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Wireless Sensor Networks for Long Distance Pipeline Monitoring

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***Abstract*—**The main goal of this seminal paper is to introduce the application of Wireless Sensor Networks (WSN) in long distance infrastructure monitoring (in particular in pipeline infrastructure monitoring) – one of the on-going research projects by the Wireless Communication Research Group at the department of Electronic and Computer Engineering, Nnamdi Azikiwe University, Awka. The current sensor network architectures for monitoring long distance pipeline infrastructures are previewed. These are wired sensor networks, RF wireless sensor networks, integrated wired and wireless sensor networks. The reliability of these architectures is discussed. Three reliability factors are used to compare the architectures in terms of network connectivity, continuity of power supply for the network, and the maintainability of the network. The constraints and challenges of wireless sensor networks for monitoring and protecting long distance pipeline infrastructure are discussed.

***Keywords*—**Connectivity, maintainability, reliability, wireless sensor network**s.**

I. Introduction

EXTENSIVE network of pipelines carrying oil and gas is an integral part of many countries' energy management plan. Nigeria presently has a total network of about 5,000 kilometers of oil pipelines, consisting of 4,315 km of multi-product pipelines and 666 km of crude-oil pipelines [1]. These pipelines criss-cross the country and inter-link the twenty two petroleum storage depots strategically dispersed across the country; including the refineries at Port Harcourt, Kaduna and Warri, the off-shore terminals at Escravos and Bonny, and the four jetties at Okrika, Atlas Cove, Warri and Calabar. For reasons of safety and security, these pipelines are buried about one metre beneath the surface along a 25-metre wide Right of Way (ROW), specifically acquired by Government for the purpose [2].

These pipeline infrastructures face several types of pressures or threats which can be classified into planned and unplanned. Planed threat can be as a result of illegal activities or terrorism. Crude oil and petroleum products Pipelines in Nigeria for instance are principally at risk of illegal bunkering and vandals.

Petroleum products theft is a particularly serious problem in Nigeria, both as a result of the lost revenue from the stolen commodity, as well as expensive theft-related down time and repairs to equipment.

Lost revenue from petroleum products being siphoned off can reach millions of dollars per year; ruptured pipelines cause disruptions that likewise prove extraordinarily expensive. Between 2001 and 2010 Nigeria losses USD 7billion per year to crude oil theft and no fewer than 2,550 people have lost their life due to fire incidence resulting from illegal oil bunkering activities; while over 35,000 barrels of crude oil have been spilled into the environment within this period [3]. This has led to degradation of environment and contamination of water wells. This poses serious challenges to aquatic life.

Moreover, unplanned threats due to natural disaster, corrosions, cracking, and process upsets, usually causes pipeline leakages which may result to large economic loss, combined with environmental pollution or risk of personnel injuries.

Thus, the security and maintenance of these pipeline infrastructures is one of the major concerns of the government of this country.

This paper discusses different sensor network architectures for monitoring long distance pipeline infrastructures. These are wired sensor networks, RF wireless sensor networks, integrated wired and wireless sensor networks, and integrated wired. The paper also compares and discusses the reliability of these architectures. Three reliability factors are used to compare the architectures in terms of network connectivity, continuity of power supply for the network, and the maintainability of the network. In addition, the advantages and disadvantages of the technologies are discussed. The paper also discusses the challenges of using ad hoc and wireless sensor networks for monitoring and protecting long distance oil and gas pipeline monitoring.

II. Current Pipeline Infrastructure Monitoring Techniques

A. Physical Patrolling Technique

To ensure the continued safe operation of the pipelines, continuous, remote, and real-time monitoring and assessment of the integrity of the pipelines is necessary. In pipeline monitoring and inspection, the ultimate objective is to identify the locations that have defects, and obtain an accurate measurement and assessment of the defects so that human operators can take appropriate actions to prevent further damage. In Nigeria, a combined team of PPMC, Community Leaders, Police and local security outfit provide surveillance to guard the pipelines. Regular aerial surveillance of critical sections of the pipelines is also carried out by PPMC/NNPC

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[4]. In spite of these security measures, statistics on oil pipeline vandalisation remain staggering.

B. Sensor Networks for Pipeline Infrastructure Monitoring

There is a number of sensor network architecture to monitor, maintain and protect gas, oil and water pipeline infrastructures. Some of these networks are specially design to detect, locate and report anomalies such as leakages, corrosion, fracture and any other damages on the pipeline infrastructures. Most of these solutions depend on the availability of network to be able to transfer the information gathered and report leakages or any other sensed data to the control station.

A major difference between the networks used for pipelines and other networks is that the network needed for pipeline applications is structured in a linear topology, where all sensor nodes are distributed on lines as illustrated in Fig. 1. This characteristic demands some reliability challenges in monitoring pipeline infrastructures such as the connectivity of the network, the continuity of power supply, and the maintainability of the network.

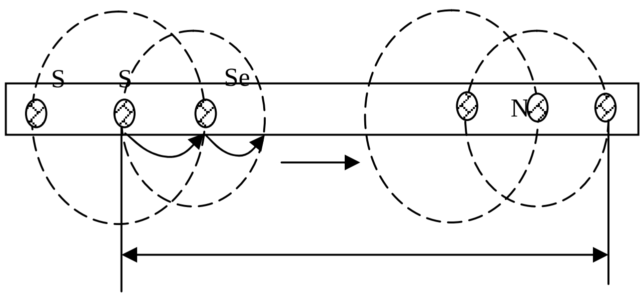

Fig. 1 Monitoring of oil pipeline with sensors

Since the pipeline network extends generally in a line, it is important for the network to be continuously connected to collect and transfer information from the sensor nodes distributed over the pipeline to the control station and also to transfer control commands to the actor and sensor nodes, which are often located inside the pipeline.

Moreover, power supply continuity is a critical feature for the pipeline to be able to operate properly. Power is needed not only to operate the network but also to operate the sensors and actor nodes.

Lastly, network maintainability should also be performed, as faults in the network or in the nodes can occur at any time for different reasons. Pipeline monitoring systems should provide mechanisms to quickly and seamlessly recover from faults and report problems and their locations to the control station(s) to be handled.

The different sensor network architectures used for reliable communication in pipeline systems are based on wired networks, wireless networks, or a combination of wired and wireless networks.

C. Wired Sensor Network Architecture

Pipeline sensors can be connected using wired networks. Wired networks are either copper or fiber optic cables. The wired networks are usually connected to regular sensor devices measuring specific attributes such as flow rate, pressure, temperature, vibration, humidity etc. The wires are used for both communication and transfer of electrical power to different parts of the pipeline system.

Although, wired sensor networks provide an easy solution for pipeline monitoring and controlling, they are unreliable due the structure and type of networks used for pipelines. If any part of the wired network is disabled for any intentional or natural reason, the monitoring system is partially or completely affected.

One possible solution to enhance the 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. Another feasible solution to enhance the reliability of wired networks is to divide the long network that extends along a pipeline into multiple separated segments where each segment covers a certain area of the pipeline. In this segmentation approach, any cut or damage to a single network, will only impact that small network. All other networks will operate without any problems. The reliability of this type of network can be enhanced further by shortening the length of each segment. However, having a large number of short segments will increase the cost of the whole networks as each segment needs a separate power supply and a communication facility with an external communication system to transmit its data.

D. Pipeline 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) [5] 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. The system architecture for traditional SCADA system is shown in Fig. 2. A typical installation has several hundred RTUs communicating over dedicated links to a central master station [5]. SCADA systems are designed to provide real-time security status of the entire pipeline so that necessary action may be taken by the human agents monitoring the central information.

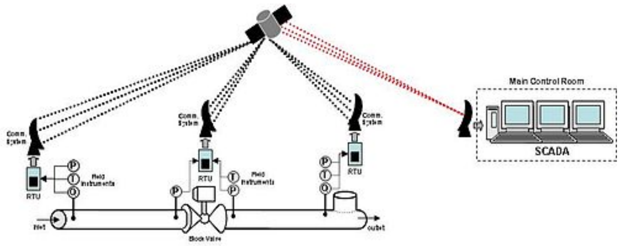

Fig. 2 Typical Oil Pipeline SCADA System Architecture

The entire operation of the SCADA system is dependent on the network that connects the RTU's 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 [5]. Even though basic authentication mechanisms exist, security in oil pipeline SCADA systems are almost exclusively related to network security and several recent security breaches [5] 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.

E. Wireless Sensor Networks

Wireless networks are broadly divided into infrastructure and infrastructureless network. Infrastructure network consists of wireless node with a network backbone and infrastructureless network consist of distributed, independent, dynamic topology, low-power, task–oriented wireless nodes. Cellular wireless network falls under the category of infrastructure network whereas ad-hoc and wireless sensor network (WSN) are part of infrastructureless network. In ad-hoc wireless networks, the wireless devices integrate and communicate with each other by making an on-spot dynamic wireless link.

A wireless sensor network is a collection of sensor nodes interconnected by wireless communication channels. Each sensor node is a small device that can collect data from its surrounding area, carry out simple computations, and communicate with other nodes or with the base station (BS). Such networks have been realized due to recent advances in micro-electromechanical systems and are expected to be widely used for applications such as environment monitoring, home security, industrial process monitoring, health care applications, etc. Fig. 3 shows a conceptual diagram of oil distribution system and monitoring using WSN.

III. WSN for Pipeline Monitoring: Challenges

Research in the field of Wireless Sensor Networks is relatively active and involves a number of issues that are being investigated. These issues are efficient routing protocols, localization algorithms, energy management, network security and link quality. Most of these issues are investigated under the assumption that the network used for sensors does not have a predetermined infrastructure [6-10]. However, the wireless sensor network needed for monitoring linear infrastructures such as pipeline is a structured network in which all sensor nodes are distributed in a line.

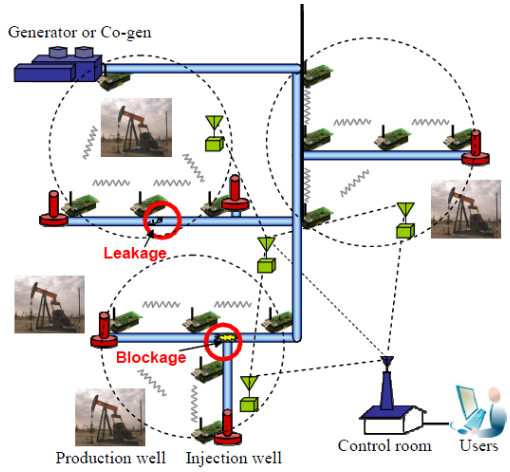

Fig. 3 A conceptual diagram of oil distribution system and monitoring using WSN

A. Energy Management for Linear Topology Wireless Sensor Network

Energy is one of the most important and scarce resources in Wireless Sensor Networks (WSN). The sensor nodes normally operate on small capacity battery. Since the replacement of these batteries after deployment is herculean task, it is crucial to properly manage their energy consumption to achieve the maximum operation (i.e. lifetime) for the WSNs.

The first challenge for a long distance linear topology WSN is the development of energy efficient communication protocols for the sensor nodes to communicate with each other and with the data sink of the wireless sensor network. Because of the unique linear topology, the radio communications between sensor nodes are limited by directional transmission along the path of sensor node distributions. 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 within the local vicinity and with the remote data sink that would enable the sensor networks to maximize their lifetime while minimizing the overall deployment cost.

B. Routing Challenges

Energy efficient routing protocol is another major challenge for long distance linear topology WSN. This is the case since the two-dimensional routing protocols that exist in the literature [9, 10] perform their route discovery and maintenance using different strategies such as flooding, and multi-dimensional propagation of request messages from the source to the destination.

Flooding process is costly in using important resources which are scarce in the wireless environment such as on-board energy, node processing capacity and storage. In addition, it causes delay in path acquisition and 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 done automatically at the intermediate nodes by using the information in the node addresses to overcome node failures. It is important to note here that address assignment is done only once at network initialization.

C. Localization Challenges

Many applications of wireless sensor networks require that sensor nodes be aware of their absolute or relative (with respect to other nodes) locations. This location information can be used to accomplish both application specific tasks and networking functions efficiently. For example, a sensor node operating in a monitoring system is typically required to not only report that an event of interest has occurred but is also required to report the location of the event. As such, the node must be capable of automatically estimating its current position. The process in which a node estimates its position in some spatial coordinate system is referred to as localization [11,12]. Localization (or position estimation) in sensor networks is required to support location aware applications, object tracking, location based routing, coverage management and collaborative signal processing.

The various localization techniques reported in the literature can be classified into two approaches: direct approaches and indirect approaches [12].

Direct approaches: This is also known as absolute localization. The direct approach itself can be classified into two types: Manual configuration and GPS-based localization. The manual configuration method is very cumbersome and expensive. It is neither practical nor scalable for large scale WSNs. On the other hand, in the GPS-based localization method, each sensor node is equipped with a GPS receiver. It is not economically feasible to equip each sensor node with a GPS receiver since WSNs are deployed with hundreds or thousands of sensors. This also increases the size of each sensor node, rendering them unfit for pervasive environments. Also, the GPS receivers only work well outdoors on earth and have line-of-sight requirement constraints.

Indirect approaches: The indirect approach of localization is also known as relative localization since nodes position themselves relative to other nodes in their vicinity. In this approach, a small subset of nodes in the network, called the beacon nodes, are either equipped with GPS receivers to compute their location or are manually configured with their location. These beacon nodes then send beams of signals providing their location to all other sensor nodes in their vicinity. Using the transmitted signal containing the location information, the other sensor nodes compute their location. This approach effectively reduces the overhead introduced by the GPS-based method.

Algorithms for locating nodes in linear topology wireless sensor networks can be much more easily designed by taking advantage of the linear structure. In order to help in this regard, a higher level addressing scheme which includes information about the node location inside the address can be used. This strategy would greatly enhance the ability of the network to easily, quickly, and precisely localize nodes.

IV. Conclusion

A major objective of this project is to investigate the potential of application of wireless sensor networks in monitoring the structural health of long distance pipeline infrastructure. To this end we are developing an outdoor, multi-hop WSN testbed that will provide invaluable resource for driving research in wireless and sensor networking.

The envisioned testbed will be a scalable, multi-hop outdoor wireless networking testbed that will provide an invaluable resource for driving research in wireless and sensor networking, in particular the WSN Experimental Testbed will be used to provide the infrastructure necessary to realize wireless sensor networks for monitoring oil pipelines in Nigeria.

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References

[1] Brume et al, *Towards Efficient Disaster management in oil pipeline corridors*, Oil and Gas journal, 2002.
[2] Elias Johnson et al, *Return to country Analysis Brief*, Oil and Gas journal
[3] P.C. Nwilo and O.T Badejo, *Impacts of oil spillage along Nigerian coast*, The Association for Environmental Health and Sciences, 2001
[4] Abayomi, F, Atilade, D, Matswamgbe, M, Onwurah, U and Okpewho, L, *Report of small arms and light weapons (SALW) survey in Delta State*, Frankard Publishers, 2005.
[5] Gordon R. Clarke et al, *Practical Modern SCADA protocols: DNP3, 60870.5 and related systems*, 2004, pp. 19-21
[6] W.Heinzelman, A.chadrakasan, and H.Balakrishnan, *Energy Efficient communication protocol for WSN*, in Proc. Hawaii International Conference of System Sciences, Hawaii, 2000.
[7] M.Younis et al, *Energy aware routing in cluster-based sensor networks*, in Proc. 10th IEEE/ACM International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication System, 2002.
[8] A. Manjeshwa et al, *A protocol for enhanced efficiency in WSNs*, in Proc. 1st international Workshop on Parallel and Distributed Computing Issues in Wireless Networks and Mobile Computing Issues, 2001.
[9] W.Heizelman, *Application specification protocols architecture for wireless network*, PhD thesis, MIT, 2000.
[10] R. shah, J.rabaey, *Energy aware routing for low energy adhoc sensor networks, in* Proc. of the IEEE Wireless Communication and Networking Conference (WCNC), Orlando, 2000

[11] C.W. Chen and Y. Wang, *Chain-Type Wireless Sensor Network for Monitoring Long Range Infrastructures: Architecture and Protocols,* Int. Journal of Distributed Sensor Networks, Vol 4, pp. 287-314, 2008.

[12] K. Cheng, K. Lui and V. Tam, *Localization in Sensor Networks with Limited Number of Anchors and Clustered Placement,* in proc. of Wireless Communications and Networking Conference, (IEEE WCNC 2007), pp. 4425- 4429, 2007.