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Survey Paper

Focal design issues affecting the deployment of wireless sensor networks for pipeline monitoring ☆

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ABSTRACT

Wireless sensor networks (WSNs) are a target technology for oil and gas pipeline monitoring because they offer benefits of low cost, ease of deployment and ability to cater for data acquisition at great spatial and temporal scales. In order for WSN to achieve trademark performance in remote monitoring of pipelines, and surpass the performance of present-day traditional monitoring systems, certain design requirements must be met. In this paper, we identify vital design issues that must be considered to facilitate the employment of WSN for pipeline monitoring. We classify these design issues into five different categories namely; sensing modality, power efficiency, energy harvesting, network reliability and localization. In addition, we discuss the concept of cooperative communication for pipeline-monitoring sensor networks deployed in sub-sea environments. We also study the employment of sensor networks for monitoring underground pipelines. Our findings are based on extensive study of the recent literature and comprehensive survey of existing WSN technologies. The WSN design considerations presented in this paper are particularly prolific for pipeline monitoring scenarios, they can however be easily extended to other oil and gas infrastructures. For example; well-head and heat exchanger monitoring, oil platform process monitoring, monitoring of natural gas storage facilities and data collection on coastal infrastructures that could support oil and gas exploration.

1. Introduction

The features of wireless sensor networks (WSNs) such as; small size, wireless architecture, ease of deployment and ubiquitous nature makes them a very attractive platform for oil and gas pipeline monitoring. Oil and gas pipelines which may transverse several kilometers of hazardous inaccessible terrains require remote incessant monitoring to enhance the safety of the infrastructure and to guarantee production flow. These critical requirements mean that traditional means of human inspection become unfeasible. Also, because these infrastructures are scalable, the cost implications of a wired sensor network will be counter-productive. As these pipelines extend further offshore, the distance and water depths make them difficult and uneconomical to access. These shortfalls have motivated research into reliable long-term economically viable options which provide ease of network expandability and are relatively flexible throughout the life of the infrastructure. WSN have recently been identified as significant means to deliver integral concepts to oil and gas pipeline monitoring. The UK Engineering and Physical Sciences Research Council [1] have demonstrated the potentials of WSN for low cost and diverse infrastructure monitoring. Research on the feasibility of deploying WSN for pipeline monitoring and event localization is exhaustive [2–4], the advantages of WSN over traditional means of off-shore data sensing and information acquisition in terms of cost, ease of installation and efficiency have been effectively documented in [5]. Extensive real world

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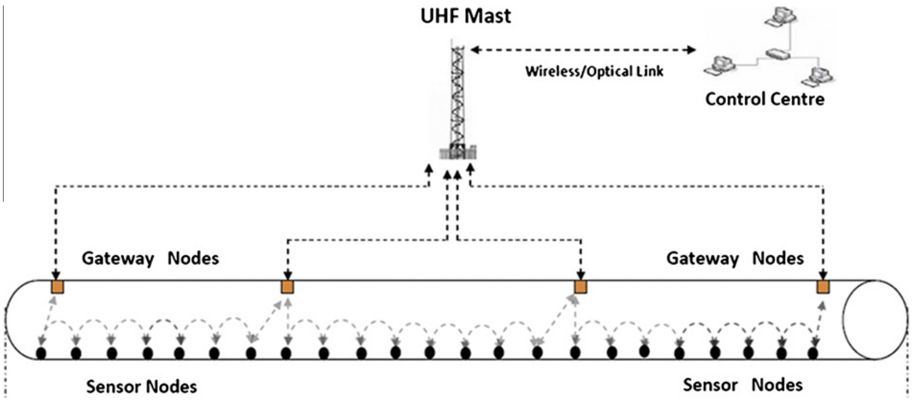

Fig. 1. Pipeline monitoring wireless sensor network.

experiments with ground truth backing carried out in [6] have indicated that WSN perform relatively well for oil and gas infrastructure monitoring when compared to traditional means of infrastructure surveillance and event localization. As a result, the applications of WSN are booming in major prototype projects like the Commonwealth's Flagship Field Monitoring Project [7], Pipenet [8], SWATS [9], and the Smart Wireless networks used by the Statoil Grane off-shore oil platforms [10].

A WSN is made up of small interconnected wireless nodes with sensing, computing and wireless communication capabilities, with power supply requirements. A pipeline-monitoring WSN, as depicted in Fig. 1, is typically made up of sensor nodes which collaborate to accomplish a common task of information acquisition in and around a pipeline, and gateway nodes which are essentially connected to the sensor nodes to aggregate or process their data and transmit to a backbone infrastructure or base station. The sensor nodes communicate dynamically with each other to route high precision data over considerable distances. The architecture sustains signal strength by breaking long distances into a series of shorter hops. The intermediate nodes do not only enhance the signal strength but cooperatively make forwarding decisions based on their knowledge of the network. The topology is also very reliable because the nodes are interconnected, if one node can no longer operate due to hardware failure, complementary nodes find an alternative route to maintain data transmission. In addition to information sensing and data transmission, these nodes are also capable of event localization to determine where an incident has occurred.

For WSN to compete effectively and surpass the performance of traditional pipeline monitoring technologies, certain design issues must comply with the pervasive, complex topology, remotely deployed and largely inaccessible nature of pipelines. These designs must also be applicable to the dynamic environments in which pipelines are expected to operate. In other words, WSN must be designed such that they meet the principal requirements of accurate sensing, long network lifetimes, reliability, localization and adaptability. In this paper, we make the following contributions; we identify the focal design issues that will elevate the performance of WSN for pipeline monitoring, and analyze how these design issues relate to each other. We also outline research efforts carried out so far on these issues.

Our work builds on the discussions on sensor technologies and network reliability carried out in [5] and the study of the applications of WSN in oil and gas installations in [11]. Our approach is similar to the survey of WSN design issues in [12] however our major contribution is that we analyze design issues and illustrate how these issues are inter-related in pipeline-monitoring scenarios. The rest of the paper is organized as follows: Section 2 presents a summary of the key design issues in pipeline-monitoring sensor networks. Section 3 deals with design issues relating to data acquisition, Section 4 discusses power conservation issues while Section 5 covers energy harvesting, Section 6 deals with network reliability and Section 7 discusses defect localization. Finally we conclude by introducing the concept of pipeline monitoring in underwater and underground environments.

2. Overview of key design issues

A pipeline-monitoring WSN will be required to accomplish major tasks of detecting structural defects and measuring production parameters. These major tasks are concerned mainly with the surveillance part of a WSN. The surveillance part is essentially the part of the sensor node that collects information from the environment. The ability of a WSN to accurately acquire information is a fundamental design issue since all other operations of the sensor network depend on this. Operational pipelines are affected by highly non-linear spatial and temporal processes which make it difficult to differentiate anomalies from random system behaviour. The critical design issue in pipeline monitoring is beyond merely detecting the occurrence of a physical anomaly. If a sensor is required to detect physical anomalies in form of structural defects for example; leaks, bursts, third party damage, corrosion or fire, the sensor must be capable of differentiating one type of physical anomaly from the other. Also, in order to monitor production parameters, a sensor must be able to accurately detect the slightest pressure, velocity or