. Because of the initial installation as well as maintenance cost[1], the deployed sensing system may not adequately cover the sensing field. As a result, each employee is required to carry with him a portable sensing device for safety reason.

As a side remark, existing sensing systems consider reports from individual sensors independently; they do not correlate reports from spatially distributed sensors in order to determine the nature of a leakage report. For example, correlation of sensed data can be helpful not only to detect and localise a leakage, but also to determine whether a leakage report made by multiple sensors is a result of actual leakages or a diffusion on air of the gas from a single source.

C. Gas Sensor Selection

Several sensing technologies exist on the market. The technologies include Semiconductor, Catalytic, Infrared Photo-ionization, Fluorescent Surface acoustic wave (SAW) and vibrating beam, and Capacitive technologies. Amongst theses, electrochemical, IR, and catalytic measurements have become popular over the years. Whereas electrochemical sensors are appropriate for toxic gases detection, catalytic and IR sensors are suitable for detecting combustible gases [1].

So et al. [22] introduce a wireless laser spectroscopic trace-gas sensor node that integrates miniature quartz-enhanced photo-acoustic spectroscopy (QE-PAS) for detecting and quantifying numerous gas species at part-per-million to part-per-billion (ppm-ppb). This and similar developments make employing wireless sensor network for toxic gas detection feasible.

D. Calibration

Gas detection instruments perform a relative measurement. Therefore, the accuracy of a measurement depends on the calibration. Scheduled calibration (every season) and pre-calibration are the usual practices in the field.

[1] All types of chemical sensors are exhaustible like dry cell batteries, i.e., they lose their sensitivity over time. The life time of a sensor (measured in ppm/hours) depends on the amount of part per million it is exposed to. Most existing sensors have an average life time of one year.

E. Alarm Thresholds and Response Time

The alarm threshold depends on the occupational exposure limits of the gas, which vary from country to country. For example, the American Conference of Governmental Industrial Hygienists (ACGIH) defines the Threshold Limit Values (TLV) as an exposure limit ”to which it is believed nearly all workers can be exposed day after day for a working lifetime without ill effect” and the Threshold Limit Value - Ceiling (TLV-C) is that ”the concentration that should not be exceeded during any part of the working exposure.”. The limit values are different based on short-term (15-minute exposure periods) or long-term (8-hour workday) exposures. Some organizations even recommend the limit value for exposure of a 40-hour work week [11].

The specific standard to be adopted depends on the user of the gas detection system. The general limit for short-term exposure is 10 part per million (ppm).

The System’s response time is a very critical performance metric for leakage detection. It is decided by the sensors’ response speed and the transmission and processing time. The nominal time is between 20 to 30 seconds, but most refineries set an upper limit of 60 seconds.

III. H_2S MONITORING WITH WSN

We spent three months of field observation at a China Petrochemical refinery to investigate the feasibility of employing wireless sensor networks for pipeline monitoring. Following the field observation and throughout the M.Sc. thesis work of the first author, we evaluated the usefulness, scope, and energy demand of existing and proposed protocols for establishing and running an H_2S monitoring wireless sensor network.

We defined the sensing task, selected and compared the performance of various protocols, and computed the overall energy demand of the network for carrying out the chosen sensing task. Our aim is to assess the feasibility of deploying such a network with existing sensors, sensor boards, processors, radio components, and other essential off-the-shelf components.

A. Deployment and Topology

There are three basic sensor-positioning strategies in theory for node deployment: spot, area and fence monitoring. In spot monitoring, only a few sensors need to be deployed, but one needs to know the exact pinpoint position of the leakage source, which is accurate but needs more time and knowledge of the field.

Area and fence monitoring are used to save time of finding the potential leakage pinpoints. In the former, sensors should be deployed in all regions where the source may spread across. It requires a large number of sensors, and cannot thoroughly avoid blind spots even at high densities. The latter constructs a maximum outer limit to guarantee that the target is in an enclosure. It is suitable for applications like detecting and reporting security relevant incidents, such as a person or animal entering a prohibited area, but it is not suitable for gas detection in workshops with people nearby.

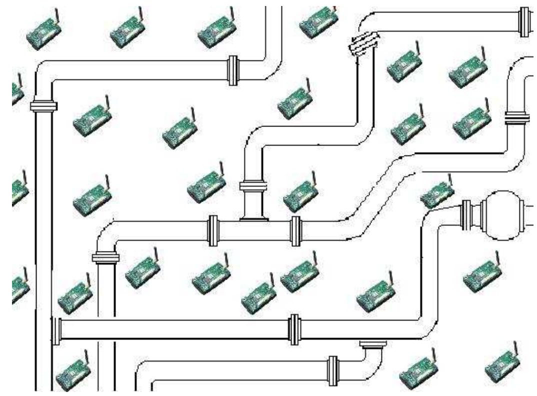

Fig. 1. 2D Poisson Distributed node deployment

Spot monitoring works well for traditional wired sensor systems, but it may have problems in coverage and connectivity in wireless sensor networks. In the next section, we will address how to resolve these two problems.

B. Coverage and Connectivity

In [2], the sensing coverage is defined as how well a given area can be monitored by the network, which is a significant performance metric. Several papers [2] [20] propose models for computing the number of sensors required to cover the entire sensing field with high detection probability.

Coverage is deployment and density dependent. For toxic gas detection, spot monitoring is the most suitable strategy since it is the safest and most energy effective. The sensor nodes are positioned at the conjunctions of pipelines. For a spot monitoring scenario, the whole area is not necessarily covered everywhere without any ”blind spots”, but all potential leakage sources are monitored.

Connectivity, on the other hand, is a fundamental aspect for our deployment scenario. To ensure the communication between source and sink nodes, at least one multi-hop path between every pair of nodes should exist. The probability that a network is connected, i.e., all nodes can communicate with the sink either directly or with the support of intermediate nodes, mainly depends on the density of nodes and their transmission range. If the border effect is not considered, this probability can be estimated by [5]:

$$P(connectivity) \cong \sqrt[1/n]{\left(1 - e^{-\lambda \pi {r_o}^2}\right)} \qquad (1)$$

where $P(connectivity)$ is the probability that the network is connected; λ is the density of the network; r_o is the threshold transmission rage; and $n >> 1$ is the number of deployed nodes. The deployment scenario for our case is depicted in Figure

C. The Sensing Task

During oil exploration and refinery process, there are two essential concerns: the long and short term impact of toxic gases release. For H_2S, the long term impact can be on employees or the ecology at large. The impact of short term release is usually on employees. Hence, we define the following sensing tasks:

1) Every sensor node should periodically report the concentration of H_2S to a sink: This is characterised as a normal case with a normal priority.
2) In case of a leakage that surpasses a threshold defined by the safety board of the refinery, an alarm should be fired off within 30 second. For this to happen, the report should be delivered to the base station in less than 30 seconds. This is characterised as an abnormal condition, with high priority[2]

IV. Network Model Assumptions

In order to carry out the sensing assignment, we model the network thus:

1) N nodes are distributed randomly on a rectangular area A of size $A = a \times b$. without loss of generality, we assume that $a \leq b$. The node distribution can be modelled as a two-dimensional Poisson distribution with average density, λ. The probability of finding k nodes in A is

$$P(k\ nodes\ in\ A) = e^{\lambda A} \frac{(\lambda A)^k}{k!} \qquad (2)$$

2) The sensor nodes are deployed with spot monitoring strategy with additional nodes for improved connectivity. Spot monitoring can guarantee the coverage of all the potential leakage. We ensure that the network density is not high but enough to meet both coverage and connectivity requirements.
3) Sensor nodes in the local network are battery powered with uniform initial energy. The batteries are exhaustible. The nodes themselves are fixed once placed.
4) There is a single fixed sink situated in the field. The sink is assumed to have sufficient power and energy.
5) All nodes in the area communicate in a multi-hop fashion because of two reasons: firstly, sensor nodes have only small transmission range and may not be able to communicate directly with the sink; secondly, multiple short-range transmissions can save considerable energy as opposed to one large hop transmission. Therefore every node in the field may act as both a data source and a relay.
6) Each node has the same radio transmission range R, and two nodes can communicate via a wireless link if their Euclidean distance $\leq R$.
7) When sensing, each sample is quantized and encoded into 16 bits.
8) For simplification, fading and path efficiency are not taken into account; we do not also consider the presence of obstacles in the path of propagation.

[2]At this stage we do not consider more complex but also more realistic sensing tasks as defined in Section

A. Network Topology

As far as topology is concerned, there are two essential types: flat and hierarchical. In flat networks, all nodes have equal rights, no global knowledge is assumed to carry out a sensing task. Collaboration is based on local and neighbourhood knowledge. the main problem with flat networks is that energy may not evenly be consumed as a result of which those nodes near to the sink will suffer earlier power depletion. In a hierarchical architecture, nodes self-organize into clusters with some acting as cluster heads. The cluster heads perform data aggregation and fusion in order to reduce the number of messages to the sink. It is energy efficient in data propagation and scalable; but the creation and maintenance of clusters are energy consuming and need global knowledge of the network.

For our network, we adopt a flat topology which impose minimum assumptions about nodes' relationship.

B. Medium Access Control

A medium access control is essential for two reasons: Firstly, we prefer multi-hop communication rather than each node communicating directly with the base station. Secondly, to reduce the overall network traffic, we should support in-network processing. One example of in-network processing is that during a normal routine sensing, each node sends to the next intermediate node the concentration of H_2S it has sensed; the receiving node compares the report with report from its own sensors as well as with reports it received from other sensor nodes; it then forward only the maximum level, since only the maxim measured leakage report is of interest. This would avoid unnecessary packet transmission.

For nodes to cooperate, an energy efficient medium access control protocol is required. The performance of a MAC protocol is highly dependent on the density of the wireless sensor network. We have considered several MAC protocols, among which are S-MAC, T-MAC and B-MAC.

S-MAC [27] is based on a combined scheduling and contention method. Each node sleeps periodically, during which time the radio is shut down and a timer is running. When the timer expires, the node wakes up to see if any other node wants to communicate with it. S-MAC uses the RTS/CTS handshake mechanism similar to 802.11, but sets it as default settings and extends this scheme to avoid overhearing by forcing all the immediate neighbours of the sender and receiver into a sleep state. All nodes are synchronized through a SYNC packet. The ratio of listen interval to the frame length is called duty cycle, by setting low duty cycle, and together with overhearing avoidance and message passing, S-MAC obtains significant energy savings compared with sleepless 802.11[12] variant protocols.

However S-MAC trades off latency for energy saving, because nodes cannot transmit or receive data in sleep mode. A modified S-MAC version[28] proposes an Adaptive Listening technique to reduce multi-hop latency by letting the node that overhears its neighbour's transmissions wakes up for a short period at the end of each transmission.

In S-MAC, active period is constant for every node and frame, which makes the duty cycle have to be enlarged for even only a short period of peak traffic load.

T-MAC [23] proposes an idea that the nodes go back to sleep when no traffic has happened for a certain time (=timeout), but it also incurs the early sleeping problem that limits the maximum throughput.

B-MAC [18] use adaptive Low Power Listening (= preamble sampling) to reduce duty cycle and provide flexible interface for reconfiguration and performance optimization. We choose S-MAC as our MAC layer algorithm for five reasons:

1) It is significantly energy efficient comparing to other MAC protocols without sleeping.
2) With configurable duty-cycle, S-MAC is more adaptable for different scenarios
3) Most other energy-saving MAC protocols originate from S-MAC's periodical sleep and wakeup scheme. Using S-MAC makes our re-search more flexible if we want to support other similar MAC protocols later.
4) Its synchronization algorithm also provides self-configure functionality, which could achieve self-organization without special algorithms.
5) Though latency is not our concern currently, it is a critical issue for the whole system. With the Adaptive Listening algorithm in S-MAC, our implementation can achieve short latency and energy efficiency at the same time.

C. Routing Protocol

A routing protocol deals with path selection and maintenance for data transmission in a network. In sensor networks, energy efficiency and data aggregation have to be in mind when choosing a routing protocol.

Popular routing protocols include SPIN [10], Directed Diffusion [13], LEACH [9] and BCDCP [21].

Directed Diffusion [13] is a data-centric routing protocol based on set up and report phases. In the set up phase, the sink floods interests to the whole network. During the propagation of interest, every hop establishes the gradients to its direct neighbour. The source whose data matches the interest will send exploratory data through multiple paths to the sink, and the sink would select and reinforce some of the paths. The criteria for reinforcing a path may be low latency or energy efficiency. Once efficient paths are selected, the data will be sent from the source to the sink along the reinforced paths. Directed Diffusion accommodates application specific, in-network data aggregation algorithms.

V. Protocols Implementation

A. MAC Layer Design

With the design goal of energy conservation and self-configuration, S-MAC uses three novel techniques to achieve dynamic medium access control.

Firstly, nodes periodically sleep and wake up, with low duty cycle to save energy and avoid collision. However, network latency caused by periodical sleeping may not comply with the strict regulation of industrial safety rules. There is a modified version of S-MAC to deal with this issue based on adaptive listening. this latter version lets a node which overhears its neighbour's transmissions (ideally only RTS or CTS) wake up for a short time at the end of the transmission. In this way, if the node is the next-hop node, its neighbour is able to immediately forward data to it instead of waiting for the next scheduled listen time. On the other hand, if there is no activity during the adaptive listening period, nodes will decide to go back to sleep again. S-MAC with adaptive meets well the requirements of our sensing task.

Secondly, neighboring nodes form virtual clusters to auto-synchronize their sleep schedules. In a large network, all nodes may not be able to follow the same schedule. This will lead nodes on the border to respond to more than one schedule and spend less sleeping time and consume more energy than others. Moreover, nodes following multiple schedules may cause undesirable delay in data transmission. To overcome this drawback, S-MAC employs the Global Schedule Algorithm [15] by which a single global schedule is established throughout the network.

Third, S-MAC uses message passing to reduce contention latency. Message passing allows a long message to be divided into several smaller packets and transmitted continuously when the node obtains a channel. This technique increases the sleep time, but leads to fairness problems.

We found out that this specific characteristic was not suitable for our sensing task, particularly in case of the detection of a leakage above the threshold of safety. Therefore, our energy model does not consider message passing.

B. Routing Layer Design

Directed Diffusion family [8] permits applications to define in-network processing policy and routing metrics. Moreover, it is adaptable to changes in data sources, network topology and the sink's quality of service priorities. The protocol implementation can be (1) two-phase pull diffusion, (2) one-phase push diffusion, or (3) one-phase pull diffusion.

1) Two-phase Pull diffusion: In this implementation, there are two phases. In the first phase, the sink distributes interests in terms of named data in attribute-value pairs. The interest is flooded in the network. Each sensor node that receives an interest packet maintains a gradients table to track where this interest comes from. With the gradients, the node could select proper node as next-hop to forward the data.

After setting up a gradient, the sensor node redistributes the interest packet by broadcasting. Nodes that have data matched interest will publish and forward the required data along all existing gradients till the sink. (This is called an exploratory data.)

In the second phase, the sink uses positive or negative reinforcement messages to select one or multiple paths to the nodes that contribute exploratory data. And subsequent data from source will be transmitted through the reinforced path(s).

Definition	Periodical report interest: normal	Leakage report interest: abnormal
Interest Example	type = normal H_2S con. $<$ 10ppm interval = 1000s expiry = 02:20:40	type = abnormal H_2S con. $\geq$ 10ppm interval = 10s expiry = 02:20:35
Gradient	minimum energy	Low-latency,
Data Example	type = normal (normal priority) instance = 5ppm id = 002 timestamp = 01:30:40	abnormal (high priority instance = 50ppm id = 001 timestamp = 01:20:40

TABLE I

DEFINITION OF INTEREST, GRADIENT, AND DATA MESSAGE

The problem with the two-phase pull suffers from interest flooding and exploratory broadcast traffics, and reinforcement message is also an energy consumption process.

Two variations of Two-phase pull diffusion are brought up for performance improvement: , which is suitable for few senders and many receivers scenario and One-phase pull diffusion, which is suitable for many senders, few receivers scenario.

2) One-phase push Diffusion: With this implementation, instead of actively sending interest, a sink keeps the interest information locally. Source nodes play active roles in communication. Exploratory data is sent through the network without gradients created according to a certain interest. This saves the cost of interest dissemination in two-phase pull. However One-phase push diffusion is not suitable for applications where many sources continuously generate data, as all the data may not be equally relevant to the sink, in fact some of them could entirely be irrelevant.

3) One-Phase Pull Diffusion: One-phase pull is a subscriber-based system. The subscribers send interest messages into the network to establish gradients. Unlike two-phase pull, when an interest arrives at a source, it does not mark its first data message as exploratory, but instead sends data only on the preferred gradient, the lowest latency neighbour. Thus One-phase pull does not require reinforcement messages, and the lowest latency path is implicitly reinforced. One-phase pull takes the assumption of the existence of a symmetric communication link between nodes.

For our scenario, the possibility that many leakages happen at the same time is very low; this implies that abnormal interest dissemination is infrequent. We can model this scenario as few sender and one sink, which is applicable to two-phase-pull. Whereas in the normal case, every node should report its monitoring data periodically, which is a typical scenario of many senders and one sink suitable for one-phase pull. The latter scenario dominates the network's lifetime. Additionally, compared to two-phase pull diffusion, there is no exchange of overhead information like reinforce messages; and routing tables require only one entry per active interest in one-phase-pull diffusion.

Basic Parameter	DefaultValue
Control message RTS/CTS/ACK	10bytes
SYNC message	9 bytes
Interest message	96bytes
Data message	136 bytes
Interest propagation frequency	300 seconds
Normal event report interval	300 seconds
Abnormal event report interval	10 seconds
Abnormal event report period	60 seconds
Abnormal event occurrence ratio	1%
Duty cycle	10%
Bandwidth	2kbps
Network density	λ
Minimum hop counts	This depends on the sensing field and the network model. The average number of hops for our case is 3
S-MAC Frame length	Message size, duty cycle and bandwidth
Adaptation time	Frame length dependent
Max retry times	5
Frequency of neighbour Discovery	50
Synchronization period	20
Data rate	2kbps
Nominal transmission Range	40m
Sensing field	7000m^2 (70m $\times$ 100m)
Transmission power	31.2mW
Receive/idle power	22.2mW
Radio@sleep status	3μ W

TABLE II

DEFINITION OF PARAMETERS

C. Analysis of Energy Budget

The energy budget of a fully functional network depends on many parameters. It accounts for the medium access control and routing; the interest dissemination, the rate at which events are propagated from any source in the network to the sink, the rate at which abnormal events are detected, the duty-cycle of the medium access control, the density of the network, the transceiver's transmission distance, the efficiency of the transceiver, the data rate, the resolution of the ADC, time synchronisation [3], and the size of the data payload, among other things. Table

For every payload packet exchange between a sender and a receiver, it is possible to compute the energy utilisation for the following modes:

1) **Transmission:** $1RTS + 1CTS + 1ACK + 1DATA$[4]
2) **Receive:** $nRTS + nCTS$[5] $+1ACK + 1DATA$
3) **Idle:** At least $1DIFS + 3SIFS + i_a$[6]
4) **Synchronization:**Because in S-MAC for every certain rounds, the nodes should exchange SYNC packets with

[3]S-MAC requires time synchronisation for nodes to exchange sleeping schedule with their neighbours.

[4]Here we take a one time transmission only; a more complex calculation depends on maximum number of retry attempt and failure model.

[5]Where n represents the neighbors of the sender and the receiver.

[6]Where i_a is the average idle time. We take 1/2 frame based on probability theory. A more detail analysis falls out of the scope of this paper.

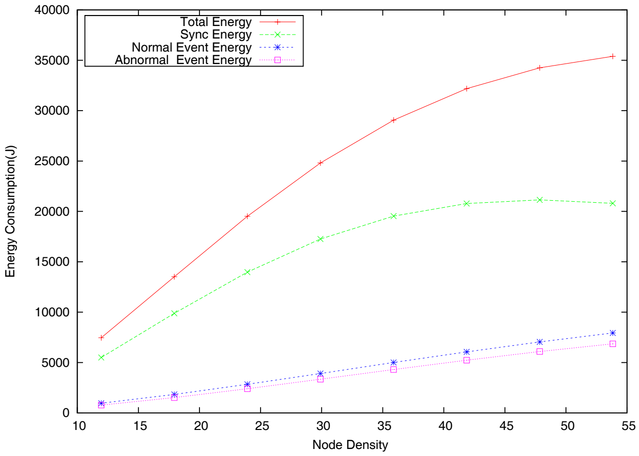

Fig. 2. The Energy demand of the network as a function of density

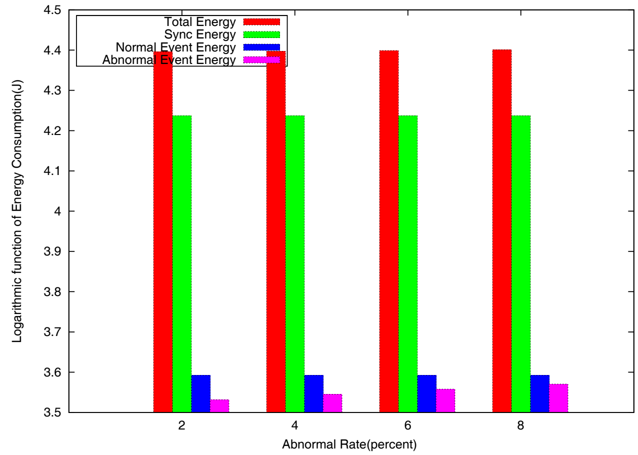

Fig. 3. The Energy demans of the network as a function of the frequency of abnormal leakage detection

one's neighbors, this depends on the node density of the network and some S-MAC synchronization settings.

5) **Sleep:** For every frame, the rest is sleeping time.

Some parameters influence the energy utilisation of the network more strongly than others. To demonstrate the degree of their influence, we have defined them as variables. These are duty cycle, frequency of schedule synchronisation, network density, the frequency of normal and abnormal interest propagation, and the average number of hops for a message to reach the sink. More precisely, schedule synchronisation consists of two components:

- Frequency of synchronisation
- Frequency of finding new neighbours

With a one-phase-pull Directed Diffusion routing protocol, interest dissemination and data propagation consists of:

- The frequency of interest propagation;
- The normal event propagation interval; and,
- The abnormal event occurrence ratio.

We computed the energy utilisation of a fully functional wireless sensor network that reflects the influence of the parameters above. The result is displayed in figure

VI. Discussion

As the density of the network increases (Figure

Synchronisation claims the most significant part of the energy budget of the sensor network. As can be seen in Figure

In our analysis, we employed the Bianchi Model[7] for computing the energy cost of time synchronisation.

The energy cost of normal and abnormal events propagation (Figure

In conclusion, our analysis provides a realistic model to determine where the bulk of the energy budget should be invested in wireless sensor network. We have learned that the energy demand of time synchronisation poses a non-trivial challenge for employing wireless sensor networks at least for toxic gas detection. In our energy model, we have not considered the energy required by the analog-to-digital (ADC)

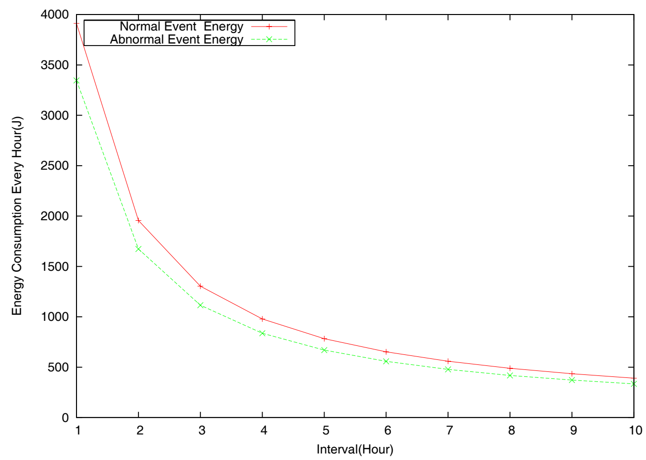

Fig. 4. The energy demand of the network as a function of the frequency of interval propagation in the network

converter to produce a high resolution senor data. In reality, the ADC consumes significant power, too. In the future, we will accommodate this fact to assess the feasibility of using existing off-the-shelf hardware in wireless sensor networks.

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