

# Reliability Challenges and Enhancement Approaches for Pipeline Sensor and Actor Networks

Nader Mohamed, Imad Jawhar, and Khaled Shuaib

The College of Information Technology

United Arab Emirates University

Al Ain, P.O. Box 17551, UAE, {nader.m, ijawhar, k.shuaib}@uaeu.ac.ae

**Abstract** - *Sensor and actor networks are used to monitor and control pipeline infrastructures. This paper discusses and compares different sensor and actor network architectures for water, gas, and oil pipeline infrastructures monitoring. These architectures are wired networks, wireless networks, separated wired and wireless networks, and integrated wired and wireless networks. The paper also discusses the reliability challenges and enhancement approaches for these network architectures. The reliability characteristics, advantages, and disadvantages among these architectures are discussed and compared. Three reliability factors are used for the discussion and comparison: the network connectivity, the continuity of power supply for the network, and network maintainability.*

**Keywords:** Pipelines Protection and Monitoring, Sensor and Actor Networks, Reliable Network Architecture

## 1 Introduction

With the increase of demand for energy and water in the world; petroleum, natural gas, and water resources and facilities have become important assets for most countries. Maintaining the economic progress of most countries is strongly dependant on maintaining and protecting these resources and facilities. One of the main and important facilities for these resources is the pipelines used to transfer the water, petroleum, and natural gas. These pipelines are considered one of the main infrastructures between producer and consumer countries. Protecting the pipeline infrastructures is one of the main issues facing these countries.

There are a number of technologies to monitor and control pipelines. Most of these technologies relay on sensors and networks to transfer sensed information collected from inside and outside pipelines to the control stations. There are usually numerous sensor points along any pipeline that provide data about the material flowing through the pipeline and the conditions of the pipelines. Data needs to be collected at each of these sensor points and sent back to a central control and monitoring point. Network components are

usually spread along pipelines to transfer the measurements collected from different distributed sensors scattered along 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 discusses and compares different sensor and actor network architectures for water, gas, and oil pipeline infrastructure monitoring and control. The proposed architectures are wired networks, wireless networks, separated wired and wireless networks, and integrated wired and wireless networks. Three reliability factors are used to compare the architectures: network connectivity, continuity of power supply for the network, and network maintainability. In addition, the advantages and disadvantages of each of these architectures are discussed.

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. Section 3 discusses the reliability issues of wired networks for pipelines while the reliability issues of wireless pipeline networks are discussed in Section 4. Sections 5 and 6 discuss separated and integrated wired and wireless networks. Section 7 concludes the paper with future planned work.

## 2 Background

Long pipelines are used for a number of applications. For example 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.

Furthermore, 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 [7]. These pipelines play a critical role in the U.S. economy. This pipeline infrastructure is mainly for providing energy supply to the U.S.

There are a number of technologies to monitor and protect pipelines. Most of these are designed specifically for detecting and locating pipeline leakages [1]. 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 [2].

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 and actor nodes are distributed on that line. This characteristic enforces some reliability challenges in monitoring pipeline infrastructures. The monitoring systems for pipelines will not be able to function properly unless the network connecting these sensors, actors, and control points functions without any problems. Having a reliable network is one of the main conditions of having a reliable monitoring system for pipelines.

Different network architectures are used or can be used for reliable communication in pipeline systems. These architectures are based on wired networks, wireless networks, or a combination of wired and wireless networks. These architectures are evaluated in this paper based on three reliability factors:

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 control station and also to transfer control commands from the control station or from other control points to the actor and sensor nodes.
2. The continuity of power supply: pipeline networks will not be able to operate unless there is sufficient power supply. Power is needed not only to operate the network but also to operate the sensors and actor 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 problems and their locations to the control station to be handled.

### 3 Wired Networks

These days most pipeline sensors and actors are connected using wired networks. Wired networks are either copper or fiber optic cables [3][4]. 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 actor points along 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, actors, 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 along the pipeline [6].
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 damaged. In addition, if there is a power outage sensors and control 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.

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. However, unlike other systems, using multiple wired networks and a fault tolerance

mechanism among them will not enhance the reliability of the pipelines network. This is due to the fact that all wires will be expanded together along the pipelines and any damage occurring in one of them may also occur in the others. More specifically an accidental (or intentional) break in the line has a very high probability of happening to all wires along the pipelines.

A more 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 other words, this approach is to divide a long wired network into multiple smaller networks in which each network covers a part of the pipeline. Each small network has to have a power supply to operate both sensor and actor nodes and other devices related to the communication. In addition, each small network needs to be connected to another external network to discharge collected sensed information and to receive control commands to and from the main control station or other control points.

The external network can be an available GSM or GPRS network. It can also be an available WiMax or satellite cellular communication network. In addition, it can be other external wired communication systems such as regular phone lines or power lines. All these network types can be used to discharge sensed information to control stations and to transfer control commands from control stations to the individual network. It is also possible to use heterogeneous types of external communication systems for segments based on their locations. For example, segments that are located within cities can be linked with available cellular GSM or GPRS communications. On the other hand, nodes which are located in remote locations far from large metropolitan areas might not be able to use standard cellular communication and would have to rely on the more expensive satellite cellular communication or available WiMax communication for transmission of their data. Furthermore, segments can depend on different types of power supplies based on their locations. For example segments located in metropolitan areas can depend on external power supplies while other segments can depend on solar energy or pipeline flow energy.

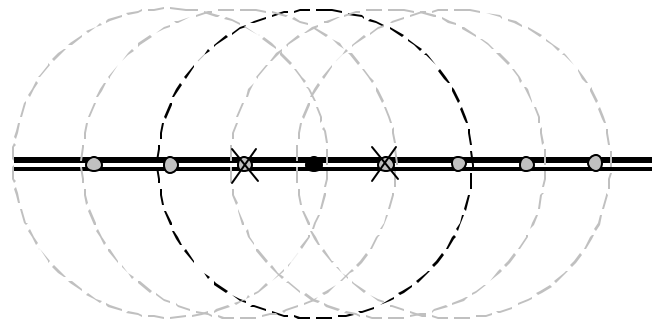
In this segmentation approach, any cut or damage to a single network, will only impact that small network. All other networks will operate without any problems. The reliability of this type of network can be enhanced further by shortening the length of each segment. However, having a large number of 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. Another enhancement to this network is to create a short overlap between the small networks so each network will have the capability to monitor its neighboring networks and report problems to the control centers. As a

result, if one of the networks is damaged, one of its neighboring networks will report it. In addition, if one network loses connectivity with its external network (e.g. the GPS, WiMax, etc.), it can relay the information through one of its neighboring networks until the damage is fixed.

## 4 Wireless Networks

Wireless sensor and actor nodes can be installed with pipeline infrastructures. Each node has a limited transmission compatibility in which each node can communicate with few neighboring nodes. Multi-hop communication is used to transfer the sensed and control information among the pipeline and from and to the main control station and other control points distributed over the pipeline.

Wireless networks can solve some of the reliability problems of current wired networks technologies in pipeline systems [5]. 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 and actor networks with a high number of nodes and/or using wide wireless transmission range, the network can maintain connectivity and the sensed and control 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.

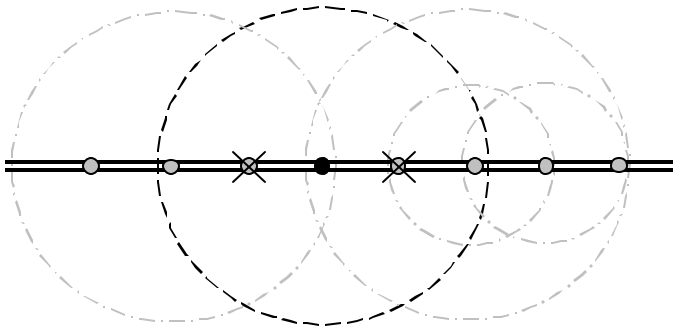


**Figure 1.** Reliability in dense sensor and actor networks

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.

Although increasing the range can provide better reliability, more energy will be consumed from the nodes. A dynamic configuration for the wireless transmission range can provide better power management. Example of this configuration is in Figure 2. In this network, nodes 3 and 5 are dead. Therefore, the wireless range for node 4 is increased to reach nodes 2 and 6 while other nodes use a smaller transmission range to reduce the power consumption.

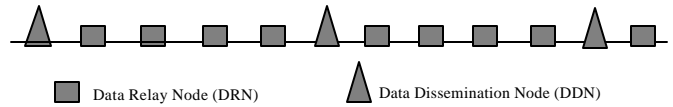


**Figure 2.** Automatic wireless range configuration.

In addition, nodes are used to route information from other nodes to the control station. As a result, 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. One of the main issues for wireless networks when used to monitor pipelines is the optimal design of 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.

One approach to enhance reliability of wireless sensor and actor networks for pipelines is to divide the network into multiple parts similar to those discussed for wired networks in the previous section. To do so, heterogeneous wireless nodes with a hierarchical structure to connect these heterogeneous nodes are needed [8]. The nodes are heterogeneous in their function and energy capabilities. Nodes can be Basic Sensor Nodes (BSN), Data Relay Nodes (DRN), and Data Discharge Nodes (DDN). BSN nodes provide sensing functions and communicate this information to a DRN using single hop direct communication. DRN nodes serve as information collection nodes for the data gathered by the BSN nodes and send filtered information to a DDN using multiple hops. Multiple DRN nodes are structured in a line along the pipelines. DDN nodes transfer the data from these nodes to the main control station through GSM, Satellite cellular technology, or any other available communication technology. DDN are also

structured in a line along the pipelines. Between each pair of DDN there is a number of DRN nodes as shown in Figure 3.



**Figure 3.** A network of heterogeneous wireless nodes for Pipelines.

Two routing protocols were developed for this network architecture: Jump Always (JA) and Redirect Always (RA) [8]. Both protocols use multi-hop communication. The JA protocol uses automatic wireless range adjustment in case of facing a faulty DRN or multiple consecutive faulty DRNs while the RA protocol redirects the message to the opposite direction in case the first direction is with a faulty DRN. Due to the use of automatic transmission range adjustment, JA provides a better reliability level [8].

## 5 Separated Wired/Wireless Networks

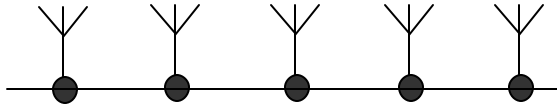
The third possible network architecture that provides better reliability for communication in pipeline systems is using two heterogeneous networks: a wired network and a wireless network. All sensors and control devices are connected to the wired network and to the wireless network. The communication with sensors and actor nodes can be done through either network. The wired network can be used as a primary network while the wireless network is kept as a backup network. The pipeline information will be transferred through the wired network unless a fault occurs. In this case the wireless network will be used to transfer pipeline information. However, using this model does not solve the problem of locating faults which is very important for maintaining the system. This architecture basically combines the features and advantages of the architectures described in Sections 3 and 4.

Although, this architecture can enhance the reliability of communication, it can be very costly. The cost of the network architecture is the cost of both the wired network and the wireless network while the added reliability feature is not significant for the communication in the pipeline systems. In addition, the processes of maintaining this network architecture can be very complex. As discussed in Sections 3 and 4, maintaining each network can be very difficult; therefore, maintaining a network architecture that consists of both networks can be more complex.

## 6 Integrated Wired/Wireless Network

As we can see from the previous sections the main reliability challenges in pipeline communication systems are network connectivity, continuity of power supply, and maintainability degree of the network. To solve all these

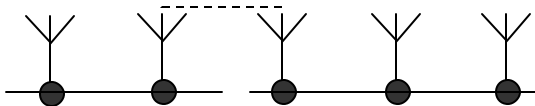
issues, we are proposing in this section a new network architecture for pipeline communication systems. The architecture in this system consists of multiple point-to-point segments as shown in Figure 4. These segments link the system nodes.



**Figure 4.** Integrated Wired and Wireless Network. The nodes are connected through wired and wireless links.

Nodes are either sensor or actor nodes. 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 have 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.

Neighborhood nodes can communicate either using 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 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 5.



**Figure 5.** Activation of wireless links when wired links break.

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 4. 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 and positioning nodes along the pipeline.

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.

**Table 1.** Summary of Main Reliability Issues for Different Network Architectures for Pipelines.

Net. Architecture	Main Reliability Issues
Wired Networks	Connectivity of the networks, wire breaks. Difficulty of breaks discovery and maintenance.
Wireless Networks	Limited battery power, fast power depletion with no renewal source.
Separated Wired and Wireless Networks	Connectivity of the networks, wire breaks. Difficulty of breaks discovery and maintenance. Limited battery power for wireless nodes.
Integrated Wired and Wireless Networks	None, however new device/network technology should be developed.

## 7 Conclusions

Reliability issues of four network architectures for pipeline communication systems were discussed in this paper. These architectures are wired networks, wireless networks, separated wired and wireless networks, and integrated wired and wireless networks. Each architecture has its advantages and disadvantages in terms of reliability. However, integrated wired and wireless networks can provide better reliability in terms of network connectivity, continuity of power supply, and maintainability. A summary of the reliability issues for all discussed architectures is in Table 1. Our planned future work is mainly to design and analyze in details the integrated wired and wireless network architecture for pipeline communication systems.

## Acknowledgment

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