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Energy-efficient Linear Wireless Sensor Networks Applications in Pipelines Monitoring and Control

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Abstract: Wireless sensor networks is a field of research which is vastly spreading because of the advancement of new technologies in relatively cheap sensors. These electronic devices have been recently improved with respect to their memory size, communication networking capabilities and their processing speed. In the last few years, a new subcategory of sensor networks known as linear wireless sensor networks (LWSN) is rising as a great focus area of research. Such wireless sensor networks have a large number of applications such as border monitoring, railway track monitoring, structural health monitoring of bridges, health care and machines surveillance. This paper focus on the use of this new technology in the monitoring and protection of the essential and critical pipelines infrastructures carrying water, oil, gas and other vital resources. The paper introduces a linear wireless sensor network model that can be used to facilitate this control and monitoring functions. Besides the paper investigated a suitable model of LWSNs nodes energy consumption.

Keywords- Wireless Sensor Networks (WSN); Pipelines; Linear Wireless Sensor Network (LWSN)

1. INTRODUCTION

The rapidly growing use of linear wireless sensor networks (LWSNs) [1] in the last few years is due to the fast evolution of new technologies for cheap sensors. These electronic devices have been recently improved in terms of their communication networking capabilities, memory size, node size and processing speed [2]. All of this advantages made it possible to use them in many important applications, such as monitoring of oil and gas pipelines [3] cathodic protection remote monitoring [4][5], safety monitoring in railway transportation [6] and structural health monitoring [7].

LWSNs is a kind of remote sensor systems, which monitors linear area, such as, mines, roads and rivers. Linear area does not always means a straight region constantly, it might be strips provincial or bended lines. There are numerous benefits for utilizing this kind of systems for monitoring and protection of linear infrastructures. These systems offer less costly and faster system localization. Likewise, the savings in essential work force mastery and network maintenance. They are more reliable and offer the capacity to exhibit adaptable multi-hop steering, which can conquer the problem of nodes failure and dying nodes.

In the literature, the design of LWSNs have been recently invoked by many research teams [3-8]. Because of their specific topology and specific applications, strategies used for common sensor networks cannot be applied directly to LWSNs. Consequently, many researchers have recently focused on improving specific design issues relevant to LWSNs applications, such as, pipeline monitoring [8] and transferring water, gas and oil from one area to another in an inexpensive way.

One of the most interesting research points in LWSNs design, is to implement a large-scale pipelines monitoring. Large-scale pipelines monitoring requires an extremely scalable and reliable wireless network solution that can be heavily deployed, runs on ultra-low power for an extended period of time, and operates in the difficult environment conditions. The advantages of wireless sensor networks in remote monitoring includes reducing the need for repetitive maintenance by ensuring high reliability, reducing the need for battery replacement, surviving through difficult weather conditions, and offering coverage in harsh terrains and big spatial areas.

For reliable data gathering in LWSNs, multi-hop data communication patterns are employed [9]. In these patterns, for the sensor nodes that are remote from the sink node and cannot send data to the sink node in a single hop, data is transferred by neighbors' nodes that are closer to the sink node [9]. However, increasing the number of transmissions could quickly consume the energy of rely nodes and minimize the lifetime of LWSNs. There are many design issues related to this kind of networks including the nodes placement strategy, the network total energy minimization, and network lifetime maximization, such as network coverage, network reliability, security and fault tolerance.

In this research paper, we discuss some applications of LWSNs in oil and gas industry. For this purpose, we present a suitable framework focusing on proposing a node energy consumption model and on addressing the main design issues involved in these kinds of networks. Fortunately, pipeline applications require the wireless sensor network to be structured in a line. Using a linear network architecture improves the communication quality and reliability in the pipeline systems.

One major problem that has been addressed in this paper is the implementation of a node energy consumption model. Our goal is to find an optimal node placing strategy in order to minimize the total energy consumption of a LWSN, assuming that all of the network relying nodes have the same initial energy. To achieve this goal, we start by finding the optimal spacing between nodes with given number of nodes in the network. Next, we calculate the minimum total energy consumed by the network using the proposed optimal strategy compared to the total energy consumed by the network in case of uniform placement strategy.

The rest of this paper is organized as follows. Section Ⅱ presents different applications in oil and gas pipelines monitoring and control. Section Ⅲ outlines the proposed system model. Section Ⅳ presents the node energy consumption model. Finally section Ⅴ presents conclusions and future work

2. OIL AND GAS PIPELINES MONITORING AND CONTROL APPLICATIONS

Nowadays, most countries economy are highly dependent on their oil, water, and gas pipelines. These pipelines are very vital for the economy of most countries. Maintaining and protecting infrastructures of these pipelines is a very important demand for these countries. For example, in the United States there are around 800,000 kilometers of gas and oil pipelines [10]. Therefore, the United States economy is highly dependent on them. To monitor and control pipelines, there are various technologies that rely on the networks and sensors for sending the gathered data from outside and inside pipelines to base stations. There are a lot of technologies intended to provide a remote solution to control and monitor pipelines infrastructure. One of these technologies is wireless sensor networks which is needed for different applications related to this field. Examples of these pipeline measurements are liquid leakages, pipeline corrosion detection, pipeline protection cameras, temperature, flow, and pressure measurements. In the next paragraphs, some different applications related to this field will be introduced.

Corrosion Detection: Aging pipelines and tanks have become a big problem in the gas and oil industry [11]. The common ordinary manual techniques to monitor corrosion is extremely time consuming, unreliable, and costly. A network of special wireless sensors can be deployed to identify issues before they turn out to be fatal failures. Rohrback Cosasco Systems, one of the biggest companies in corrosion monitoring services and products for different type industries, aims to meet the advances in critical infrastructure needs with the SmartMesh® WirelessHART Microcor Wireless Transmitter (MWT) [12], which allows fast corrosion rate data communication, maximizing overall asset life and providing a great view with respect to potential environmental troubles caused by corrosion.

Leak Detection in Underground Pipelines: Leakage detection technologies have been growing very fast in the last two decades because they offer economic savings, fluid shortage reduction, improving consumption and reducing pipeline network damages [13]. Leakage can be detected by identifying material drip out at certain place. In some cases, leakage may be observed, but the location is not known because of wide distribution of pipe network. The probability of the system corruption becomes higher as the system becomes wider, so maintaining the system continuously guarantees a perfect and safe system. The primary purpose of Leakage Detection Systems (LDS Systems) is to assist pipeline controllers in detecting and localizing leaks. LDS Systems are important aspects of pipeline technology. There are four basic activities for leakage reduction and their pressure management, active leak control, speed and quality repairs, maintenance and renewal of the pipeline [14]. Underground wired network for communication suffers from damages and it is very costly. Wireless networks, on the other hand, are much more robust and efficient. It also provides flexibility and simple system deployment, but underground wireless communications have yet to be developed and realized. However, wired base communication can be used for information transmission for long distance for reaching remote administration nodes [15].

3. SYSTEM MODEL

In this section, LWSN system model is introduced. The proposed model depends on taking measurements only at each sensor node without any correlation between the data collected and the inter-node distance considering both the transmission and receiving power for each sensor node [16][17]

Consider a linear wireless sensor network, consisting of a group of wireless sensor nodes (X_i) localized along a narrow and long area with sink node (S_n) at the end, as shown in Figure 1. The distance between X_i and X_{i-1} is d_i, and L is the total length of the network. So ($\sum_{i=1}^{n} d_i = L$), to ensure the coverage note that $d_i \leq D_{max}$ for all i. Table 1 summarizes the mathematical notations used in this paper. Below, the basic design issues of our system model will be illustrated.

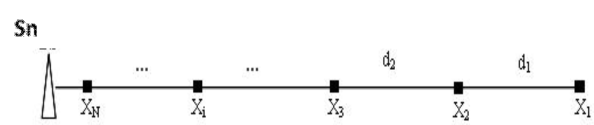

Figure 1. Network model

Table 1. Mathematical notations used in paper

Parameter	Symbol	Parameter	Symbol
Data stream collected	R	Network length	L
Distance between nodes	d_i	Node index	i
Maximum node coverage area	D_{max}	Energy consumed in data transmission	E_{send}
Path loss exponent	K	Energy consumed in data reception	$E_{receive}$
Number of nodes	N	Characteristic distance	d_{char}
Node initial energy	E_o	Energy dissipated in the transmit amplifier in free space model	$\varepsilon_{amp}(fs)$
Network lifetime	T	Energy dissipated in the transmit amplifier in multipath model	$\varepsilon_{amp}(mp)$

Sink node: In the adopted model, the sink nodes communicate to the central base station using a long distance communication techniques, such as, satellite, GSM/GPRS and HSDPA. Therefore, it consumes more energy than any other rely mode in the network so it must have a fixed and stable power source. Because of the great importance of the sink node as it carries the whole network data, the network must have a hot stand by redundant sink nodes in case of main sink node failure.

Power source: one of the most important parameters to be considered in the design of LWSNs is the nodes power source, the most common ways of powering this kind of networks is battery powered nodes which are controlled by the routing protocol to minimize its awaken time in order to extend node lifetime, the other method is to use solar cells with battery packs to ensures a long lifetime work with a more flexible design, longer distances and more data rate to handle.

Routing protocol: One of the most important design parameters in sensor networks is routing. Different routing protocols have been presented for different applications and topologies in LWSNs. Other parameters like energy efficiency and network lifetime are highly dependent on the routing protocol. For example, Performance and Usage Aware Routing (PUAR) protocol for monitoring of tunnel has been discussed in [18]. PUAR is suitable for the sensor networks having linear and long structure. PUAR focus on some factors based on the linear and long infrastructure including quality of service, global or local energy balance, and energy efficiency and then integrates them to formulate the best framework in PUAR.

Nodes placement strategy: The information activity in linear wireless sensor networks is not uniformly distributed over the network nodes. Relay nodes closer to the sink nodes have data load more than the other remote rely nodes, since they gather data within their coverage area and the collected information from other nodes as well. Such an uneven data load leads to an unbalanced energy consumption pattern among the network nodes. Since the power consumption and data load at each node is directly affected by the nodes position, rely nodes with more data load have more energy consumption and as a result die quicker. Thus, relay nodes position procedure will greatly affect the system operation time. Considering the waste of effort, cost and time of replacing the battery after installing the sensor nodes along the network, so it is very important to efficiently handle their power consumption to achieve the maximum network lifetime.

Reliability: In common sensor networks, sinks can be contacted through multiple routes which increases the reliability of the network. On the other hand, in LWSNs, the number of possible routes are limited. If failure happened in a group of neighbored nodes in a LWSNs, gapes may be created and the network is broken down. Therefore, the nodes in one section may not be able to reach the nodes in other section. Hence, sensor nodes which are positioned between gapes may not be able to send their data. This problem minimizes the network's sensing area. In [19][20] reliability analysis for LWSNs has been discussed to improve the network reliability.

Network security: Security is a very important parameter in wireless sensor network applications. Because of the linear structure of LWSN's it has some unique issues. Therefore, the security strategies used in common networks cannot be applied directly to LWSNs. In [21], some targets of a sensor network security have been considered, some of the targets are; entity authentication which authenticates the base-station/user/node is indeed the entity to which it claims to be. Availability guarantees desired service may be available whenever required, and Integrity guarantees that data has not been changed by foreign nodes. Access control: prohibits access to resources to privileged entities.

Nowadays, many wireless sensor technologies have been presented for many applications. The selection of one technology over another is determined by the application's power consumption, security features, usability, surrounding environment, availability and other factors. In this paper, any selected wireless sensor technology can be applied as the network nodes. But these nodes should be able to meet most of the following specifications; support for different data rates, low power consumption, support for various network topologies, support for standard based protocols, support for various transmission distances, cost effective, support for mesh networking and to support both non-line of sight and line of sight RF communication.

Referring to [22] we can conclude that Zigbee is designed as a low cost, low complexity, low data rate and low power consumption wireless communication standard. Zigbee can be considered as the best available sensor MAC technology for this network since it meets most of the required specifications.

4. ENERGY CONSUMPTION MODEL

It has been noticed that the energy consumed in communication is usually an important component of the network total energy consumption.. E_{send} refers to the energy consumed to send data, and $E_{receive}$ refers to the energy consumed to receive the data. For a sensor node to send R bit-data packet over a distance d, the transmitter dissipated energy is

$$E_{send} = R*E_{elec} + R*\varepsilon_{amp}\, d^k \qquad (1)$$

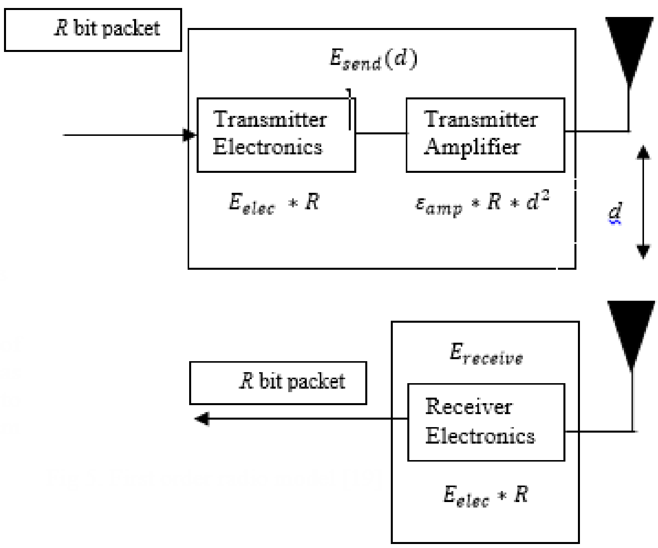

Figure 2. First order radio model

Where E_{elec} is the energy per bit consumed in the transmitter or receiver circuit, and ε_{amp} accounts for the energy dissipated in the transmit amplifier.

$$E_{send} = \begin{cases} R * E_{elec} + R * \varepsilon_{fs}\, d^k, & d < d_{char} \\ R * E_{elec} + R * \varepsilon_{mp}\, d^k, & d \geq d_{char} \end{cases} \qquad (2)$$

The distance d_{char}, called the characteristic distance is the boundary separating the two power consumption modes the free space mode and multipath mode and it's given by,

$$d_{char} = \sqrt[k]{\frac{\varepsilon_{fs}}{\varepsilon_{mp}\,(k-1)}} \qquad (3)$$

The energy needed to receive 1 bit-data packet is

$$E_{receive} = E_{elec} \qquad (4)$$

The path loss exponent k normally ranges from 2 to 6 [23]; when the propagation happens between transmitter and receiver in free space it is closer to 2 and in some environments, such as stadiums, buildings, and other indoor environments, the path loss exponent can go up to 6. In this research, we are using LWSNs in oil and gas pipelines monitoring applications assuming that these pipelines located in dense urban areas. So we will assume k= 4.

According to various channel models, long distance communication is highly penalized, because the total energy consumed over several short distances is much less than energy consumption over a long distance as shown in equation (5).

$$\left(\sum_{i=1}^{N} d_i\right)^k >> \sum_{i=1}^{N} d_i^k \qquad (5)$$

In this work, a simple model is assumed where the radio dissipates E_{elec} = 50 nJ/bit to run the transmitter or receiver circuitry and ε_{amp} (free space) = 100 nJ/bit/m^2, ε_{amp} (multipath) = 0.001 pJ/bit/m^4 for the transmit amplifier to achieve an acceptable $\frac{Eb}{No}$, R= 1 bit, from equation (3), we can obtain that the threshold d_{char} is equal to 76 m.

5. ENERGY-EFFICIENT NODE PLACEMENT SCHEME

The objective is to minimize the total energy consumption given the constraint $\sum_{i=1}^{n} d_i$ = L and number of sensor nodes n, we have to determine the optimum node spacing {di}, i =1: n; to minimize the objective given in Eq. (6). Under the constraint of Eq. (7)

$$E_{total} = \sum_{i=1}^{n}\left(\left(E_{elec} + \varepsilon_{amp}\, d_i^{\,4}\right)\sum_{j=1}^{i} R_j + E_{elec}\sum_{j=1}^{i-1} R_j\right) \qquad (6)$$

$$\sum_{i=1}^{n} d_i = L \qquad (7)$$

The network lifetime (T) is described as the duration of time starting from the network initialization to the time when all network nodes die. For the equal space placing, nodes closer to the sink have more data loads and run out of energy quicker because it consumes more power, and thus leads to the minimization of the network lifetime.

By using the Lagrange multiplier strategy, assuming that each node gather the same amount of information, we have one more constraint R1 = R2 = ... = Rn, so the optimal solution of di can be represented as the following:

$$d_i = \frac{L}{\sqrt[3]{i} * \sum_{i=1}^{n} \sqrt[3]{\frac{1}{i}}}, \quad 1 \leq i \leq n \qquad (8)$$

Eq. (8) is the node spacing for node (i) to minimize total network energy consumption with given node number n. The value di in this strategy is only chosen by the information gathered by node Ri, the monitor region length L and the path loss exponent k.

6. NUMERICAL RESULTS AND EVALUATIONS

The evaluation of the efficiency of the suggested optimal sensor placement scheme using MATLAB® software is presented in this section assuming that L=500, k=4, E_o=1.

Figure. 3 compares the consumed energy of the optimal placement scheme and the equal distance placing. The total energy consumed by the network increases with more sensor nodes forwarding the data. The results prove that the optimal scheme is significantly improved than the equal distance placement in terms of the total energy consumed. It is observed that when n =20, the total energy consumption of the uniform placement is 0.0082 and the total energy consumption of the optimal strategy is 0.0058, the network consumes almost 70% less total energy using the optimal placement scheme than the uniform placement scheme.

It is also noticed that increasing the number of nodes will increase the total energy consumption of the network and the maximum number of nodes in the network is only dependent on the total cost of the network which limits the number of nodes allowed to be deployed over the network (In the simulation, it is assumed that the maximum number of nodes is 30). The minimum number of nodes in the network if we used uniform placement strategy and optimal strategy will equal the total length of the network divided by the node maximum coverage distance (L / D_{max}) which equal 7 nodes in the presented case.

Figure. 4 shows the effect of changing the number of nodes on the distance between nodes. The nodes in-between distances changed with different number of nodes n deployed along the network using optimal placing scheme. Distance d is inversely proportional to the number of nodes in network. When n is small, the calculated distance highly changes; when n is large curves are smoother. We draw a horizontal line when distance equals to D_{max}. It intersects the curve at the point when n=11. To guarantee effective communication between nodes distance d must be less than D_{max}. So when the length of network is 500 meters at least 11 nodes must be deployed along the network.

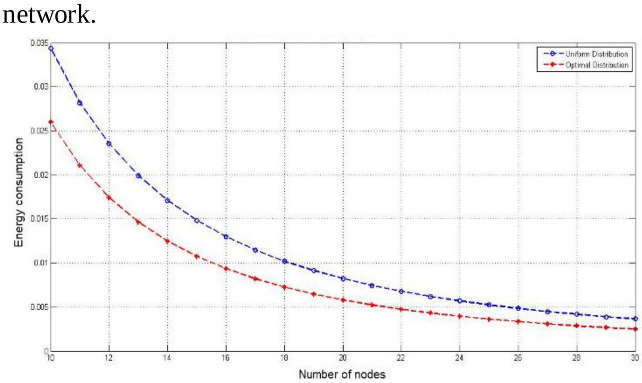

Figure 3. Total energy consumption comparison

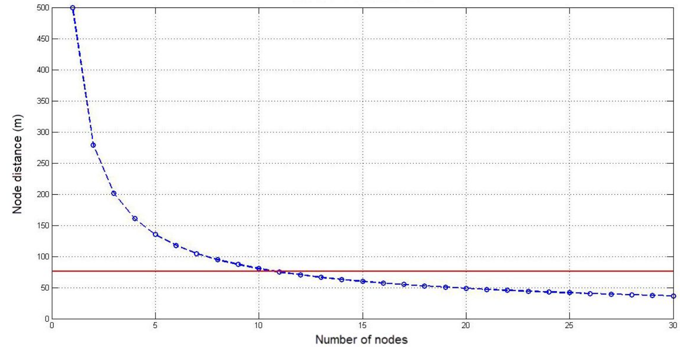

Figure 4. Distance d of different number of nodes for length of network L=500m

7. CONCLUSIONS AND FUTUREWORK

In this paper, the potential applications of wireless sensor networks especially LWSNs in monitoring and the control of pipeline infrastructure are investigated. The paper introduces a suitable framework for LWSNs explaining its important design issues that should be considered in different applications. In addition, a suitable node energy consumption model is investigated. Using the strategy of minimal total energy consumption, this research presents an energy-proficient nodes arrangement strategy, where the optimum node number and nodes distance are calculated. Contrasted with the uniform placement strategy, the suggested strategy clearly extends the network lifetime and also minimizes the total energy consumption. This paper will help in designing application-specific frameworks, protocols and models and will help in increasing the efficiency of linear wireless sensor network.

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