Optimal Transmission Power in Self-sustainable Sensor Networks for Pipeline Monitoring

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Abstract—In this paper, we present a self-sustainable sensor network model for integrity monitoring of pipeline infrastructures. Sensor nodes consist of energy harvesting modules which help them to be always alive and hence monitor the pipeline continuously. These nodes report in a multi-hop fashion to more expensive sink nodes that can broadcast to the base station. The main objective of the paper is to compute the minimal number of sinks required to keep the network connected and satisfy the required constraints. Firstly, we present an algorithm (CON_NET) for determining if a network is connected. We propose a modified bisection algorithm to compute the maximum sampling rate for a given number of sinks nodes. Further, we propose an algorithm for computing the minimal number of sink nodes required. We illustrate the use of algorithms by providing design guidelines for a sensor network on a linear pipeline structure.

I. INTRODUCTION

Transportation of oil, gas or other materials continuously across lands is commonly accomplished via pipelines. In highly populated areas, the pipelines are buried under the ground to alleviate the effects of leaks or breakages to their infrastructures, especially when transporting hazardous materials. In general, the effects of harsh environments, acts of nature and third-party-induced damages present an imminent danger to pipeline infrastructures. Hence it is important to continuously monitor them to prevent such infrastructural damages.

The Trans-Alaskan Pipeline System (TAPS) is one of the major oil pipelines connecting oil fields in northern Alaska to a sea port where it can be shipped to other states in the US. The TAPS is about 800 miles long running through remote terrains under severe weather conditions and passing near many Alaskan towns. Geological activities in the regions have caused considerable damages to the pipelines on many occasions. This pipeline is surveyed frequently for maintenance purposes, mostly by air. Other examples of large-scale pipelines include the Baltic Gas Interconnector whose construction is expected to be completed by 2009 and will carry natural gas between Germany, Denmark and Sweden, Trans-Afghanistan pipeline (TAP) that will carry natural gas from Turkmenistan through Afghanistan, Pakistan and India and the Iran-India gas pipeline that stretches from Iran to India via Pakistan. Goldfields Pipelines is an example of a water supply scheme that runs for 330 miles across various cities and towns in Australia.

Pipelines are often subject to vandalism, sabotage and are the target of terrorist attacks. Furthermore, the materials being carried by the pipelines can cause corrosion thus resulting in infrastructure damages. Monitoring of pipelines is often done manually and at regular intervals. Other possible approaches to control damages to the pipelines are through design specifications on wall thickness, strength, and toughness. Physical barriers can be built around pipelines to prevent external damages. These methods however will result in high construction costs and can make repair work on pipelines harder. Furthermore real-time in-service integrity monitoring of these large-scale and distributed infrastructures is currently not available [1]. Proactive real-time monitoring using miniaturized sensors to detect and prevent infrastructural damages offer a cost effective alternative [2-4]. Further we believe that large networks of self-harvesting miniature sensors are necessary to capture the underlying complexities and dynamics required for real-time diagnosis of large and critical infrastructures [4, 5].

Advances in Micro Electro Mechanical Systems (MEMS) have enabled the production of low cost and tiny wireless sensors. A large number of such sensors can be deployed on a pipeline to achieve an overall sensing objective. Different kinds of sensors such as acoustic, vibration and temperature sensors can detect wall thinning or thickness through temperature or noise measurements, leakages by analyzing real-time flow, and pressure measurements etc. In addition to sensing and collecting data, these sensors are also equipped with processing capabilities to deduce how to route the data packets through the neighbors to an Internet-connected base station or sink. The wireless sensor nodes are usually battery powered or have energy harvesting units built in them to prolong their lifetime. Due to the small sizes of such wireless
sensors, their sensing and communication capabilities are restricted to within a small neighborhood. Furthermore, the energy harvesting capabilities are also small implying that power consumption is important in prolonging the lifetime of a Wireless Sensor Network (WSN) [6].

In this paper we propose a sensor network model and study the problem of finding the optimal number of sensors and sinks required for continuous monitoring of large-scale pipeline structures. The sink nodes are either wired to a power supply or are expensive nodes that have access to unlimited power supply. The power for the sensor nodes are generated from a self-harvesting module. The sensors gather data on the vibrations induced by the flow rate. Messages from these sensor nodes are transmitted via other nodes (multi-hop) or directly to the sink. The sink nodes then transmit all the received messages to a base-station for diagnosis. The diagnosis module captures the underlying complexities inherent in the data to characterize the health of the pipeline system [4]. Transmission distances are bounded to ensure that the energy harvested is sufficient for sensors to expend energy in performing all their activities (transmitting, receiving and sensing). This will ensure that the sensor nodes are always alive and can continuously monitor the infrastructure. Further we calculate the minimum number of sinks to ensure the network is connected (all the sensor nodes can reach a sink node) given a required sampling rate. The sampling rate is required to be above a certain threshold in order to capture the necessary frequencies for diagnosis [4].

The rest of the paper is organized as follows. In section II we present the sensor network model for a pipeline configuration. Section III discusses the computation of Maximum tolerable Transmission Distance (MTD) for a sensor given the energy harvesting rate, sampling rate, data size and the number of slave nodes. In section IV we present the routing mechanism and an algorithm (CON_NET) for determining if a network is connected for a given sampling rate and data size. In section V we propose a modified bisection method which uses the CON_NET algorithm to compute the maximum sampling rate for a given number of sinks. Further we present an algorithm for calculating minimal number of sink nodes required. In section VI we present the experimental results for a linear sensor network model. We discuss how we can design the network based on the plots obtained from the above algorithms. Finally we conclude with future work in section VII.

II. SENSOR MODEL

In our model sensor nodes and sink nodes are equally spaced along the pipeline. The density of the sink nodes is smaller in comparison to the density of the sensor nodes. Fig. 1 shows the configuration of a WSN on a specific pipeline structure. Every sensor node can choose its transmission distance dynamically from the set of permissible finite power levels and route information accordingly. If the geographically closest sink is within a sensor’s transmission distance then the information is sent to the sink directly. Otherwise, the information is sent via a neighboring sensor in a multi-hop fashion to the closest sink. The sensor network can be divided into clusters of nodes, where each cluster consists of a group of sensor nodes and one sink [7-9]. Clustering is a commonly used technique to gather distributed data from a sensor network. Furthermore, it provides the sensors with a virtual architecture for routing data in a hierarchical manner to the sink and then to a centralized observer. There exists many algorithms that can determine the clusters in a WSN dynamically [7-9] based on many factors such as geographical distribution, residual energy etc. In the case of pipelines, the linear arrangement of sensors and sinks provides a natural partitioning of nodes into clusters. That is, the clusters consist of a sink which is the geographically closest to all sensor nodes within the cluster (see Fig. 2). As a result for a given sensor node, its geographically closest sink will remain the same throughout the lifetime of the WSN as will the cluster it belongs to.

A. Sensor properties

Sensor nodes consist of a sensor, power source, energy harvesting module, limited memory, transmitter and a receiver. They perform a sensing task and transmit the information in every fixed time interval. The fixed time can vary depending on the nature of sensor network application or diagnosis method. The data is sent in a multi-hop fashion via neighbors to the nearest sink. Power is consumed during the sensing, transmission and receiving processes. At the same time the energy harvesting module recharges the power-source continuously.

Fig. 1. A pictorial representation of sensors and sinks on a spatially dispersed pipeline infrastructure.

Fig. 2. A pipeline monitoring sensor network having a sink node and n sensors

\[
m > n \text{ and } n = \begin{cases} \frac{m+1}{2} & \text{if } m \text{ is odd} \\ \frac{m}{2} & \text{if } m \text{ is even} \end{cases}
\]
1) Energy consumption for communication: The following radio model is most commonly used for power consumption in a sensor [7]. To transmit a \( k \)-bit message a distance \( d \), the radio expends:

\[
E_{Tx}(k, d) = E_{Tx-elec}(k) + E_{Tx-amp}(k, d)
\]

\[
E_{Tx}(k, d) = E_{elec} \times k + E_{amp} \times k \times d^2
\]

And to receive this message, the radio expends:

\[
E_{Rx}(k) = E_{Rx-elec}(k)
\]

\[
E_{Rx}(k) = E_{elec} \times k
\]

2) Energy Consumption for Sensing: Generally, the energy consumption for sensing depends on the sampling rate. Since the size of data to be sent to a sink node is proportional to the sampling rate, we assume that a sensor spend its energy to sense \( k \)-bit data packet as follow.

\[
E_{sen}(k) = E_{Sen-elec}(k)
\]

\[
E_{sen}(k) = E_{elec} \times k
\]

3) Power generation module: We assume that the module generates a fixed amount of power per unit time \( (R_EH) \). Based on [6], 1 mW/sec can be generated from a piezoelectric sensor. In this paper, we use an integrated sensor consisting of vibration, wireless communication, and the piezoelectric sensor. The integrated sensor uses the piezoelectric sensor as its power module.

4) Transmission power: Sensors have discrete adjustable transmission power levels [10, 11]. This paper assume that each sensor has \( L \) finite power levels, \( \{P_1, P_2, ..., P_L\} \). The reachable distance with \( P_i \) is denoted by \( d_i \), \( i \in \{1, 2, ..., L\} \).

B. Sensors and sink nodes

Sensors are placed at equal distance with a density per unit distance. The density is mostly determined by a pipeline integrity diagnosis method. This paper assumes that sensors are placed uniformly over the pipeline to meet the requirement of a diagnosis method.

Also, each sensor is aware of whether other sensors are closer or farther from its sink node. For this purpose, it is not necessary for sensors to have information about the position of other sensors. By broadcasting messages in a multi-hop fashion from the sink nodes during a setup period, sensors can identify which sensors are closer to their sink nodes.

III. Maximum Tolerable Transmission Distance

To guarantee that sensors never deplete their energies, the amount of energy used for sensing, transmission, and receiving processes should be less than or equal to the amount of energy harvested during time \( T \). Let \( R_{EH} \) be the energy harvested per unit time. The amount of energy harvested in time \( T \) is \( R_{EH} \times T \). Let the sampling rate be \( S_{rate} \). The required energy for sensing task during time \( T \) is the product of the number of sensing tasks, \( S_{rate} \times T \), by the consumed energy for a sensing task, \( E_{sen}(k) \). While, in the case of transmission and receiving, the frequency of these processes on a sensor depends not only on transmission rate but also the number of slave nodes which communicate with the sink through the sensor. Let \( N_{slave} \) denote the number of slaves of sensor \( i \).

Note that slave nodes of a given sensor’s slave node are also the sensor’s slaves, because this paper considers a multi-hop communication scheme. During time \( T \), sensors transmit and receive data packets \( n_{slave} \) and \( n_{slave} + 1 \) times, respectively.

Since a sensor transmits every sensed data, the sensor uses its powers for transmission and receiving process by \( S_{rate} \times T \times E_{Rx}(k) \times (n_{slave} + 1) \) and \( S_{rate} \times T \times E_{Rx}(k) \times n_{slave} \). Given a sensor, we can build the following inequality (1) to ensure that a sensor never dies due to energy depletion.

\[
R_{EH} \times T \geq S_{rate} \times T \times E_{elec} \times k + S_{rate} \times T \times E_{elec} \times k \times n_{slave}
\]

\[
+ S_{rate} \times T \times (E_{elec} \times k + E_{amp} \times k \times d^2) \times (n_{slave} + 1)
\]

(1)

Applying \( E_{amp} = 100 \text{ pJ/bit/m}^2 \) and \( E_{elec} = 50 \text{ nJ/bit} \) [7] to Equation (1) we obtain equation (2).

\[
R_{EH} \geq S_{rate} \times k \times (n_{slave} + 1)(10^{-7} + 10^{-10} \cdot d^2)
\]

(2)

Since the energy harvesting rate, \( R_{EH} \), and the size of packet, \( k \), depends heavily on the application of sensor networks, this paper consider these two variables is given. Using Equation (3), each sensor can calculate its maximum tolerable transmission distance (MTD) so that it never dies due to energy depletion with the number of slave nodes and a sampling rate.

\[
d_{max} = \left( \frac{R_{EH} \times 10^{10}}{S_{rate} \times k \times (n_{slave} + 1) \times 10^3} \right)
\]

(3)

Fig. 3 shows the relationship among \( n_{slave} \), \( S_{rate} \), and MTD with \( k = 1000 \text{ bit} \) and \( R_{EH} = 1\text{ mW/sec} \). As \( n_{slave} \) and \( S_{rate} \) increase, MTD decreases and, conversely, high values of \( n_{slave} \) and \( S_{rate} \) incur the low of MTD. Even though sensors can calculate MTD, the MTD might not be applicable directly
since sensors only have finite power levels. Therefore, with the MTD, sensor $i$ selects its applicable MTD (a-MTD) through Equation (4).

$$J = \arg \max(d_j^i), j = \{1, 2, ..., L\}$$  \hspace{1cm} (4)

If sensor $i$ has no $j$ such that $d_j^i \leq d_{\text{max}}$, the sensor can not meet the given sampling rate. Otherwise, sensor $i$ can set its transmission power to $P_i^j$ as its a-MTD.

### IV. Connectivty of Network

Sensors that cannot communicate with one of the sink nodes directly should hire another sensor as a mediator or a next hop node to send data to a sink. To select the next hop, the sensors consider their neighboring sensors that are closer to their sink nodes and within their transmission ranges. $NE_i$ denotes the set of neighboring nodes of sensor $i$. Each sensor determines its next node through Equation (5). $S_i$ and $d_{mS}$ represent sensor $i$’s sink node and the distance between sensor $m$ and sensor $i$’s sink node respectively. $d^i_j$ is the reachable distance of sensor $i$ with transmission power $P_i^j$.

$$M = \arg \min \left\{ d^i_{mS} \mid \forall m \in \text{neighborhood of } S_i \right\}$$  \hspace{1cm} (5)

Based on Equation (5), sensor $i$ selects its sink node as the next hop node if it can reach its sink. Otherwise, sensor $i$ selects the sensor closest to its sink as the mediator.

Even though sensors in a sensor network can determine their next hop nodes and, consequently, the topology of network can also be established, it is still required that the network be connected. To guarantee connectivity, the sum of the number of sensors that can communicate with sink nodes directly and the number of slave nodes of these sensors should be equal to the number of sensors in the whole network. With $S_{\text{rate}}^{\text{given}}$, $k^{\text{given}}$ and the positions of sensors, CON_NET Algorithm builds the topology of the network and checks the connectivity of the network. The inputs of this algorithm are the number of sensors, their positions, target sampling rate, and the size of a data packet. The result of this simulation is a Boolean type. If the result is 1, the simulated network is connected. Otherwise, the network is disconnected. Fig. 4 gives a high level description of CON_NET algorithm.

### V. Search Methods for Maximum Sampling Rate and Minimum Number of Sinks

In this section, we discuss two search methods. The first search method is for maximizing the sampling rate, given the number of sensors per sink. Whereas, the second method is to determine the number of sinks to satisfy a given sampling rate.

#### A. Maximum Sampling Rate

Given a sampling rate, $S_{\text{rate}}$, each sensor has different maximum tolerable transmission power according to its location in the network and consequently, the network topologies vary with $S_{\text{rate}}$. It is difficult to model and solve a mathematical problem to maximize $S_{\text{rate}}$ because the complexity of the problem by change of network topology is too high. Thus, this paper proposes a modified bisection method using the CON_NET algorithm explained in the previous section.

**Modified Bisection Method (MBM)**

**Step 0** Let $[a_0, b_0]$ be an interval such that $\text{CON_NET}(a_0) = 1$ and $\text{CON_NET}(b_0) = 0$, and set $u = 0$.  

**Step 1** Let $x_u = (a_u + b_u)/2$.  

**Step 2a** If $\text{CON_NET}(x_u) = 0$, let $[a_{u+1}, b_{u+1}] = [a_u, x_u]$.  

**Step 2b** If $\text{CON_NET}(x_u) = 1$, let $[a_{u+1}, b_{u+1}] = [x_u, b_u]$.  

**Step 3** If $|b_u - a_{u+1}| < \varepsilon$ for a preset tolerance $\varepsilon > 0$, stop and declare $x^* \approx x_u = (b_{u+1} - a_{u+1})/2$. Otherwise, set $u = u + 1$ and goto Step 1.

To determine $a_0$ and $b_0$ where $\text{CON_NET}(a_0) = 1$ and $\text{CON_NET}(b_0) = 0$, we consider the following inequality obtained from Inequality (2).

$$S_{\text{rate}} \leq \frac{R_{EH}}{k \cdot (n_{\text{slave}} + 1) \cdot (10^{-7} + 10^{-10} \cdot d^2)}$$  \hspace{1cm} (6)

From Inequality (6), the case of a sensor having no slave node and $d_j$ as the transmission distance provides an upper bound.
for \( S_{\text{ave}} \). While, the \( S_{\text{ave}} \) of a sensor having all sensors except itself as slaves and the highest transmission power, \( d_i \), is set to the lower bound. As shown in Equation (7), \( a_0 \) and \( b_0 \) are set to \( S_{\text{upper}} \) and \( S_{\text{lower}} \). It is possible that \( \text{CON}_{\text{NET}}(a_0) = 1 \) only if the sensor network has one sensor. If \( \text{CON}_{\text{NET}}(b_0) = 0 \), there is no way to build a connected network with given specifications of sensors. Except in these two cases, \( \text{CON}_{\text{NET}}(a_0) = 0 \) and \( \text{CON}_{\text{NET}}(b_0) = 1 \) always.

\[
S_{\text{upper}} = \frac{R_{EH}}{k \cdot (10^{-7} + 10^{-10} \cdot d_i^2)} = a_0, \quad \text{and}
\]

\[
S_{\text{lower}} = \frac{R_{EH}}{k \cdot n \cdot (10^{-7} + 10^{-10} \cdot d_i^2)} = b_0
\]  

(7)

Algorithm 2 is valid when two following conditions are satisfied.

C1. If \( \text{CON}_{\text{NET}}(x_u) = 0 \) and \( x_u > x_u+1 \), \( \text{CON}_{\text{NET}}(x_u+1) = 0 \).
C2. If \( \text{CON}_{\text{NET}}(x_u) = 1 \) and \( x_u < x_u+1 \), \( \text{CON}_{\text{NET}}(x_u+1) = 1 \).

These conditions are always satisfied if the distance between two neighboring sensors is equal and the configuration of the pipeline is linear. Hence the conditions are satisfied for a linear pipeline. In rest of our analysis, we assume that the pipeline is linear in structure. This is a realistic assumption since large-scale pipelines are almost linear in structure. Even otherwise, we believe that \( \text{CON}_{\text{NET}} \) can satisfy C1 and C2 by adding few constraints on choosing the next hop nodes. Further analysis is a subject of future work.

B. Minimum number of sink nodes

We propose a simple heuristic method to determine the minimum number of sink nodes assuring a target sampling rate. Firstly, the method builds a network and checks the connectivity of the network with \( \text{CON}_{\text{NET}} \) for the target sampling rate. If the network is disconnected, the search method increase the number of sink nodes by one and repeats \( \text{CON}_{\text{NET}} \) with the target sampling rate. This process continues until the network built by \( \text{CON}_{\text{NET}} \) is connected.

Calculation of the number of Sink node

Step 0 set \( ns = 1 \)

Step 1 \( nn=ns/ns \)

Step 2a If \( \text{CON}_{\text{NET}}(S_{\text{target}}) = 1 \), stop and declare \( ns^* = ns \).

Step 2b If \( \text{CON}_{\text{NET}}(S_{\text{target}}) = 0 \), \( ns = ns + 1 \) and goto Step 1.

\( ns \) and \( nn \) denote the number of sink node and the number of sensors per sink. Through this process we can calculate the optimal number of sink nodes, \( ns^* \).

VI. EXPERIMENTAL RESULTS

To validate our approach, we consider a sensor network having \( n \) sensors and a sink node located at the right end of the sensor network on a linear pipeline (see Fig. 2). It is more efficient than a sink node located at the middle of a pipeline in terms of energy and transmission delays. However, as shown in Fig. 2, the sensor network can be considered as two sensor networks one on each side of the sink. Therefore, this section focuses on the area \( A \) that can represent the whole sensor network. Similarly, even if a sensor network has more than one sink node, we can find the area \( A \) by dividing the network by the number of sink nodes. For simulation we coded the \( \text{CON}_{\text{NET}} \) and \( \text{MBM} \) in section IV and V in JAVA programming language. In this experiment, the energy harvesting rate and the size of packet are \( 1 \) mW/sec and 1000 bit, respectively. Sensors are located every 20 meters along the pipeline. Each sensor has 5 finite transmission power levels and the reachable distance increase by 20 meters with the power level.

Table I gives the result of MBM search with a sensor network having 100 sensor nodes. From Equation (7), \( S_{\text{lower}} = 0.009001 \) and \( S_{\text{upper}} = 7.142858 \). As show in the last column of the table I, the maximum tolerable sampling rate, \( S^* \), for the given network increases with iteration. The MBM terminate the iteration when \( S^* = 0.071374 \) and \( |b_{ns}-a_n| < 0.0001 \).

Fig. 5 plots the maximum tolerable sampling rate, \( S^* \), against the number of sensors per sink. This figure can

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**TABLE I**

<table>
<thead>
<tr>
<th>Iteration (k)</th>
<th>( a_n )</th>
<th>( b_n )</th>
<th>( x_n )</th>
<th>( S^*_n )</th>
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</table>

\( *_{\varepsilon=0.0001} \)

![Fig. 5. Maximum tolerable sampling rate with the number of sensors per sink node.](image)
provide a guideline for the selection of the number of sink node. This figure can be used to select the number of sensors per sink satisfying the target sampling rate. For example, to be tolerable for $S_{\text{rate}} = 0.3$, the number of sensors per sink should be less than 23. In other words, given the size of packet and energy harvesting rate, the maximum number of sensors per sink can be calculated with this guideline.

In Fig. 6, we apply different values of two given parameters, the size of packet and energy harvesting rate, to MBM. In Fig. 6(a), the size of data packet varies from 1000 bits to 5000 bits. Fig. 6(b) plots the maximum tolerable sampling rates with two energy harvesting rates, 1 and 10 mW/sec.

VII. CONCLUSION

In this paper we discussed a sensor network model for continuous integrity monitoring of pipeline infrastructures. We studied the problem of optimal number of sensor and sink nodes. The power of the sensor nodes are generated from a self-harvesting module. Transmission distances are bounded such that the energy harvested is sufficient for all the activities of the sensor node. This will ensure that the sensor nodes are always alive and continuously monitor the pipeline. We presented an algorithm (CON_NET) to determine if a network is connected for a given sampling rate. We then proposed a MDP algorithm to compute the maximum sampling rate for a given number of sink nodes. In addition, we proposed an algorithm for calculating the minimal number of sink nodes required for a specific sampling rate. We illustrate the use of these algorithms by considering a sensor network on a linear pipeline. We provide design guidelines for choosing the optimal number sink nodes. As a part of future work, we would like to extend this analysis for pipeline structures that are not linear.

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