

A Fault Tolerant Wired/Wireless Sensor Network Architecture for Monitoring Pipeline Infrastructures

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Abstract

This paper proposes a new fault-tolerant sensor network architecture for monitoring pipeline infrastructures. This architecture is an integrated wired and wireless network. The wired part of the network is considered the primary network while the wireless part is used as a backup among sensor nodes when there is any failure in the wired network. This architecture solves the current reliability issues of wired networks for pipelines monitoring and control. This includes the problem of disabling the network by disconnecting the network cables due to artificial or natural reasons. In addition, it solves the issues raised in recently proposed network architectures using wireless sensor networks for pipeline monitoring. These issues include the issues of power management and efficient routing for wireless sensor nodes to extend the life of the network. Detailed advantages of the proposed integrated network architecture are discussed under different application and fault scenarios.

1. Introduction

Gas, oil, and water pipelines have become the veins of economy and the life of most countries. Maintaining the life and economic progress of most countries is strongly dependant on maintaining and protecting these resources and facilities. Protecting the pipeline infrastructures is essential for these countries.

There are a number of technologies to monitor and control pipelines. Most of these technologies relay on sensors and networks to transfer data collected from inside and outside pipelines to the control stations. There are usually numerous monitoring points along any pipeline that provide data about the material

flowing through the pipeline and the internal and external conditions of the pipelines. In addition, there are some sensor technologies used to monitor the area around the pipelines to detect any unauthorized actions. Data needs to be collected at each of these control points and sent back to a central control station. Network components are usually spread through pipelines to transfer the measurements collected from different distributed sensors scattered through pipelines. A network is usually needed on the pipelines to provide communication media for data acquisition, video monitoring, control and command systems, etc.

This paper proposes a fault-tolerant network architecture based on integrated wired and wireless networks. The wired part of the network is the primary network for all nodes in the system, while the wireless network part is used as a backup between sensor nodes when there is any failure in the wired connections between them. This new network architecture enhances the reliability and performance of currently used and proposed networks for pipeline monitoring. Detailed advantages of the proposed network architecture are discussed with different application and fault scenarios.

The rest of the paper is organized as follow: Section 2 provides background information on pipelines usage and current network technologies used for monitoring these pipelines. In addition, it discusses related work. Section 3 discusses the reliability issues of currently used wired networks and the recently suggested network, wireless sensor networks, for pipeline monitoring. Section 4 develops the architecture of the new integrated wired and wireless network for pipeline monitoring while the advantages and the evaluation of the proposed network architecture are discussed in Section 5. Section 6 concludes the paper with future planned work.

2. Background and Related Work

Long pipelines are used for a number of applications. For example, oil and gas industries in the world heavily depend on pipelines for connecting shipping ports, refineries, oil and gas wells, and power plants. For example, there are around 500,000 miles of oil and gas pipelines in the United States that also extend to Canada and Mexico [1]. These pipelines play a critical role in the U.S. economy. This pipeline infrastructure is mainly for providing energy supply to the U.S.

Furthermore, long pipelines are used to transfer water from desalination plants, which are usually located close to the sea, to cities that are far away from the sea. For example a big city like Riyadh in Saudi Arabia, home to over four million people, is completely dependant on the water transferred through huge and long pipelines from the Shoaiba Desalination Plant in Al-Jubail in the east part of the Saudi Arabia. Saudi Arabia is now the world's largest producer of desalinated water supplying major urban and industrial areas through a network of water pipes which run for more than 3,800 km.

There are a number of technologies to monitor and protect pipelines. Most of these are designed specifically for detecting and locating pipeline leakages [2]. These technologies were designed to allow a remote facility to detect and to report the positions of any leakage. Most of these available solutions rely on the availability of a network to transfer the information and report leakages [3]. These networks are usually wired or wireless sensor networks. Both wired and wireless sensor networks have some reliability limitations as we will discuss in Section 3. This paper proposes an integrated wired/wireless network which provides better reliability in monitoring pipeline infrastructures.

The integrated wired and wireless network architecture is found in many types of networks. It is found in local area networks (LAN) to provide flexible mobile and fixed access to voice and data services [4]. SiNett's design integrates on a single chip for wireless and wired packet processing, switching, security, mobility and traffic management [5]. This chip can be deployed in network switches to reduce processing latency for sensitive traffic such as voice. Metropolitan area networks can be also a combination of wired and wireless networks. The main research issues in such networks are designing efficient integrated routing protocols and guaranteeing the end-to-end QoS [6].

In the sensor networks field, the main objective of integrating wireless and wired networks is to enable transmission of information collected from wireless sensor networks to wired networks via a gateway [7]. The wired network can be the Internet. This integration was achieved by designing an advanced routing protocol based on modifying existing ad hoc routing protocols to enable access to wired networks.

3. Current Sensor Networks for Pipelines

One of the main differences between the networks used for pipelines and other networks is that the network needed for pipeline applications is structured in a line where all sensor nodes are distributed on that line. This characteristic can be utilized to enhance the communication quality and reliability in the pipeline systems.

Different network architectures can be used for pipeline monitoring. These architectures provide different reliability degree in term of:

1. The connectivity of the network: since the pipeline network extends in a line, it is important for the network to be continuously connected to transfer information from the sensor nodes distributed over the pipeline to the main control station and also to transfer control commands from the control station to the sensor nodes and other devices distributed through the pipeline.
2. The continuity of power supply: pipeline networks will not be able to operate unless there is sufficient supply of power. Power is needed not only to operate the network but also to operate the sensors nodes.
3. The maintainability of the network: faults in the network or in the nodes can occur for different reasons at any time. Dependable networks should provide mechanisms to quickly and seamlessly recover from faults and when necessary to report occurring problems and their locations to the control station to be handled.

Two types of network architectures are used for pipeline monitoring: wired sensor networks and wireless sensor networks. In this section, the reliability advantages and disadvantages of these architecture types are discussed.

3.1. Wired Sensor Networks

These days most pipeline sensors are connected using wired networks. Wired networks are either copper

or fiber optic cables [8][9]. The wired networks are usually connected to regular sensor devices that measure specific attributes such as flow rate, pressure, temperature, etc. In addition, the wired network connects different devices through the pipeline system in which the flow of the material transferred through the pipelines can be controlled.

The wires are not used for communication only but also to transfer electrical power to different parts of the pipeline system to enable the sensors, flow control devices, and communication devices to function. Electrical power for the pipeline resources and network can be provided by different sources:

1. Solar Energy: using arrays of solar cells that generate power for the pipeline infrastructure. This power is supplied to the different communication, sensors, and flow control devices.
2. Pipeline Flow Energy: electric power can be generated using turbines embedded through the pipeline. These turbines rotate under the pressure of the fluid moving through the pipelines and generate electrical power. This power can be used for the different devices installed through the pipeline [10].
3. Other External Energy: power can be provided from external resources such as external gas-based power generators or third-party power generators.

Wired networks are considered the traditional way for communication in pipeline systems. However, there are a number of reliability problems related to using wired networks with regular sensors for monitoring pipelines. These problems are:

- If there is any damage in any part of the wires of the network, the whole pipeline communication system will be compromised. In addition, if there is a power outage, sensor nodes will not operate.
- It is easy for unauthorized people to disable the communication system by cutting the network wires.
- It is difficult to locate the location of the fault in a wire. This problem is even more difficult with underground and underwater pipelines. This makes the process of maintaining a faulty network a very complex task.

All these problems make wired networks for pipeline communication systems undependable. Although, wired networks provide an easy solution for pipeline monitoring and controlling, they face a number of major reliability and security problems. The main reason of these problems is 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 can be partially or completely affected.

3.2. Wireless Sensor Networks

Wireless networks can solve some of the reliability problems of current wired networks technologies in pipeline systems [11][12]. For example, wireless sensor networks can still function even when some nodes are disabled. Faults in sensor nodes can be easily tolerated by using other available nodes to cover the faulty ones. Using dense sensor networks with a high number of nodes and/or using wide wireless transmission range, the network can maintain connectivity and the sensed information can be transported through the network to its destination even with the existence of some node or sensor failures. For example, each node in Figure 1 can communicate with two nodes to the left and two nodes to the right. If for example node 3 and 5 are damaged, node 4 can still send its sensed data through nodes 2 or 6.

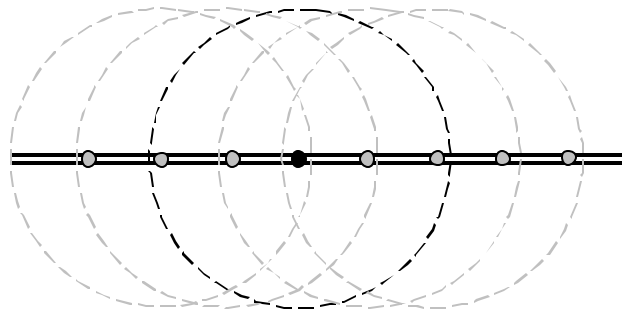


Figure 1. Each node can communicate with four nodes.

Each sensor node for monitoring pipelines is usually equipped with a transceiver, a processor, a battery, memory, and small storage in addition to one or more sensor devices. Power consumption is critical to the life span of pipeline wireless communication systems. Pipeline systems are usually installed to be used for years. Therefore the associated communication systems should also be long lived. Unlike wired networks where the power is not at all a constraint in building the system, network designers have to consider power as one of the main constraints in the wireless system. Power in a node can be consumed when data is sent through the transceiver, when the transceiver is turned on waiting to receive data from

other nodes, when sensor devices are turned on, and when the processor is active. Careful scheduling of these resources is needed to optimize power consumption.

In addition, nodes are used to route information from other nodes to the control station. Therefore, nodes close to the station will consume more power than other nodes since they will route more packets. All nodes will have the same level of sensing activity; however, closer nodes to the station will consume more power due to more packet routings.

The main design issues for the wireless networks for monitoring pipelines are in designing a network protocol that balances the power consumption of batteries on the nodes with and without node failures. This balancing is crucial to extend the life of the network.

4. Integrated Wired/Wireless Networks

As we can see from the previous section that the main reliability challenges in the pipeline communication systems are the network connectivity, the continuity of power supply, and the maintainability degree of the network. To solve all these issues, we are proposing in this section a new network architecture for pipeline communication systems. The architecture in this system consists of multiple point-to-point segments as shown in Figure 2. These segments link the system nodes.

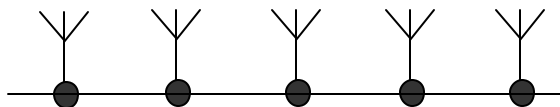


Figure 2. An Integrated Wired/Wireless Network. The nodes are connected through wired and wireless links.

Each node is connected to a transceiver and a wired network interface. Sensor nodes also consist of processor and memory and storage units. The nodes are connected through wireless and wired links. Wires are used for networking and for transferring power to the nodes. Unlike completely wireless nodes in the wireless architecture, nodes in this architecture consist of rechargeable batteries which are charged by the received power through the connected wires. The power can be provided for this network architecture using the techniques used for wired network architecture as discussed in Section 3.1.

Neighborhood nodes can communicate either using the wired or wireless communication. The transceivers in the normal case are turned off and the wired network is used for communication. Therefore the connectivity of the network is through the wired links in the normal case.

Each node periodically checks the status of the right side of the network wire by sending echo messages to the neighboring nodes on the right. Each node also periodically checks the status of the left side network wire by receiving/replying to the echo messages received from the neighboring node on the left. A break of a wired link between two nodes can be discovered by the left node when it does not receive replies for the echo messages that it just sent. The break can be discovered by the right node if there are no echo messages received from the left node. When both nodes discover the break, they will activate their transceivers and communicate through the wireless link. This wireless link between the two nodes can provide connectivity for the pipeline network and sensed and control information can be still transported through the network as shown in Figure 3.

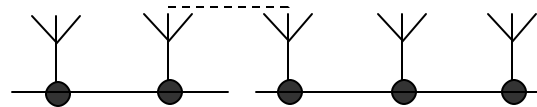


Figure 3. The wireless link will be activated if there is a cut in the wire link between any two nodes.

The nodes that discovered the break will report it along with the location information to the control station for immediate maintenance. If an intermediate node is disconnected from the left and from the right, the node can operate temporarily using the rechargeable battery until the wire breaks are fixed.

Link breaks due to faulty nodes can be recovered by using a wider transmission range in which each node can communicate using the wireless links with multiple nodes on the left and multiple nodes on the right as discussed in Section 3.2. Discovered faulty nodes can be also directly reported to the control station. The network connectivity will remain even with multiple breaks on multiple segments occur while any node faults or wire breaks will be discovered and reported for maintenance. In addition, with the availability of rechargeable batteries, the power constraint issue is terminated. Ordered id codes can be used for identifying nodes and let them distinguish between their right and left nodes.

To enhance the reliability further for long pipelines, it is possible to embed some high capability wireless nodes that are used to communicate the collected data from sensor nodes to the main control station through GSM, Satellite cellular technology, or any other communication technology. This approach can be used for long wired networks, long wireless multi-hop networks as well as for integrated wired/wireless networks to enhance the communication reliability. In this approach, two types of wireless nodes will be embedded on the wire. The nodes of the first type are used to enhance the reliability of connectivity in the wired network. These nodes will be activated whenever there is a break in the wired network. The nodes of the second type are used to enhance the reliability of connectivity in the wired network as well as they will be used to provide another backup channel to deliver some important collected information to the main control station.

5. Evaluation and Discussion

The network architectures mentioned in this paper provide different advantages for different applications objectives and requirements. Wired sensor networks usually provide higher communication bandwidth than wireless sensor networks. Hence wired networks can be used for pipeline monitoring applications that demand high bandwidth such as camera-based monitoring [13]. On the other hand, wireless networks provide better reliability for pipeline monitoring applications such as fire detection or sudden damages detection. These applications are event based applications that do not need high communication bandwidth. Events occur only if there are exceptions discovered by the sensors which they need to communicate. The integrated wired and wireless network architecture can provide high bandwidth as well as good reliability for event-based applications even if some parts of the network are damaged.

The network architectures mentioned in this paper also have different degrees of reliability. The wired network may completely fail with a single point failure. On the other end, using wide transmission range in wireless networks can solve the problem of full network failure due to failure of one or more nodes. The reliability degree of the wireless network can be increased as we increase the transmission range. However, this increase of the wireless transmission range, causes a significant increase in power consumption. Therefore, the battery will be consumed rapidly and the life of the network will be reduced

significantly [14]. In the integrated wired and wireless network, the limitation of power sources is not an issue. Therefore, the node can be designed to use a wide transmission range for communication to provide better reliability

Further to the feature of increasing the reliability of the network, the availability of wireless nodes that are embedded in the wired networks can be used for other applications. One possible application using external wireless sensor nodes, as shown in Figure 4, to monitor some aspects of the pipeline such as monitoring if there is any movement, sound, or hazards around the area of pipeline. The external nodes can send their information to the main control station through the integrated wired/wireless network. The integrated wired/wireless network represents the backbone for transferring the collected information to and from the main control station. The external nodes can be inexpensive sensor nodes with limited capabilities and scattered randomly.

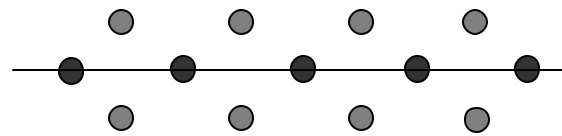


Figure 4. External wireless sensor nodes communicate with the main network through the embedded wireless nodes.

The external nodes can be moving vehicles that need to communicate with the pipeline infrastructure. One example of using this type of communication can be used on maintenance vehicles that need to collect more information about the pipeline status. Another example is security vehicles that need to send special signals to the network not to report the movement of the vehicle to the main control station in case the pipeline infrastructure is equipped with motion sensors that automatically report approaching vehicles. Although the external nodes option can also be made available with completely wireless sensor networks for monitoring pipeline infrastructures, the existence of a wired network can provide higher communication bandwidth and reliability.

6. Conclusion

The integrated wired and wireless sensor network provides better reliability for pipeline monitoring systems in terms of network connectivity, continuity of power supply, and maintainability than other network architectures such as completely wired or completely

wireless sensor networks. In the integrated wired and wireless sensor network, the wired network is the primary one while the wireless network serves as a backup. Wireless nodes are embedded in the wired network and the wireless capability can be automatically activated whenever there is a failure in the wired network.

Our planned future work is mainly to design and evaluate a routing protocol for the integrated wired and wireless network architecture for pipeline communication systems. In addition, we plan to investigate the type of technology suitable for the embedded wireless nodes.

Acknowledgment

This work was supported in part by UAEU Research grant # 03-03-9-11/08.

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