Review on the Use of Wireless Sensor Network Systems for Oil Pipeline Surveillance

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Abstract- The use of integrated Wireless Sensor Networks (WSNs) for oil pipeline monitoring activities by concerned stakeholders in the oil and gas industry has become commonplace. One of the many challenges of oil pipeline distribution system in Nigeria, and indeed in many other countries, is the issue of accurate localization of bursts and leakages. These leakages may be attributed to intentional vandalism of pipelines by oil thieves and criminals, corrosion, pipeline integrity compromise during physical activities like excavations, or even due to ageing and fast decaying. WSN systems have been found to be very useful and effective in the management of pipeline bursts and leakages. Low-power, low-cost and smart WSNs capable of robust and reliable multi-hop communications are standardized in the IEEE 802.15.4 specification. This paper takes a cursory look at the various attempts made by researches to utilize the WSN technology to address the above challenge. Some of these works include MISE-PIPE, PIPENET, Raspberry Pi and Arduino-based WSN system, Acoustic Sensor-based WSNs, and SCADA. However, although these solutions have achieved milestones in addressing the problem, they have been found to have limitations such as inefficiency, frequency or bandwidth issues, monitoring not being real-time, and inability to locate exact point of leakage.

Key words: *WSN, pipelines, surveillance, leak detection, vandalism, localization.*

A. INTRODUCTION

In countries that have deposits of oil and gas resources, and do make use of transmission pipelines for oil and gas distribution, it is desired that the security and overall integrity of such pipelines should have the minimum possible degradation or outright disruption. This is because for such oil producing countries, these transmission networks form an important part of the national energy-transportation infrastructure, which in turn is vital to the stability and growth of the national economy (Imad, Nader, & Khalid, 2007). The situation becomes even more critical for countries that have large deposits of this so-called black gold, and whose economy is largely oil-based, an example of which is Nigeria. Since these transmission pipelines are operated at high pressure, pipeline failure would inadvertently cause severe damage to human health and property, interruption of gas or oil supplies, and consequently economic downturn.

Crude oil exploration is embarked upon by specialists/experts in order to extract huge deposits of the natural resource embedded beneath the earth surfaces. The term crude oil refers to combustible mixture of hydrocarbons and other organic materials naturally occurring in the earth crust. It is usually refined into different usable types of fuel such as gasoline, diesel, kerosene and other petrochemicals. Oil exploration is a lucrative business in Nigeria, especially in the South-South region of the country. However, it comes with inevitable harmful health implications, which in most cases may lead to great public health concerns.

Crude oil spills which often contain appreciable amount of heavy metals result in the bioaccumulation of heavy metals in the surviving food crops (Ordinioha, & Brisibe, 2013). Severe exposure to these can cause acute renal failure (Otaigbe & Adesina, 2020). Mercury is known to be one of the highest toxic pollutants in the environment (Arif, et al, 2015) and is also among the highly bio-concentrated metals in human food chain. When mercury is emitted in significant amounts from the earth crust during oil exploration, it is deposited on the earth surfaces. It then finds its way to plants grown on the soil and when eaten can pose a great danger to humans. The organic form of mercury found in crude oil is very hazardous and has been classified by the Environmental Protection Agency (EPA) as possible human carcinogen (Ravichandran, 2011).

It is against this background that researchers around the world have attempted to tackle through various means, this hydra-headed challenge of disruption of oil and gas transmission and the consequent oil spillage, either occasioned by natural bursts and leakages, due to ageing or even third party invasions during excavations, or intentional vandalization of pipelines by criminal elements. In practice, the Nigerian National Petroleum Corporation, NNPC, for example, safeguards the oil pipelines and installations through the police anti-pipelines task force, the Nigeria Security and Civil Defence Corps (NSCDC), private security providers such as Chukan Security Solutions Limited and members of the neighbourhood watch groups. One of the most recent trends in the use of technology for this purpose is the design and deployment of Wireless Sensor Network systems to carry out surveillance on these pipelines, which in turn promotes the security of such infrastructure of national and even international economic importance.

A. THE WIRED SENSOR NETWORK

Currently, some pipeline sensors are connected using wired networks. Wired networks consist of either copper or fibre optic cables. There are many research projects with different levels of success regarding the use of fibre optics in maintaining the integrity of pipeline infrastructure (Li, Li & Song, 2004). The wired networks are usually connected to regular sensor devices that continuously measure specific attributes of fluid flow such as flow rate, pressure, temperature, sound, vibration, motion, and other important attributes. A vast amount of literature and research exists regarding the use of acoustic or vibration measurements for pipeline monitoring (Gao, et al, 2005). The transfer of electrical power to different parts of the pipeline system to activate the sensors and communication devices is a secondary responsibility of the wires, and not just signal communications. Power for the pipeline resources and networks can be provided by different sources such as through *Solar Energy* in which case arrays of solar cells can be used to generate electric power for the pipeline infrastructure. This power is supplied to the different communication and sensor devices. While this option is suitable for aboveground pipelines, it is not applicable for underground pipelines. Another source of power is the *Pipeline Flow Energy*. In this case, electric power can be generated using turbines embedded throughout the pipeline. These turbines rotate under the pressure of the fluid moving through the pipelines and generate electric power. This can be used for the different sensor and communication devices installed along the pipeline. In addition, there is also the possibility of generating power from *external sources* such as external gas-based power generators or third-party power generators.

Wired networks are regarded as the traditional way of communication in pipeline systems. They are easy to install and provide power supply through the network wires. However, there are a number of reliability problems associated with the use of wired sensor networks for monitoring pipelines. For instance, any damage in any part of the wires of the network, would lead to a total or partial damage of the pipeline sensor communication system, depending on the topology adopted. If the communication is done in one direction on the wire, then a single cut on the wire will disconnect all the nodes after the cut from the Network Control Centre, NCC. However, if there are two or more cuts in the network, then all nodes between the cuts will not be able to communicate with either of the NCC. In addition, if there is a power outage, some of the nodes may not be able to operate. One possible solution to the challenge of poor reliability of a wired network is to use multiple networks that expand through the whole area. One of these networks will be used as primary while others are kept as backup.

B. THE WIRELESS SENSOR NETWORK, WSN

A WSN is made up of wireless sensor nodes, which are small low-powered devices that have limited processing and computing resources and are inexpensive compared to traditional sensors (Callaway, 2003). A WSN system does not require the detailed electrical wiring infrastructure often associated with common motoring systems. Nonetheless, the issues of lower speeds and higher latency are unavoidable. These can be attributed to the wireless interfaces that characterize such systems. Nowadays, WSNs have become a popular approach in research due to the advances in processing power of single-board micro-computers in addition to the reduced power consumption of embedded devices. A wireless sensor network may be designed and configured in such a way that it could have different topologies and structures. Some pipelines are classified as over-ground while others are underground. It is known that the radio frequency, RF transmission range in soil is significantly lower than in air. Consequently, communication between nodes is much more limited in such systems. This imposes limitations on routing protocols and the overall structure of the underground WSN. Moreover, the topology of the network is restricted by the topology of the pipeline.

A typical underground WSN designed for pipeline surveillance is shown in figure 1 (Sadeghioon, et al, 2014). It is made up of sensor nodes which communicate with both nodes in front and behind itself through RF signals. For every 4 to 5 nodes (up to maximum of 10 nodes) there is a master node which has the capability to communicate with the sensor nodes via RF transmission. In addition, these master nodes connect to the Internet and transmit the received data from the nodes to the cloud. Data in the cloud can then be accessed via different devices with Internet connectivity.

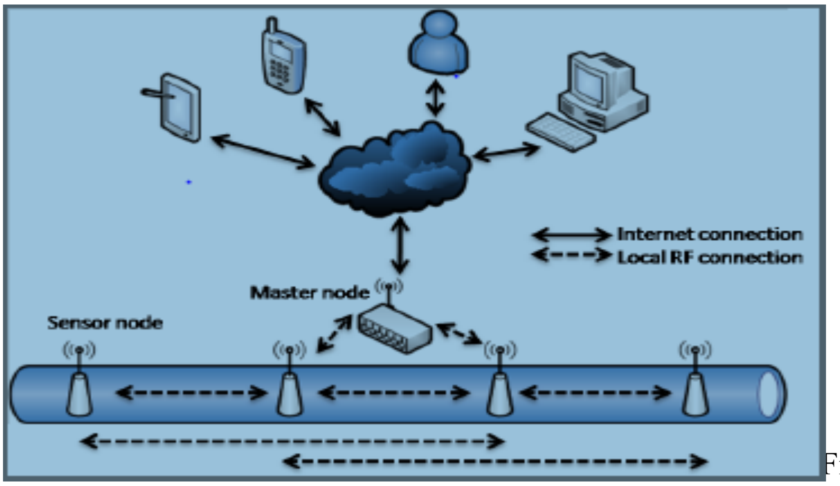

Figure 1: Generic schematic of a Wireless Sensor Network architecture for pipeline monitoring (Sadeghioon, et al, 2014).

C. REVIEW OF SOME EXISTING SOLUTIONS

a. *MISE PIPE*

There is a new solution, the magnetic induction (MI)-based wireless sensor network for underground pipeline monitoring (MISE-PIPE), introduced to provide low-cost and real-time leakage detection and localization for underground pipelines. MISE-PIPE detects and localizes leakages by jointly utilizing the measurements of different types of sensors that are located both inside and around the underground pipelines. By adopting a Magnetic Induction waveguide technique, the measurements of different types of the sensors throughout the pipeline network can be reported to the administration center in real-time.

MISE PIPE Research challenges

Based on the system architecture and operational framework of MISE-PIPE, there are some research challenges requiring further investigations. To accurately detect and localize the pipeline leakages, it is important to ensure that the adjacent soil property sensors are not deployed too far from each other. Also, the first-phase leakage detection carried out by means of the transient-based approach in the MISEPIPE operational framework depends on the number and locations of the inside pressure sensors (Kapelan, et al, 2003). Again, different types of devices such as MI transceivers and relay coils, pressure sensors and acoustic sensors located inside of pipelines, as well as aboveground gateways are generally characterized by different cost and deployment/maintenance complexity. Thus, an optimal deployment strategy is required to determine the number and locations of different devices.

Furthermore, MISE-PIPE is designed to fetch information from multiple sources including the soil property measurements, acoustic vibration measurements, and the flow pressure measurements to make decisions regarding exact leakage detection locations. Specifically, in phase 3 of the MISE-PIPE operational framework, the soil property measurements taken from all the sensors along the points in the pipeline suspected to be having leaks, as well as the inside flow pressure measurements and the acoustic vibration measurements at the two ends of those pipelines, are made available at the hubs for processing. Some low-complexity communication protocols are desired for extended lifetime and high system efficiency in the distributed networks. This is attributed to the limited power and computation capacity of the underground soil property sensors. In addition, there is a limitation in the bandwidth of the MI channel and there is need for in-network data processing. Moreover a maintenance strategy based on inductive charging was adopted in order to further prolong the system lifetime of MISE-PIPE. Inductive charging makes use of magnetic field to transfer energy from one object to another. In MISE-PIPE, the communications between underground soil property sensors are accomplished by magnetic induction.

b. ***ACOUSTIC SENSOR-BASED NETWORKS***

A sensor network is composed of a large number of geographically distributed sensor nodes (Myles, 2011). Though each sensor is characterized by low power constraint and limited computation and communication capacities, potentially powerful networks can be constructed to accomplish various high level tasks via sensor cooperation, such as distributed estimation, distributed detection, and target localization and tracking. Data processing using acoustic sensors distributed along the pipelines differs substantially from conventional centralized processing methods. In conventional data processing, all the sensors transmit their measurements at every time step to the central unit for final processing. However, there are two main reasons why centralized processing is not preferred for pipeline monitoring. Operational pipelines are subject to complex, often highly non-linear, and localized temporal and spatial processes. Hence we want to perform some local processing to collect information in the neighborhood of localized defects. Moreover, the central node needs to handle matrix operations that increase in size as the number of sensors increases. The sensors should be made to shoulder some of the computational burden. Therefore, data processing by sensor networks requires integrated methods and methodologies including conventional distributed systems, distributed control, distributed estimation and detection, distributed statistical signal processing (López-higuera, et al, 2011). The basic approach by the authors was to develop a general framework based on a ubiquitous network of acoustic sensors and controllers that provides continuous monitoring and inspection of pipeline defects. In the study under review, although the problem is complex, the authors focused on using signal processing techniques to detect, analyze, and locate pipeline defects.

Acoustic Signal Detection

The discrimination between noise and signals (from defects) is essential for pipeline monitoring. The operational environment of a pipeline is usually very noisy. A noise analysis must be conducted to characterize the frequency bands of noise at different sections of a pipeline. The authors applied denoising procedures to reduce or remove electronic and other noise that contaminate the signature signals from pipeline defects. The denoising techniques including bandpass filtering and more sophisticated wavelet based filtering reduce the noise level in the received acoustic signals. Signals generated by acoustic sensors that propagate along the pipeline can be used to infer defects. For pipelines that do not contain defects, their propagation characteristics can be calculated from modeling.

When defects, for example, corrosions occur, the acoustic signals may reflect and scatter due to the defects. Hence, the received signals differ from those propagating in the normal condition. The researchers used simple discrimination techniques such as signal cross-correlation to discriminate defects. They discovered that the cross-correlation of signals originating from similar parts of a structure shows a high correlation. Based on detailed knowledge of the structure, certain regions can be monitored directly by storing in memory the values of cross correlation between the actually recorded signal and a reference signal, yielding a simple map of signal similarities. Detection of burst signals caused by accidental heavy equipment impact is challenging. This is because burst signals can be very short in duration and may also be much lower in amplitude than the normal background acoustic signals. In order to detect third party damage signals, it becomes necessary to continually compare new acoustic signals to the background acoustic signal at that location. Fourier transform analysis is a power tool to achieve this goal. Fourier transform provides the synchronized signal characteristics required to properly remove background signal characteristics from new acoustic signals so that unique frequency variations caused by pipeline impacts can be revealed.

c. PIPE NET

In this section, we describe PipeNet, a system based on wireless sensor networks which aims to detect bursts and leaks, and also localize and quantify them as well as other anomalies in transmission pipelines. Some of the challenges include blockages or malfunctioning control valves. PipeNet was developed in various stages. The goal of such a system is to monitor a complicated challenge characterized by associated multipl3e variables. This is why such systems are difficult to design and build. The developers of PipeNet first carried out an evaluation of some of the critical components of PipeNet through a real deployment and eventually developed some algorithms for detecting and localizing with some degree of precision, the exact point of leaks. These were tested under laboratory conditions during the second stage of their work.

Thus, PipeNet provides a novel system based on Intel Motes that takes care of the drawbacks inherent in previous attempts of past researches. Some of the new approaches it adopts is that it performs remote monitoring on almost a real-time basis. It is also characterized by variable sampling rate and prolonged battery life. PipeNet also supports high data rate and time-synchronized collection of data from multiple locations. On the other hand, current data acquisition technique within the monitoring systems industry relies mainly on portable loggers and a few remote monitoring stations with low-duty cycle. The disadvantage of such remote monitoring stations is that they do not have high data rate acquisition capabilities, or even local processing or high-bandwidth transmission.

d. SCADA

Oil pipeline Supervisory Control and Data Acquisition (SCADA) systems monitor and help control pipes transporting both crude and refined petroleum products. Typical SCADA system architectures focus on centralized data collection and control. The oil pipeline SCADA has several hundred remote terminal units (RTUs) (Ravichandran, 2011). that are connected to field instruments that measure pressure, temperature, and rate of flow of the oil flowing through the pipes, as well as change the statuses of valves and pumps along the pipeline. The RTU's communicate with a central master station using communication links such as satellite, cable, cellular, or fiber optic transmission media. A typical installation has several hundred RTUs communicating over dedicated links to a central master station (Ravichandran, 2011). SCADA systems are designed to provide real-time security status of the entire pipeline so that the human agents monitoring the central information may take necessary action.

The entire operation of the SCADA system is dependent on the network that connects the RTUs with the master. Oil pipeline SCADA systems communicate over several hundreds to thousands of miles and therefore need wide-area networking or the Internet to support their operations (Ravichandran, 2011). Even though basic authentication mechanisms exist, security in oil pipeline SCADA systems are almost exclusively related to network security and several recent security breaches (Ravichandran, 2011) have occurred through the network. Therefore, security is a major challenge in using SCADA for pipeline monitoring. Another major drawback of typical SCADA systems is their inflexible, static architecture, which largely limits their interoperability with other systems. A third drawback of the current SCADA systems is their limited extensibility to new applications. The rigid design of current RTUs makes it hard to extend the SCADA from one application to another.

D. CHALLENGES OF LONG DISTANCE PIPELINE MONITORING

A. Challenges associated with Communication protocols

The first challenge for WSN with a long distance linear topology is the development of energy efficient communication protocols for the sensor nodes to communicate with each other and also with the data sink of the wireless sensor network. The radio communications between sensor nodes are limited by directional transmissions along the path of sensor node network distribution. This is attributed to the unique linear topology in use. These protocols will determine when the radio communications should be activated based on a minimum energy principle and how the sensor nodes should coordinate the data transmission that takes place within the local vicinity and with the distant data sink that would enable the sensor networks to maximize their lifetime while minimizing the overall deployment cost. This is the target of an efficient system.

B. Challenges associated with Routing

Ensuring a routing protocol that is sufficiently energy-efficient is another major nut to crack for long distance linear topology WSN. This is due to the fact that the two-dimensional routing protocols that exist in the literature as stipulated in (Myles, 2011) perform their route discovery and maintenance routines using different strategies. Some of these strategies include flooding, and also multi-dimensional propagation of request messages from the source node to the destination node. Flooding process is costly in that it uses important resources, which are scarce in the wireless environment such as the energy that is on-board, the system, the processing capacity of the node and storage capacity. In addition, it causes delay in path acquisition as well as maintenance. However, routing protocols that are designed for linear sensor networks will not need to use such a costly process for route discovery. In fact, they can exploit the linearity of the network to possibly eliminate or drastically reduce the route discovery process. For example, an addressing scheme can be used in order to perform the routing without the need for route discovery. In addition, route maintenance can be configured to take place automatically at the intermediate nodes by using the processed data in the node addresses to glide over node failures.

C. Challenges associated with Localization

There are a number of applications of wireless sensor networks that require that sensor nodes become aware of their either absolute or relative locations (with respect to other nodes). This very important location information can be used to accomplish both application specific tasks and networking functions very well. As an instance, a sensor node operating in a monitoring system is typically required not only to transmit report that an event of interest has occurred but is also required to report the location of the event. Consequently, the node must be capable of automatically calculating and estimating its current position. This process of estimating these locations in some spatial coordinate systems is referred to as localization (Khulief, et al, 2012). Localization (or position estimation) in sensor networks is necessary in order to support location aware applications, and other important system operations such as object tracking, location based routing, coverage management and collaborative signal processing.

E. CONCLUSION

This work centred on highlighting some of the attempts at proffering solutions to the challenge of accurate localization of bursts and leakages in pipelines using wireless sensor networks, WSNS. WSN systems have been found to be very useful and effective in the management of pipeline bursts and leakages. Low-power, low-cost and smart WSNs capable of robust and reliable multi-hop communications are standardized in the IEEE 802.15.4 specification. However, although these solutions have achieved milestones in addressing the problem, they have been found to have limitations such as inefficiency, frequency or bandwidth issues, monitoring not being real-time, and inability to locate exact point of leakage. More work therefore needs to be done to address the highlighted bottlenecks.

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