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Kamal Al-Hawashem
AUTEUR DE LA THÈSE / AUTHOR OF THESIS

M.A.Sc. (Electrical Engineering)
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School of Information Technology and Engineering
FACULTÉ, ÉCOLE, DÉPARTEMENT / FACULTY, SCHOOL, DEPARTMENT

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TITRE DE LA THÈSE / TITLE OF THESIS

H. Mouftah
DIRECTEUR (DIRECTRICE) DE LA THÈSE / THESIS SUPERVISOR

CO-DIRECTEUR (CO-DIRECTRICE) DE LA THÈSE / THESIS CO-SUPERVISOR

EXAMINATEURS (EXAMINATRICES) DE LA THÈSE / THESIS EXAMINERS

A. Boukerche

M. St-Hilaire

Gary W. Slater
Le Doyen de la Faculté des études supérieures et postdoctorales / Dean of the Faculty of Graduate and Postdoctoral Studies

Highly Reliable and Delay Bound Wireless Sensor Network Protocol for Oil and Gas Plants

by

Kamal Al-Hawashem

A thesis submitted to the
Faculty of Graduate and Postdoctoral Studies
In partial fulfillment of the requirements
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Faculty of Engineering
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Abstract

Communication networks for oil and gas plants predominantly employ wired communication infrastructure. The wired communication infrastructure is used to carry control and monitoring data used for plant process control and automation. Data carried on plants networks are of critical nature and thus require strict Quality of Services (QoS) treatment. The existing wired communication protocols provide required reliability and delay bound performance. However, wired communication infrastructure imposes high cost and lack flexibility. The advancements in Wireless Sensor Networks (WSN) make it an attractive alternative for wire based plant networks because of WSN low cost and flexibility. However, WSN suffers from error prone wireless medium, limited resources and lack of central control which make it challenging to meet plant networks QoS strict requirements. In this thesis, we propose a novel WSN architecture protocol called HARD for oil and gas plant networks which meet the strict QoS requirements. We have formulated the design guidelines for plant network WSN topology to meet the given QoS requirements. The maximum delay bound and the reliability performance have been formulated. Simulation results confirmed the analysis of the HARD protocol delay bound of 40ms and showed reliability performance of near 100% for experiments with failure probability of 60% and below.

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I dedicate this thesis to my parents and my wife.

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Acronyms

CAP	Contention Active Period
CSMA	Carrier Sense Multiple Access
DCF	Distributed Coordination Function
DCS	Distributed Control System
EDCF	Enhanced Distributed Coordination Function
FFD	Full Function Device
GTS	Guaranteed Time Slot
HART	Highway Addressable Remote Transducer
HCF	Hybrid Coordination Function
IEEE	Institute of Electrical and Electronics Engineers
ISA	International Society of Automation
LR-WPAN	Low-Rate Wireless Personal Area Networks
MAC	Medium Access Control
OLMQR	On-demand Link-state Multi-path QoS Routing

OLSR	Optimized Link State Routing
PAN	Personal Area Network
PCF	Point Coordination Function
PLC	Programmable Logic Controller
QoS	Quality of Service
RF	Radio Frequency
RFD	Reduced Function Device
RSS	Received Signal Strength
SCADA	Supervisory Control And Data Acquisition
TDMA	Time Division Multiple Access
TSMP	Time Synchronized Mesh Protocol
UWB	Ultra-Wide Band
WSN	Wireless Sensor Networks

Chapter 1

1. Introduction

1.1 Background

The oil and gas plants depend on control and monitoring applications as integral part of their operations. The process control and automation of a plant rely on interconnected monitoring and control devices. A typical process automation device, programmable logic controller (PLC), takes monitoring input, applies logic instruction set and provides an output. An example of a plant device which can be operated by PLC is a controllable plant valve. A feedback of pressure or flow speed values in a pipe can be fed to the PLC. The PLC process is the inputted values and output is control signals to further open or close valve gate according to a desired action. In a typical oil and gas plant there are hundreds of such devices that require monitoring and control to operate. Interconnecting such devices can be organized in complex systems such as distributed control systems (DCS) and supervisory control and data acquisition (SCADA) systems. Those plant control systems rely on wired communication infrastructure to inter-network. A number of proprietary communication protocols are used in such networks. The communication protocols of plant networks focus on reliability and delay bound delivery of control and monitoring traffic. In addition to the communication software design and infrastructure architecture to support delay and reliability goals, the fiber and coaxial cables provide low error communication medium. The installation and maintenance of communication wire cables in plant environments are costly. As in plant environments strict safety requirements have to be considered, such as flame-proof and explosive-proof communication cable wires. In addition, installation or maintaining cables requires ground trenching which may cause part of the plant to be offline and loose production efficiency.

The control and monitoring industry for plants automation have been exploring the use of wireless communications. The adoption of wireless as a communication medium for plant networks saves cost and adds flexibility. The largest portion of the cost of deployed plant networks is the cable wiring part. By implementing wireless based plant networks, the cost is reduced significantly. The reduction of cost opens the opportunity to control and monitor extra plant devices deemed previously unfeasible due to high cost. In addition, cable free control and monitoring opens up new plant areas and devices were deemed prohibitive due to reachable and operational difficulties. Rotating equipments such as gas turbine is an example of a plant device that cannot be monitored by wired communication means. In the past few years there have been a significant research work and industry involvement in the field of wireless sensor networks (WSN). The advancements on miniature design of WSN and developments of integrated low power wireless transceivers made WSN an attractive option for plant networks control and monitoring applications. The low cost and small WSN nodes have enough computing power and communication resources to implement plant devices control logic programs and communication protocols stacks. The plants automation goal is to deploy the low cost WSN control and monitoring system while keeping the reliability and delay performance of wired plant networks.

1.2 Motivation and Objectives

The recent advances in wireless and computing miniaturization coupled with progress in sensing technologies, made wireless sensor networks realization feasible. Wireless Sensor Networks (WSN) consist of presumably a large number of nodes that can be stationary or mobile and communicate using wireless medium. The networked nodes sense information from the physical world, process sensed data and route the data of interest to gateways for control and monitoring applications. Each sensor node is built of low power processor, small memory, low power wireless transceiver, sensing hardware and a power source (e.g. battery). WSNs have a wide range of sensing and control applications in the areas of: military, environmental, industrial, home and health care. It is envisioned that WSNs would be deployed in very large numbers and in various locations to sense all possible physical world phenomena [1-3].

Quality of Service (QoS) of a given network provides different classes of network performance applied to appropriate application demands. Each QoS class is a set of network operational requirements set by the end user application for best experience. In traditional computer networks performance metrics include end-to-end delay, delay variations (jitter), packet loss probability, bandwidth and minimum cost. In the context of WSN there are additional challenges to satisfy QoS classes and other unique set of performance requirements [4-7]. An example of WSN specific performance metric is coverage [8, 9]. Given an area of interest to sensing data, how well a set of WSN nodes can report sought information data is called coverage. If the area of interest is a moving target, the ability to sense this target is called exposure [8, 10].

The industry sector used wired sensing and control systems for many years. It has been used for example in manufacturing for production automation where Token Ring [11] communication protocol used to automate assembly lines. In the oil, gas and petrochemical sector Fieldbus [12] proprietary communication protocol has been used to transport and interconnect control, monitoring and automation systems. The applications running on classical networks such as the Web, e-mail, file transfer and multimedia require large packets size (Megabytes) and their traffic pattern is bursty in nature. Some of those applications like e-mail can tolerate network delay. Also multimedia traffic can tolerate some degree of packet loss. Unlike classical computer networks traffic, the industrial application communication networks have low data packet sizes, delay bound, periodic traffic and reliability requirement. When designing wireless communication protocols those industrial application requirements have to be satisfied for a protocol to be adopted. In the case of WSN environment additional requirements and challenges arise [13-18]. In this thesis, we are interested in the performance of network protocols in terms of delay and packet loss (reliability). The interest of QoS protocols is focused on the real-time class and how this class performs in term of latency and reliability. Throughout this thesis we use QoS term referring to the real time class performance. The discussion of the different classes of QoS protocols, such as non-real-time and loss tolerant classes, are out of the scope of this thesis.

The objective of this thesis is to propose a wireless sensor communication protocol architecture for the applications of control and monitoring of oil and gas plants networks. The HARD protocol is expected to meet the performance of existing wired protocols for plants networks in terms of reliability and delay performance. The overall objective of the thesis can be summarized in the following sub objectives:

- Propose a network architecture and MAC protocol that is based on location service, time synchronization, cross layer design and grid topology.
- Select an existing transport and physical layer protocols that can work best in harmony with our proposed architecture of routing and MAC protocol.
- Propose design guidelines for wireless sensor network topology deployment based on oil and gas floor plans.
- Develop mathematical model of reliability and delay for the HARD protocol
- Develop a simulation program for the proposed architecture along with MAC protocol.

1.3 Thesis Contribution

The contributions of this thesis can be summarized as follow:

- Introduced a novel protocol architecture for a highly reliable and delay bound WSN communication protocol for oil and gas plants applications.
- Provided a simple analysis and formulation of the HARD protocol delay and reliability performance.
- Developed a simulation for the performance evaluation, in terms of delay and reliability, of the HARD protocol architecture.

1.4 Thesis Outline

The thesis is organized as follows. Chapter 2 gives a background and literature survey for QoS WSN protocols of real time traffic class, presents challenges to provision QoS real time class performance for WSN and provides examples of WSN QoS based routing protocols for real time traffic. Chapter 3 presents the proposed highly reliable and delay bound WSN protocol HARD for oil and gas plants, presents related work and analyzes the performance of the HARD protocol. Chapter 4 presents the HARD protocol simulation setup and discusses results. Chapter 5 provides concluding remarks and future work.

Chapter 2

2. Background and Literature Survey

2.1 Introduction

In this chapter we introduce the WSN area and provide a background for provisioning QoS for real time traffic in WSN environments. The QoS performance metrics on classical networks and specifically for WSN environments is discussed. The different challenges arising when applying QoS of real time traffic class for WSN are laid out. Also the factors affecting a protocol design are discussed. The chapter concludes with an example of QoS of real time traffic class protocols for WSN emphasizing and highlighting the different methods applied.

2.2 Wireless Sensor Networks

Wireless Sensor Networks is typically a collection of miniature computing devices that sense the physical world and deliver data to collection points by wireless communication means. The WSN device node main components are the computing, communication and sensing parts. Additional components such as the power source and actuation are customized based on the targeted application. WSN has unique characteristics that affect protocol design such as limited computing resources and harsh communication environments. Also the limited power resources add a challenge to WSN performance and reliability. The topology of WSN is typically infrastructure-less and can be deployed randomly or by design. The WSN nodes can be mobile in some applications such as sensing a moving target. There are a number of applications were WSN can be employed such as in: health care, plants monitoring, security, environment monitoring and military applications [1-3].

The anticipated applications and wide deployments of WSNs dictate their design to be low cost, low power and scalable. In addition, there are a number of challenges WSNs have to overcome for practical large deployments to take place. The operating systems and routing protocols of WSNs have to demand low computing power and storage size. The medium access and link control protocols as well as routing protocols of WSNs have to account for unreliable and error prune wireless medium. The vulnerable nature of WSNs to adversary attacks and unreliable nodes/medium makes security and fault tolerance important design considerations [1-3].

The power consumption management is critical component of WSNs operation. The power source used in sensor nodes is typically battery based which is irreplaceable power source. Despite the limited power source, the WSN nodes and overall network life expectancy is in years. In addition, WSN nodes are expected to be deployed in remote and hard to reach areas that make replacing the power source (e.g. battery) not practical. The top power consuming operations in WSNs are wireless transmission and wireless reception. The rest of the operations are small compared to wireless transmission/receiving (Table 2.1) [1-3].

Operation	nAh
30-byte Packet transmission	20
30-byte packet reception	8
1ms radio listening	1.25
Sensor analog sample	1.08
Sensor digital sample	0.347
Reading sample from ADC	0.011
Flash read data	1.111

Table 2.1: WSN Node Mica Mote Power Consumption [3]

2.3 QoS in Wireless Sensor Networks

Quality of Service (QoS) provides different classes of network performances satisfying different application performance demands. In traditional computer networks QoS performance metrics includes end-to-end delay, delay variations (jitter), packet loss probability, bandwidth and minimum cost. In the context of WSN there are additional challenges to satisfy QoS required performance and other unique set of QoS requirements [4-7]. An example of WSN specific QoS metric is coverage [8, 9]. Given an area of interest to sensing data, how well a set of WSN nodes can report sought information is called coverage. If the area of interest for sending data is moving target, the ability to sense this target is called exposure [8, 10].

2.3.1 QoS Performance Metrics

2.3.1.1 Physical Layer

The physical layer of the WSN as any wireless medium is vulnerable to errors, noise, and interference, multipath and shadowing [5] [19-20]. In addition, WSN nodes have limited power source where the activity of physical wireless transmission consumes the most power. Thus it is crucial for end-to-end wireless data transmission to exhibit low bit error rate in order to avoid wasted power. The bit error rate also can be used as a physical layer QoS performance metric to influence packet routing in WSN [21]. The signal to interference ratio metric affect bit error rate and achievable bandwidth. Thus the path with best signal to interference ratio can indicate higher bandwidth to satisfy a QoS route requirement for a given class [22]. The node power level information can be used as a QoS physical layer performance metric passed to the routing layer. A routing algorithm that is power aware reduces the possibility for WSN nodes to fail and affect network connectivity which eventually influence overall QoS performance of the WSN network [23-26].

2.3.1.2 MAC Layer

The objective of the MAC in the WSN is to manage the communication medium efficiently. This can be accomplished by maximizing the throughput of the wireless medium, minimizing medium access delay, achieving fairness and avoiding transmission collisions. Those MAC layer objectives can be used as QoS performance metrics. A deterministic performance of MAC can be accomplished using contention free protocols. For example, using Time Division Multiple Access (TDMA) technique in the MAC provides deterministic throughput and delay expectations. However, TDMA MAC is inefficient in low traffic and requires global synchronization which is a challenge for WSN environments [27]. Other contention free MAC techniques include frequency, phase, code and space divisions. Those MAC techniques however require more complex RF circuits which increase the cost of the sensor node. On the other hand, contention based MAC protocols, such as CSMA, are simple to implement and therefore cost less. Contention based MAC protocols perform well in low traffic scenarios. However in high traffic cases, collisions can increase which cause poor throughput and unpredictable delays. Other techniques such as central coordination and prioritization can be incorporated in CSMA to enhance QoS performance. The efficiency of the MAC protocol (data to control overhead ratio) can be used as a QoS performance metric [28]. Also the efficiency of the MAC protocol power consumption is another QoS performance metric [29]. The MAC channel access delay can be used as a MAC layer metric passed to routing for QoS path selection of real time traffic class [30]. The MAC layer link reliability and stability is affected by bit error rate, wireless transmission failures, nodes failure and node mobility. A QoS real time traffic class path selection can be based on MAC layer stability and reliability [30-34].

2.3.1.3 Network Layer

The objective of a QoS routing protocol is to offer different classes of service satisfying a number of performance metrics such as throughput, end to end delay, jitter and reliability. A QoS routing protocol with multiple constraints to be satisfied is found to be NP-Complete problem [4]. The end to end path throughput in WSN can be communicated and used as a QoS performance metric for routing decisions [35]. Another network layer QoS performance metric used for path selection is the end to end delay and jitter [36]. The WSN node free buffers space is a QoS performance metric that may indicate delay incurred by each node. This measure can be used for QoS real time class traffic path selection to minimize delay [37]. The packet loss measurement on a certain path or link can be used to indicate QoS reliability performance metric [29].

An example of routing protocol using network layer performance metrics to offer different QoS classes is the Tickets Based Routing Protocol [36, 38]. Tickets are given to nodes with which represent how many node/path can be explored to find the satisfying path providing required QoS class performance. The more tickets are granted the more thorough is the search for the best satisfying path of QoS class performance requirement. So if the QoS class performance requirements are high, more tickets are needed to satisfy the requirements. There is a tradeoff between the number of tickets granted, the control overhead and the delay it takes to satisfy the QoS class performance requirement. The other un-chosen paths that does not fully satisfy QoS class performance requirements are being saved for backup paths in case of state information changes caused by nodes mobility or failure. The idea behind using tickets is to reduce the QoS call admission failures. However, a path with the targeted QoS class performance criteria is not guaranteed.

2.3.1.4 Transport and Application Layer

Traditionally most of the QoS functions are performed by network and data link layers. Where transport focus mainly in data flow control and end-to-end reliable transport. There is little work done in the field of QoS transport protocols for WSN [39-42]. Transport layer can regulate traffic according to information passed up by lower layers (i.e. network and MAC) to satisfy QoS performance requirements. A QoS transport layer protocol can work in harmony with lower layers to achieve low latency, reliable and power aware end-to-end while avoiding congestion. For example, a transport layer can initiate transport session when MAC layer nodes signal duty cycle to minimize delay and conserve power. Also, a transport layer will not initiate traffic while network layer is in the state or route discovery.

Depending on the application type, WSN frames delivery models maybe classified as event-driven, query-driven and continuous [8, 43]. Also the application QoS performance requirements may be end to end for some and for other WSN applications may require QoS for limited number or area of the WSN. Some application requires information sent only in one direction (i.e. end nodes to sink) and some require interactive information flow. While other applications are delay tolerant, some applications require real time reporting. Also a class of applications is mission critical where there is zero tolerance to losing packets while other applications may tolerate few packets loss that may be corrected in higher layers [8]. Application layer can perform some functions of lower layers such as error checking and correction [44]. This additional application layer function enhances QoS performance by avoiding retransmission which save WSN energy, lower latency and improve reliability. Application layer also can classify sensed data with required QoS class performance level and pass it on to lower layers. The application session acceptance and blocking ratio along with application session completion and dropping ratio can be used as a metric to measure application layer QoS performance [29].

2.3.2 Provisioning QoS Challenges in WSN

There are a number of challenges for provisioning QoS protocols in WSN which communication protocols design need to overcome. Nodes of WSN operate in wireless environments where unreliable channel, noise, shadowing, multipath and interference are common place [19, 29]. The broadcast nature of WSN adds further challenges to the medium access control. At the MAC level, there are challenges of collisions, fairness, efficiency, hidden terminal problem [45] and exposed terminal problem [46]. An illustration of the hidden terminal problem is given in Figure 2.1 where nodes A and B have ongoing communication that is interfered by node C trying to establish communication with terminal B. The cause of the problem is that terminal C is out of the transmission range of node A. The exposed terminal problem illustrated in Figure 2.2 takes place when the ongoing communication between nodes C and D prevents the establishment of communication between terminals B and A. The clear to send and ready to send control frames can be used to solve some scenarios of the hidden and exposed terminal problems. The infrastructure-less and lack of central control in WSN make it difficult for QoS protocols to efficiently and effectively reach its objectives. For example, QoS state information is distributed along the nodes of WSN which needs to find a mechanism to share them to reach a common goal of high performance QoS routing. Node mobility in WSN adds another layer of QoS state information variation. In addition, node mobility may cause additional collisions, noise and interference to the wireless channel. Nodes in the WSN have limited resources of power, processing and memory. Routing protocols and MAC algorithms for high performance QoS require frequent updates for state information. Those updates of state information consume wireless transmission power and considerable memory space. Also, QoS algorithms are complex and thus require significant computing power [29].

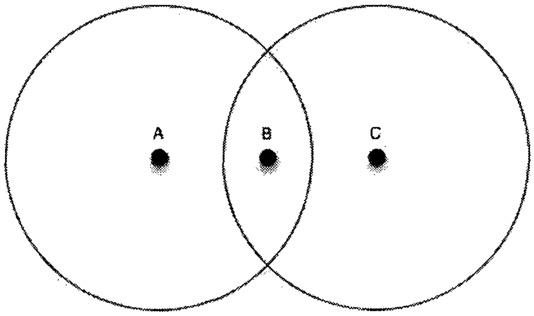


Figure 2.1: Hidden Terminal Problem

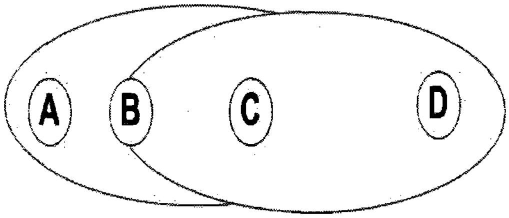


Figure 2.2: Exposed Terminal Problem

2.3.3 Factors Affecting Performance of QoS in WSN

There are a number of factors affecting the performance of QoS routing protocols that need to be considered as design issues for WSN. The WSN network size in terms of number on nodes and area covered affect network state information propagation [47]. The larger the network the more overhead and latency incurred during the distribution of network state information. Routing protocols delivering high performance QoS of WSN may depend on inaccurate or outdated state information and thus make suboptimal routing decisions. Node mobility may break link layer neighborhoods, route paths and change QoS protocol network state information. The frequency of network state information exchange required to be higher than the speed of node mobility in order to have accurate state information [28, 48]. Also the nature of the sensing application in terms of the amount of sensed data and the frequency of sensing will influence QoS routing design [28]. Transmission power increase may enhance the probability to receive the frame error free as the wireless transmission may overcome noise and interference. More error free frame transmission means lower retransmissions and better QoS performance (i.e. less delay and more throughput) [24-26, 29].

2.3.4 Provisioning QoS Approaches Tradeoffs

There are a number of tradeoffs arising when designing QoS routing protocols for WSN. There are broadly three approaches for QoS routing discovery in WSN. The proactive scheme [47, 49] periodically updates routing and QoS network state information. Therefore, the most accurate state information is available for QoS routing protocols but at the cost of addition overhead and inability to scale. The reactive scheme [47] inquires for QoS network state information when there is a route request. This method incurs less overhead but may not be suitable if the QoS objective is to reduce delay. A middle ground scheme is the hybrid approach where clusters or zones [33] enclose WSN nodes. Each cluster or zone has a primary node called cluster head. Communications through cluster heads follow the on-demand approach. The other nodes in the cluster can communicate only through cluster head nodes. Nodes within clusters can communicate using proactive scheme. This method solves the overhead and scalability issues but may result in less accurate QoS state information. There is also a tradeoff between network capacity and delay in QoS performance routing design for WSN, where an approach of having multiple copies of the same packet sent in multipath to reduce delay [50]. Also chopping the packet into smaller portions sent in multipath to destination [51] reduces delay and adds reliability. However, those methods reduce the overall available capacity in the network. Another tradeoff is between the accuracy of network state information and the network power resources conservation. The more nodes go off sleep the more up-to-date and accurate state information can be obtained for high performance routing protocols. But this consumes more energy and may lead to nodes failures [52].

There is a tradeoff between the wireless transmission ranges of nodes with delay [53]. The further is the transmission range the least number of hops needed to reach destination and thus less latency. However, increasing wireless transmission range consumes more node power energy and may cause interference or noise. Also in some cases individual WSN nodes objectives may collide with network global objectives. A multipath routing may add reliability and lower latency network wide but at the same time consume more individual nodes power and capacity [29].

2.4 QoS Based WSN for Industrial Applications

2.4.1 Industrial Applications QoS Requirements

The industry sector has used wired sensing and control systems for many years. Wire line communication method has been used for example in manufacturing for production automation where Token Ring [11] communication protocol used to automate assembly lines. In the oil, gas and petrochemical sectors, Fieldbus [12] proprietary communication protocol has been used to transport and interconnect control, monitoring and automation systems. Unlike classical computer networks traffic where large packet sized data, burst like, delay tolerant and loss tolerant are common place. The industrial application communications networks have low data packet sizes, delay bound, periodic traffic and reliability requirement. When designing wireless communication protocols those industrial application requirements have to be satisfied for a protocol to be adopted. In the case of WSN industrial environment additional requirements and challenges arise [14-18, 40].

2.4.2 WSN QoS Based Protocols for Industrial Applications

2.4.2.1 SensiNet

SensiNet of SensiCast [54] is a proprietary wireless communication protocol for industrial applications. A classical SensiNet network consist of coordinator, mesh routers and sensor nodes organized in a star topology as seen in Figure 2.3. The protocol uses frequency hopping while adaptively avoiding channels with high error rates. In a simulation experiment of SensiNet consisting of 1 coordinator, 4 mesh routers and 10 sensor nodes, it was found that SensiNet exhibit high reliability nearing 100% but perform poorly in power consumption [16, 55].

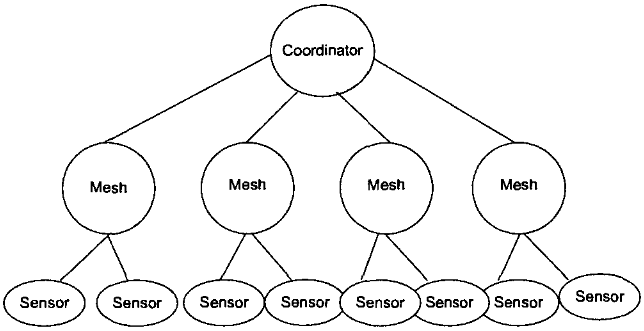


Figure 2.3: SensiNet Topology

2.4.2.2 Time Synchronized Mesh Protocol

Time Synchronized Mesh Protocol (TSMP) is a proprietary communication protocol developed by Dust Networks for WSN. The operation of TSMP uses synchronized time slots called guaranteed time slots (GTS). The GTS ensures low power operation and low bandwidth reliability. The TSMP architecture consists of one coordinator and multiple sensor nodes up to 250 nodes (see Figure 2.4). Each sensor node can operate as mesh router providing resiliency and reliability. This protocol adaptively avoids paths with high error rates and high delay and search continuously for better performing paths. In an experiment operating TSMP with coexistence of IEEE 802.11b, some paths suffer from high error rates and high delay. The adaptive feature of TSMP gradually chooses other paths with fewer errors and less delay [56, 57].

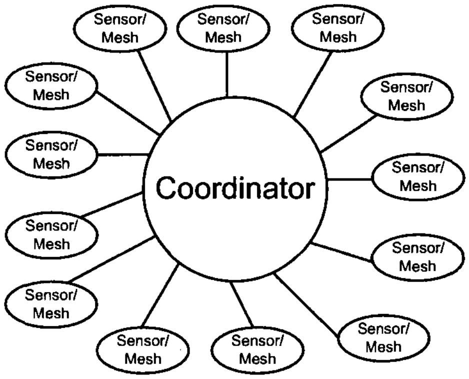


Figure 2.4: Dust Network TSMP Network Topology

2.4.2.3 Wireless HART

The wireless HART is an evolution of industrial communication protocol Highway Addressable Remote Transducer (HART). The wireless HART uses the physical layer of the standard IEEE 802.15.4 with a modified MAC layer. The operation of the protocol involves synchronized time slot transmission along with some slots allocated for event based. The protocol topology consists of multi-hop mesh router nodes architecture. A frequency hopping mechanism is incorporated for added wireless transition reliability [16, 58].

2.4.2.4 Zigbee Pro

The Zigbee Protocol of the Zigbee Alliance introduces a network and application layer for the standard IEEE 802.15.4 which defines MAC and physical layers. The Zigbee protocol was introduced targeting industrial, consumer and commercial applications. It is based on low power, low range and low data rate communications. The Zigbee network can be organized in peer to peer or star topology as seen in Figure 2.5. The Zigbee protocol runs over IEEE 802.15.4 Low-Rate Wireless Personal Area Networks (LR-WPAN). The IEEE 802.15.4 is a simple, low range, low data rate and reliable protocol. The manufacturing cost of IEEE 802.15.4 protocol is intended to be very low. Also it is designed to consume small amount of power to be applicable for WSN applications. The physical layer of IEEE 802.15.4 can operate in three bands 868 MHz (single channel), 915 MHz (10 channels) and 2450 MHz (16 channels). For a reliable operation the physical layer employs clear channel evaluation, link quality measurement. The radio can go on and off for power efficient operation. In the MAC layer two types of IEEE 802.15.4 nodes are defined: Reduced Function Devices (RFD) and Full Function Devices (FFD). Also there are other MAC functions performed by Personal Area Network (PAN) coordinators such as multi-hop communications.

In the peer to peer operations FFDs can communicate with other FFDs or RFDs in the same frequency channel. The FFD functions include beacon transmissions, synchronization and managing join network requests. The PAN coordinator function in the peer to peer topology is multi-hop communications. In the master slave topology, PAN coordinator or FFDs can take the role of master nodes. The slave nodes can be FFDs or RFDs. The communication model is based on polling from master nodes to slave nodes. The MAC can operate in two modes: super-frame mode and un-slotted CSMA-CA mode. In the un-slotted mode channel access is contention based and communications between nodes with PAN coordinators are poll based. On the other hand, on the super-frame mode there is contention free period (CFP) and contention active transmission periods (CAP) harmonized by PAN coordinators (see Figure 2.6). In the CFP mode, nodes with reserved slots announced in the super-frame period can only send frames to the shared medium. The real time traffic can utilize CFP mode to send delay bound frames. The other traffic with non real time requirements can be sent during the CAP mode where CSMA is used to transmit frames [16, 59-61].

The latest addition to the Zigbee Alliance protocol is Zigbee Pro where additional profiles have been added to the application stack such as home automation and automatic meters reading. There are a number of areas which have been improved in the Zigbee pro, such as security, where a central security key authority has been introduced. There are also enhancements to power management support for Zigbee end devices where more control is given to the user to conserve energy. There were also enhancements on the interference management and support for larger networks. In addition, a new support of mobility to handle moving Zigbee nodes is added [62].

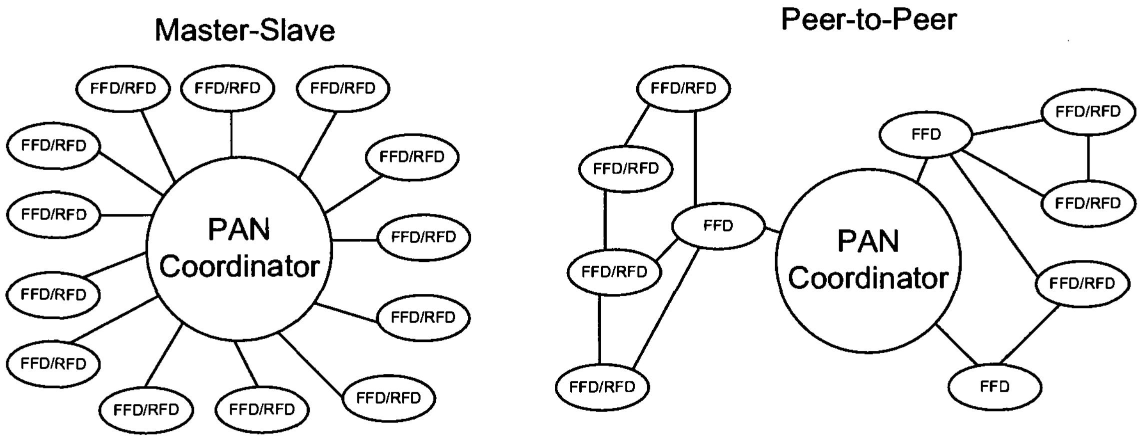


Figure 2.5: Zigbee IEEE 802.15.4 Topologies

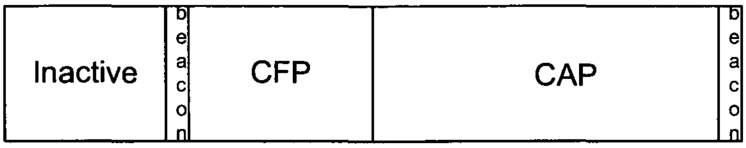


Figure 2.6: Zigbee IEEE 802.15.4 Super-frame

2.4.2.5 ISA SP100

The International Society of Automation (ISA) develops standards for control and automation in industrial environments. The ISA SP100 is a set of standards for wireless communication for industrial applications. The ISA SP100 ratified in 2008 to be a replacement for wired control and automation communication protocols. It is designed to conserve the same QoS requirements, reliability requirements and security of wired communication protocols. The ISA SP100 is designed to coexist with Wireless HART, Bluetooth and IEEE 802.11. The wireless ISA SP100 nodes are expected to consume low energy. Also as a reliability feature, it is expected to be resilient to interference and noise. The architecture of ISA SP100 consists of routing devices and non routing devices. It also supports mobile devices such as handhelds as shown in Figure 2.7. All devices can be connected to wired backbone routers which connect to the plant network control system [63].

2.5 QoS Techniques Employed in WSN

2.5.1 Reservation Based

In a reservation based QoS WSN protocols the access medium is regulated so that bandwidth and delay are guaranteed. In addition, the communication medium becomes collision free and thus save power energy for WSN nodes. An example of reservation based protocols is Cluster TDMA [38, 64].

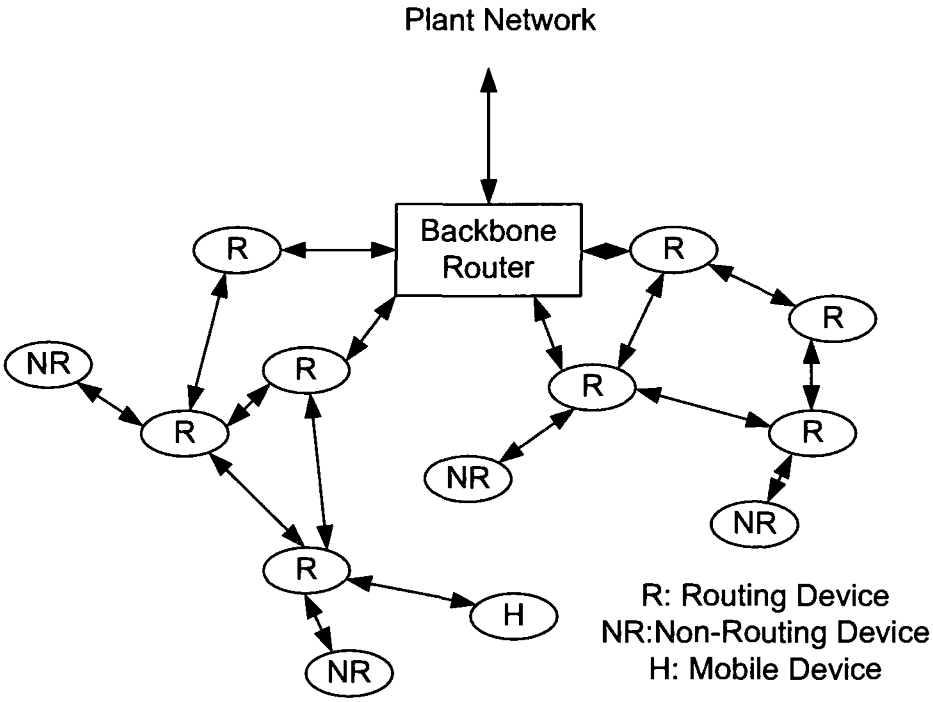


Figure 2.7: ISA SP100 Architecture

Nodes are organized in clusters with elected cluster heads. Cluster heads are one hop away from other cluster heads as shown in Figure 2.8. The reservation based slotted TDMA are utilized by nodes within the cluster to transmit data. The transmitted frames consist of control phase and data phase. The control portion distributes reservation information. There are slots reserved for real time traffic and the best effort traffic takes the remaining free slots similar to slotted ALOHA.

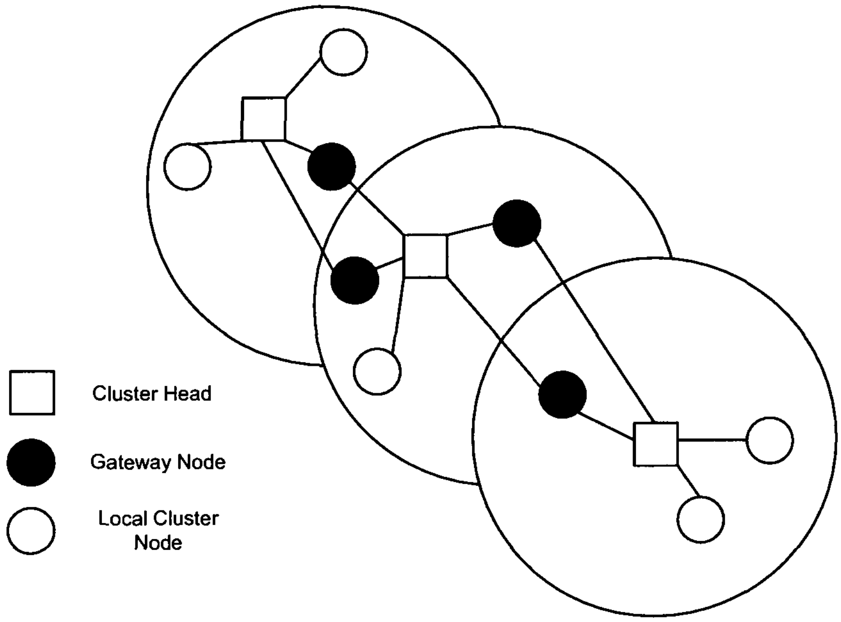
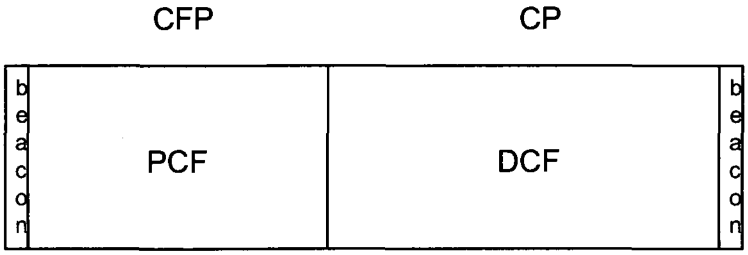


Figure 2.8: Cluster TDMA

2.5.2 Contention Free MAC

In the contention free MAC protocols high performance is satisfied by avoiding collisions and prioritizing traffic. An example of such protocols is the IEEE 802.11e. IEEE 802.11 MAC [64] classically uses distributed coordination function (DCF) where traffic is treated in best effort manner with the use of CSMA/CD to reduce collision and back off timers. The Point Coordination Function PCF uses contention free period for real time traffic and contention based for best effort traffic (see Figure 2.9). PCF has a disadvantage however where contention free time may be taken by prolonged contention period and the real time traffic has to wait. Also the back off timers of all traffic is uniform so there is no class of service in the DCF. The IEEE 802.11e with enhanced DCF EDCF [65] is introduced to solve PCF issues.

At the IEEE 802.11e EDCF (see Figure 2.10) each station maintains multiple queues with different priorities for its queued traffic. The EDCF MAC protocol prioritization employ different back off timers for each queued traffic based on that higher priority traffic has faster access to the shared channel (i.e. less back off timer). In the hybrid coordination function (HCF) the advantages of EDCF and PCF are combined. The HCF [66] can take the communication medium into contention free periods where stations can be polled to send EDCF traffic at contention free periods. When the HCF is not in control of the shared medium, the MAC operation falls back to normal EDCF. Those QoS methods are good for classical traffic with different QoS requirements, like data, voice, and video [38].



CFP: Contention Free Period
CP: Contention Period
PCF: Point Coordination Function
DCF: Distributed Coordination Function

Figure 2.9: IEEE 802.11e Frame

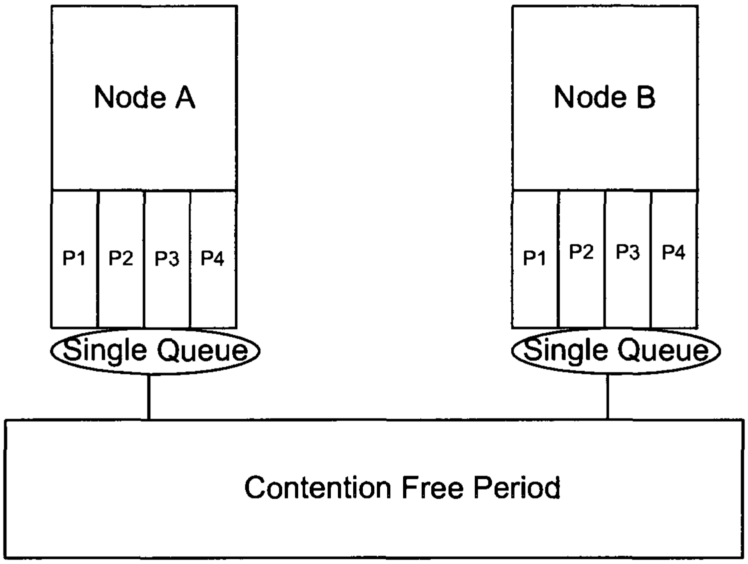


Figure 2.10: IEEE 802.11e EDCF Prioritization

2.5.3 Multi-Path Routing

The use of multi-path routing scheme for QoS increases the probability to find the best satisfying QoS path, increases reliability and lowers delay. An example of such protocol is the On-Demand Link-State Multi-Path QoS Routing (OLMQR). In OLMQR, multiple paths of the WSN network are discovered to satisfy the QoS requirement. The best path is chosen to route packets and other second to best routes are kept as backup. The disadvantage of this method is the overhead associated with multi-path routing discovery [38, 67].

2.6 Summary

In this chapter we introduced WSN and gave a background for provisioning QoS in WSN environments. The QoS performance metrics on classical networks and specifically for WSN were discussed. The different challenges introduced when demanding high performance QoS for WSN were laid out. Also the factors affecting protocol design were discussed. The chapter ends with examples of high performance QoS protocols for WSN emphasizing different methods applied.

Chapter 3

3. Highly Reliable and Delay Bound WSN Protocol

3.1 Introduction

In this chapter we propose a highly reliable and delay bound WSN protocol, called HARD, for oil and gas plant applications. First, we review the related work in the field of high performance WSN protocols. Then, we present the different layers of the protocol HARD. At the end, we analyze the delay and reliability objectives of the proposed protocol.

3.2 Related Work

3.2.1 High Performance QoS in Wireless Sensor Networks

There are a number of WSN applications where real time protocol performance is required. The WSN protocol can classify the different traffic types into different classes based on performance requirements. For example, a fire sensed in an environment will need a real time performance treatment where sensed air temperature can be sent over best effort QoS class. In application specific WSN protocols a single class treatment for traffic can be implemented. The different layers of WSN protocol can share data between each other to coordinate high performance operation. Such protocol approach can be called cross-layer design.

The objective of the MAC in the WSN is to manage the communication medium efficiently. This can be accomplished by maximizing the throughput of the wireless medium, minimizing medium access delay, maintaining access fairness and avoiding transmission collisions. The objective of a high performance routing protocol is to satisfy a number of metrics such as throughput, end to end delay, jitter and reliability. A high performance QoS routing protocol with multiple constraints to be satisfied is found to be NP-Complete problem [68]. Traditionally most of the QoS functions are performed by the network and data link layers. On the other hand, the transport layer focuses in basic objectives of mainly data flow control and end-to-end reliable transport. There is little work done in the field of QoS and high performance at the transport layer for WSN [39-42].

Transport layer can regulate traffic according to information passed up by lower layers (i.e. network and MAC) to satisfy QoS requirements. A high performance transport layer works in harmony with lower layers to achieve low latency, reliable and power aware end-to-end while avoiding congestion. There are a number of challenges for provisioning high performance network operation in WSN which a given network protocol design need to overcome. Nodes of WSN operate in wireless environments where unreliable channel, noise, shadowing, multipath and interference are common place [19, 29]. The broadcast nature of WSN adds further challenges to the medium access control. At the MAC level, there are challenges of collisions, fairness, efficiency, hidden terminal problem [45] and exposed terminal problem [46]. The infrastructure-less and lack of central control in WSN make it difficult for high performance protocols to efficiently and effectively reaches its objectives.

There are a number of factors affecting the performance of routing protocols that need to be considered as design issues for WSN. For example, the WSN network size in terms of number on nodes and area covered affect network state information propagation and thus affect network performance [47]. There are a number of tradeoffs which arise when we design high performance routing protocols for WSN. There are broadly three approaches for routing discovery in WSN. The proactive scheme [47, 49] periodically updates routing and network state information. Therefore, the most accurate state information is available for routing protocols but at the cost of additional overhead and inability to scale. The reactive scheme [47] inquires for network state information when there is a route request. This method incurs less overhead but may not be suitable if the high performance protocol objective is to reduce delay. A middle ground scheme is the hybrid where clusters or zones [33] enclose WSN nodes where proactive schemes take place at small scale. This method solves the overhead and scalability issues but may result in less accurate state information.

3.2.2 Multi-Path and Reliable Routing for WSN

The MAC channel access delay value can be used as a MAC layer metric passed to routing layer for high performance requirement path selection [30]. A high performance route selection in the MAC layer can be based on a reliability and stability of the link. The MAC layer link reliability and stability is affected by a number of metrics such as bit error rate, wireless transmission failures, nodes failure and node mobility [30-34]. The medium access and link control protocols and routing protocols of WSNs have to account for unreliable and error prone wireless medium. The vulnerable nature of WSNs to adversary attacks and unreliable nodes or medium makes security and fault tolerance important design considerations [1-3].

The use of multi-path routing scheme for high performance routing increases the probability to find the best satisfying high performance path, increases reliability and lowers delay. An example of such protocol is the On-Demand Link-State Multi-Path QoS Routing (OLMQR). This protocol uses the approach of having multiple copies of the same packet sent in multipath to reduce delay [50]. Also it uses the technique of chopping the packet into smaller portions sent in multipath to the destination [51] which reduces delay and adds reliability. However, those methods reduce the overall available capacity in the network.

In [73] the author proposes an Energy Aware Multi-path Routing protocol that incorporates energy levels in nodes as a part of the routing decisions. Multi-path routing protocols have been proposed in the context of wireless sensor networks for two main objectives: load balancing and reliable routing. The multi-path load balancing routing chooses a number of disjoint routes that will result in load balancing of power consumption across different nodes. The multi-path reliable routing protocol sends a number of copies of the same packet through different routes that will increase the probability of an error free arrival of packet to destination. Those two routing protocols exhibit two main drawbacks. The multi-path routing algorithms do not consider the battery power levels of individual nodes into route decisions. This may cause some nodes in the wireless sensor network to go out of power and thus becomes nonfunctional. This will further cause the network to be split into islands of connected nodes. Wireless sensor nodes in those islands will not be able to communicate with each other. The other weakness is the additional overhead caused by the multi-path routing protocols. Some of the multi-path routing protocols exhibit 30% overhead compared to normal single path routing protocols. The overhead increases as the density of the wireless sensor network decreases [73].

3.2.3 Location Based Routing

Location based routing uses position information to make routing path selection decisions. By implementing location based routing, route discovery overhead becomes unnecessary. Also routing forwarding table is not needed in WSN nodes. Those advantages reduce overhead, save nodes power and require small node resources (i.e. memory and computing). There are a number of protocols proposed in the literature to obtain position information. Some protocols use mobile GPS nodes to feed position information to other WSN nodes. The Received Signal Strength (RSS) can be used to obtain position information. A number of WSN with known fixed locations which are distributed through the network can provide reference location information to other nearby WSN nodes. There are other methods that use RSS along with time arrival or time difference of arrivals with a known node location. Also multilateration and trilateration [55] with known location nodes can be used to determine position information. The location information can be inferred by single hop or multihop [55]. The forwarding mechanism of location based routing can forward traffic to a certain geographic area (i.e. Geocasting). Another forwarding method is to use greedy algorithms such as the most forward greedy routing. However, greedy routing needs recovery mechanism in some cases such as FACE-2 [60]. An example of location based routing that incorporates QoS in its routing decisions is the optimizing cost over progress ratio routing [74] which proposes a framework to solve a number of routing problems in WSNs such as power aware routing, maximum network life-time routing, QoS based routing and physical medium based routing. The load over progress optimization ratio formula is:

$$Next\ Node \xrightarrow{Selection} \frac{Load}{Progress\ to\ Destination}$$

It is assumed that each node has its own location information that is used to calculate the neighbor that satisfies the most progress toward destination node. The load information is shared through the hello control messages exchanged between neighbors. A given node will forward a packet to the neighbor node that satisfies the minimum load over the most progress toward destination. The ratio formula employed by this algorithm does not have the occasional erroneous effect of thresholds. But it does suffer from routing stuck in local optima that require recovery mechanism [74].

3.2.4 Grid Topology

The topologies of WSN nodes affect the MAC protocols, routing protocols, time synchronization, power efficiency and location information. The nodes of WSN can be deployed in random topology, line topology, star topology or grid topology. In the grid topology (see Figure 3.1), WSN nodes are organized on identified grid cells. A grid topology has an advantage of organizing cell in small clusters, enable scalability, assist location based routing and in time synchronization. Simulation results show that WSN nodes organized on grid topology exhibit lower and consistent delays compared to random deployments of nodes [75]. An example of a routing protocol that uses grid topology is Grid Optimized Link State Routing (Grid-OLSR) where a link state routing protocol takes advantage of grid position based routing. The advantages include added reliability and scalability [76].

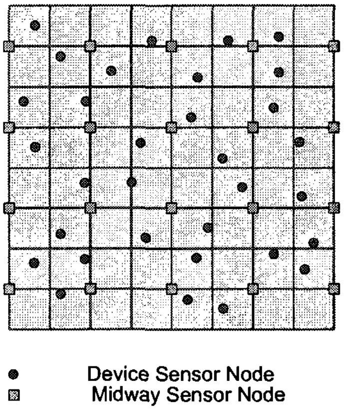


Figure 3.1: Grid Topology

3.3 Problem Discussion

In this thesis we provide a novel simple protocol to solve the problem of providing reliable and delay bound WSN protocol for oil and gas plants environment. The wireless environment where WSN nodes operate is prone to errors, noise, interference, shadowing and multipath. The outdoor environment of oil and gas plants with its metal construction adds challenges to the wireless transmission. The wireless solution is sought to reduce the high cost of wired control and monitoring systems. The lower cost of WSN in control and monitoring applications encourages adding more plant devices to the sensing network. In addition, there are some plant devices that are vibration based or moving based where wired means of communication is unfeasible. The WSN system is expected to perform similar to existing wired system (see Figure 3.1). The WSN nodes are limited in power resources and computing resources. A proposed protocol should consume low power and demand limited computing resources.

Control Traffic Characteristics				*Implication on WSN Protocols*	*Link Layer*	*Network Layer*	*Trans-port Layer*
Category	*Class*	*Application*	*Description*				
Safety	0	Emergency Action	always critical	small amount of data; real time; reliability crucial	large number of neighbors; time sync	Multi-route; multi-path; backhaul use	UDP like (no ack)
Control	1	Closed Loop Regulatory Control	often critical				
	2	Closed Loop Supervisory Control	usually non-critical	small amount of data; real time; reliability important	large number of neighbors	Multi-path; backhaul use	UDP like (no ack)
	3	Open Loop Control	human in the loop				
Monitoring	4	Alerting	short term operation consequences	large amount of data; delay tolerant; tolerate some reliability hits	couple of neighbors	patch routing	TCP like (ack)
	5	Logging /downloading/ uploading	no immediate operation consequences				

Table 3.1: Solving Problem Design Options

3.4 The Reliable and Delay Bound Protocol HARD

3.4.1 Assumptions

In our proposed protocol assumptions, we tried to be close to real life consideration for oil and gas plants environment as much as possible. The plant takes the shape of square or rectangular, where there are areas of structure steel and free space areas. The areas of structures can consist of plants buildings, plants devices and equipments. Light bulb poles are assumed to be uniformly distributed across the plant area (used for 24 hours work schedule and security considerations). Each 4 light bulb poles create a grid cell where Device sensor nodes are located, while each light bulb pole carries a mounted Midway node. A Midway node is a super node that connects to the backbone of the plant networks via wired communication. A midway node also connects with Device nodes located within a grid cell via wireless communication. All midway nodes communicate with each other via fully non-blocking switched medium. All neighbor midway nodes synchronize their traffic and activities. Midway nodes get power from light bulb pole while device nodes have battery based power or power harvesting schemes. Device nodes learn their location information from Midway nodes within grid cell accuracy. Each Device node in a grid cell is synchronized and maintains a prioritized ID. It is assumed that data generated by Device nodes are small in size.

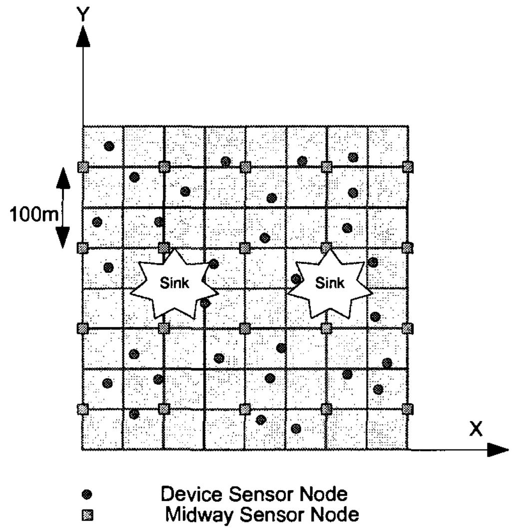


Figure 3.2: HARD Protocol Environment

3.4.2 Sensor Nodes Power Sources

A Midway node get power from light bulb poles while device nodes have battery based power. So the super Midway nodes have unrestricted power source. The Device nodes can be powered by battery energy. In our protocol HARD, Device nodes wake up and transmit only if it has data to send or receive. Most of the energy consumed in WSN nodes are from transmit or receive activities (see Table 2.1). With low duty cycle, battery replacement can be extended with obsolescence device replacement (i.e. 3-5 years). Other power sources can come from energy harvesting technologies applicable to plants environment such as vibration power harvesting, solar power and heat power.

3.4.3 Suggested Physical Layer

The physical layer of HARD protocol is suggested to be based on Ultra-Wide Band (UWB) radio technology. There are a number of advantages introduced by UWB to the HARD protocol. For example, UWB is very resilient to multipath, interference and noise. This adds another layer of reliability to HARD protocol especially that the HARD protocol is targeted for plants environment where multipath and noise is a common place. The wireless transmission of UWB can reach high data rates depending on bandwidth used and distance. As HARD protocol demands low amount of traffic, multiple copies of the data frames can be transported in one UWB transmission. This technique increases the probability to deliver error free frames to destination. In addition, UWB is a low power radio technology which makes it suitable to WSN environments. As HARD protocol depends on location information for routing, UWB has built-in features for position information within meter precisions.

3.4.4 Proposed MAC TDMA

Device nodes are organized in grid cells. Each Device node is able to communicate to at least 4 Midway nodes. Device nodes within a grid cell are synchronized with reachable Midway nodes. Each device node has a unique ID within the grid cell. If there is data to be sent by a Device node, it has to wait for its reserved slot based on its ID to send traffic carried by Midway nodes. At the initial phase, each grid cell node gets time synchronized and prioritized on its ID order. In each Device node transmission, at least 4 Midway nodes receive the transmitted packet. This is a design goal intended for added reliability at the MAC layer. All Midway nodes have different channel for communication and are always in constant communication. (See Figure 3.3)

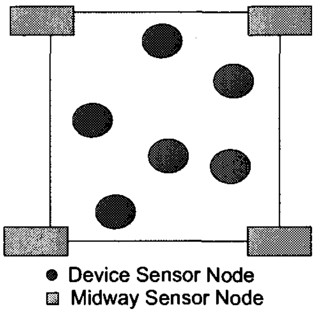


Figure 3.3: Propose Protocol Grid Cell

3.4.5 Location Based Multi-Path Routing

The HARD protocol takes advantage of location information and grid topology to forward packets to sinks in multi-paths fashion. When a Device node completes a packet transmission, the first Midway node correctly received the complete packet forwards it to the sink. The Midway node will duplicate the packet and send a copy to each primary sink and backup sink. The path taken will use location based disjoint node and link paths through the wired based interconnected Midway nodes (See Figure 3.4). As the two sinks are located in the opposite sides of each other in the grid, each copy of sent packet heads to one sink hopping different midway nodes. The opposite sides location of the sinks and the use of location based most forward routing by midway nodes create node and link disjoint paths. The location based routing minimizes the need for sensor nodes to store routing table information. In addition, location based routing computing demand is low and does not increase with the increase of the number of network nodes or neighboring nodes. The multipath routing increases the probability of error free packet delivery and thus enhances the reliability of the HARD protocol.

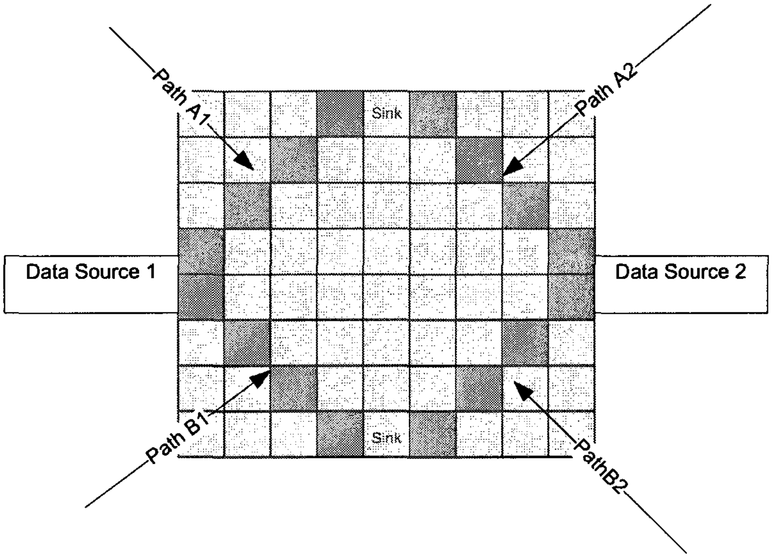


Figure 3.4: Dual Disjoint Routing

3.4.6 Backhaul Node Communications

The Midway nodes are assumed to be mounted on light bulb poles. The selection of light bulb poles as mounting structures for Midway sensor nodes is based on a number of reasons. Light bulb poles are existing high altitude poles suitable to mount wireless sensor nodes for enhanced data transmission. Midway sensor nodes are super nodes that perform extra tasks such as routing backbone traffic, synchronizing device nodes and serve as location server for grid cell nodes.

We propose to use data communication over power lines [77] to take advantage of existing electricity infrastructure and avoid wire installation. In addition, wire communication will provide a higher bandwidth, more reliable transmission and lower latency for backhaul Midway nodes communications. The Midway nodes are connected with their neighbors by fully switched non-blocking forwarding network. The route of packet traffic to the sink is based on location information where a multi-path routing take disjoint nodes and paths. The Midway nodes are assumed to have much higher bandwidth and data rates than Device nodes.

3.5 Protocol Analysis

3.5.1 HARD Protocol Flow Chart

In this section, we present the flow chart of the HARD protocol MAC and routing layer operations. The protocol operation in the chart can be classified into three phases. The first phase is the initialization where Device nodes within the grid cluster get synchronized with the surrounding Midway nodes. Also, the nodes get prioritized based on their IDs in order to access the synchronized medium transmission slots. The location information is distributed by the Midway nodes for every grid cell containing Device cells. The second phase is the MAC operation; when a Device node gets data to send and its reserved slot becomes available. The Device node broadcasts the frame and only one

Midway node gets the correctly received complete frame and will have the right to forward it. In the third phase, the Midway node forwards the packet to the primary and secondary sinks in dual disjoint route paths.

3.5.2 Delay Analysis

A given number of interconnected Midway nodes M_n are organized in grid clusters. Each Midway node M_n can communicate with each other within the radius distance of R_M.

All Device nodes D_n are synchronized and prioritized to access contention free reserved slots based on their assigned IDs.

If S_T is the time taken by Midway node M_n to store and forward packet P_i,

if N_I is the number of Midway nodes M_n where a given packet P_i gets routed through till it reach the sink,

if Q_d is the maximum delay allowed by the application to send a packet from source device node to the sink,

thus the algorithm has to maintain $S_T \times N_I \leq Q_d$ (4.1)

and therefore the path depth to primary sink or secondary sink has to be kept less than or equal to $\boldsymbol{Q_d / S_T}$. (4.2)

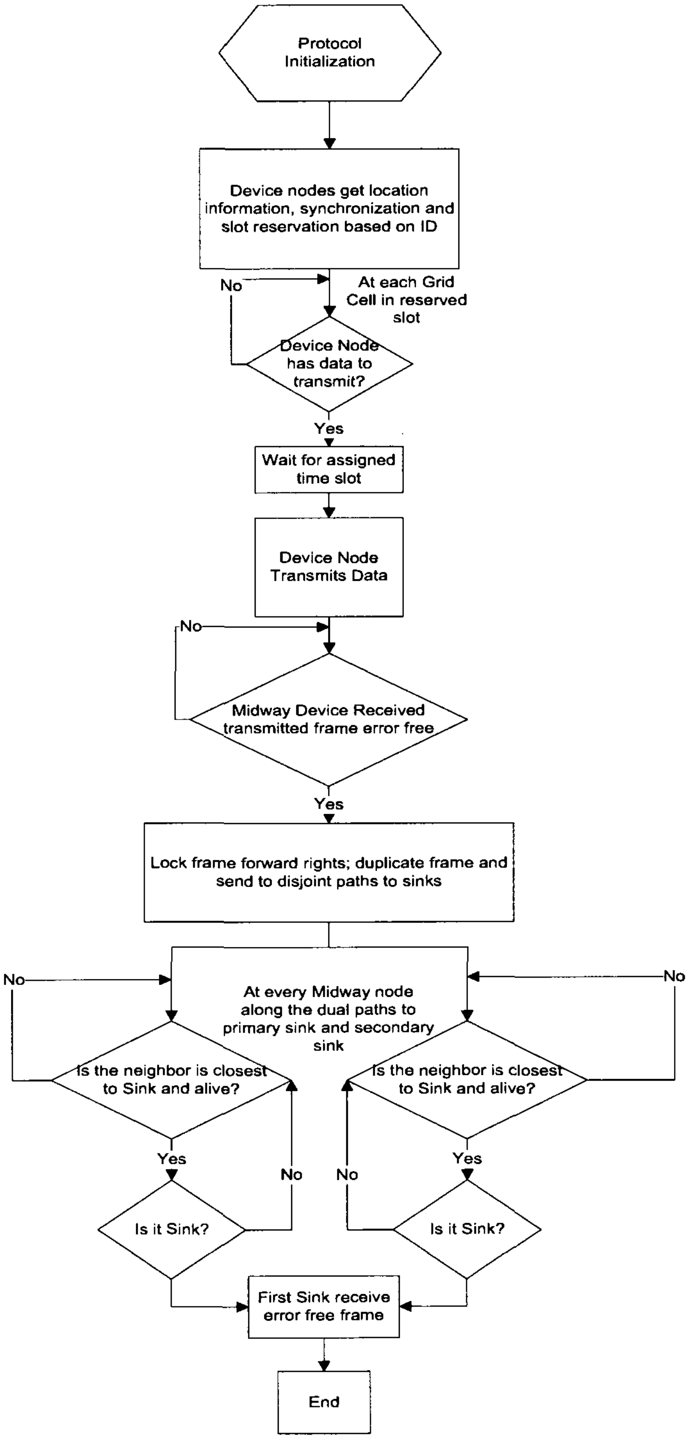


Figure 3.5: HARD Protocol Flow Chart

3.5.3 Reliability Analysis

Given the reliability of wireless link to fail is $\mathrm{R_W}$. This failure probability affects Device nodes transmitting traffic to Midway nodes. The failures type cover wireless medium failures (ex. interference) and Midway nodes failures.

Given the reliability of wired link failure probability is R_{WL}. This failure type covers link failures and Midway nodes failures.

Given the path length in terms of number of hop nodes to reach the primary or secondary sink is P_L.

The reliability of packet delivery to a single sink can be expressed as

$$\mathrm{R} = \mathrm{R_W} \times \left({R_{WL}}^{P_L}\right) \tag{3.3}$$

$$The\ reliability\ of\ dual\ path\ routing: \begin{cases} R_{SinkA} = R_{Wpat\ hA} \times ({R_{WLpat\ hA}}^{P_{Lpat\ hA}}) \\ R_{SinkB} = R_{Wpat\ hB} \times ({R_{WLpat\ hB}}^{P_{Lpat\ hB}}) \end{cases} \tag{3.4}$$

3.6 Summary

In this chapter we have proposed a WSN protocol called HARD for reliable and delay bound performance for industrial application. First we have reviewed related work in the field of high performance WSN protocols. Then, we have presented the different protocol layers of the proposal. At the end, we have analyzed the delay and reliability objectives of the HARD WSN protocol. The main differences between the HARD protocol and other related protocols can be summarized in the following three points. The HARD protocol utilizes reserved time slots for all transmitted frames to guarantee the delay performance. The other protocols utilize in general both reserved slots and random access that may not deliver actual real time performance in all cases. The grid topology of the HARD protocol with the uniform distribution of Midway nodes provides multiple disjoint paths to the sinks. This architecture gives the advantage of high reliability in comparison to other protocols for the high number of fault tolerant paths. The proposed architecture protocol takes advantage of the plant environment for node topology deployments, node power sources and location information. This architecture customization to the deployment environment provides enhanced features compared to other protocols.

Chapter 4

4. Simulation Results and Analysis

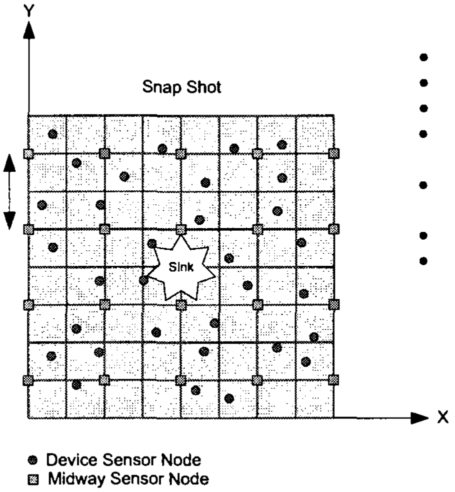
4.1 Introduction

In this chapter we present the simulation of the WSN protocol HARD. The simulation setup is shown. The Pseudocode of a single path and dual path routing is presented. The simulation results for the delay and the reliability are analyzed and discussed.

4.2 Simulation Setup

The simulation of the WSN protocol HARD is created in Java programming language. The environment setup for the simulation is a 4000m × 4000m square floor plan. The program reads from a file the assumed plant floor plan of structures and free areas. The square floor plan is organized as evenly distributed grid cells of size 100m × 100m. The simulation program chooses randomly the number of Device nodes of up to 10,000 Device nodes distributed evenly in the grid cells. Each grid cell accommodates 4 Midway nodes located in the corners. The Device nodes in the grid cell have transmission radius of 150m and thus can reach a minimum of 4 Midway nodes. The written program simulates the link layer and routing layer of the proposed WSN communication protocol. It is assumed that we have an ideal connectionless transport (e.g. UDP) and application layer.

The Midway sensor nodes are distributed evenly across the grid topology so the sensor network will always be connected. The Midway sensor nodes provide the location information and synchronization to Device sensor nodes within the cluster grid. At every packet forward decision, the instantaneous status of receiving Midway sensor node is checked. This is possible because each receiving Midway node will communicate to other peers its status in error free reception of the forwarded frame. The Midway sensor node that received first the complete error free frame will lock into it and have the right to forward it alone. The grid topology area and sensor nodes distribution along with the sink positioning allows a maximum of 40ms delay in normal operation. A packet originates from the boundaries of the grid passes through 20 nodes before it reaches the sink in fault free network environment. Each node is assumed to add 2ms delay to the overall end-to-end packet delivery delay.



- Plant Size 4Km X 4Km
- Node transmission range 150m
- Average 1600 midway nodes ; max of 10,000 device nodes
- Midway sensors make the network always connected; serve as location service node ; serve as synchronization agent
- Every device sensor see min of 4 midway sensors; facilitate multi path routing
- Routing uses location information and instantaneous state information
- Assume sink in middle ; logical control & monitoring in center of plant. Also assume every node takes 1ms to receive a packet and transmitted to next node. Maximum application delay is 40ms

Figure 4.1: Simulation Setup for Single Route Scenario

4.3 Simulation Pseudocode

4.3.1 Single Route Multi-Path Pseudocode

In this section, the Pseudocode of the simulation program for the proposed protocol HARD is presented. This Pseudocode illustrates the scenario of a single route multi-path routing of the protocol. The protocol operation starts with initialization phase where Midway nodes are organized geometrically along the grid intersections with 100m separation distance between them. The Device nodes are randomly distributed in the grid cells according to a uniform distribution function. The location information of Midway nodes is predetermined and fixed. The Device nodes use location information of Midway nodes to get location information. The location information shall be obtained once at the initial phase as the nodes are assumed to be static. The Device nodes are given different priorities to access transmission time slots according to their IDs. The network does not require exchange of routing information as the routing is location based. The majority of the control overhead frames are transmitted in the initial phase and are kept to minimum in the operation of the protocol. The control frames during protocol operation is limited to time stamp synchronization frames and ACK frames for successful frame receiving. A packet transmitted from a given node has multiple path options in every hop transition. Multiple nodes within the receiving area may listen to the transmitted frame, however the first node receives the whole frame correctly has the right to forward it. This mechanism ensures the minimum end-to-end delivery delay of a given frame transmission. The single route scenario does not duplicate the frame at the source node and maintains one copy of the frame during the routing process. The reliably performance of single route scenario is obtained from the multipath feature. As the multipath mechanism chooses the best link and node available in every hop along the route.

```
BEGIN
SET Uniformly Distribute Midway Nodes
SET Randomly Distribute Device Nodes
SET Synchronizes Sensor Nodes
SET Get Location Informotion of Nodes
SET Prioritize Sensor Node Based on ID
FOR Each Tim_Tic in millisecond
        Generate Random Packet
        At Each Device Node
                IF My Turn
                        If Have Traffic to Send
                        Broadcast Frame
                        END IF
                END IF
        At Each Midway Node
        IF Received Complete Error Free Frame
                IF I Am First To Complete Frame Reception
                        SET Lock The Right To Forward Frame
                END IF
                WHILE Sink Not Reached
                SET Forward To Closest Available Midway Node to Sink
                SET Tim_Tic = Tim_Tic + 1
                IF No Available Node To Forward Frame
                        BREAK
                END IF
                END WHILE
                IF Sink Received Frame
                SET Report Delay
                END IF
        END IF
        END FOR
END
```

4.3.2 Dual Route Multi-Path Pseudocode

In this section, the Pseudocode of the simulation program for the proposed protocol HARD is presented. This Pseudocode illustrates the scenario of Dual route multi-path routing of the protocol. In this scenario, two copies of the transmitted frame is routed through the network to the sinks. In this case, the network maintains a primary and secondary sinks positioned in the opposite sides in the grid with maximum vertical distance separation. At the source nodes a duplicate frame is forwarded to two different nodes given each next hop node should be the closest to the destination sink (i.e. the primary and secondary sinks). Using the approach of most forwarding routing, the next hop maintains the maximum vertical distance separation. This method enhances the reliability of packet delivery by establishing two disjoint routes to two separate sinks. The cost of added reliability is the increase in overhead which reduces bandwidth capacity and increases energy consumption of the wireless sensor network.

```
BEGIN

    SET Uniformly Distribute Midway Nodes
    SET Randomly Distribute Device Nodes
    SET Synchronizes Sensor Nodes
    SET Get Location Information of Nodes
    SET Prioritize Sensor Node Based on ID
    FOR Each Tim_Tic in millisecond
        Generate Random Packet
        At Each Device Node
        IF My Turn
            IF Have Traffic to Send

                Broadcast Frame

        END IF
    END IF
    At Each Midway Node
    IF Received Complete Error Free Frame
        IF I Am First To Complete Frame Reception
        SET Lock The Right To Forward Frame
        SET Duplicate The Frame
        SET Forward Each Frame To Two Disjoint Paths
        SET Tim_Tic = Tim_Tic + 1

    END IF
    WHILE Sink Not Reached
    SET Forward To Closest Available Midway Node to Sink
    SET Tim_Tic = Tim_Tic + 1
        IF No Available Node To Forward Frame
        BREAK
        END IF
    END WHILE
    IF Sink Received Frame
        IF I AM First Sink Received Error Free Complete Frame
        Lock Packet Receiving Notification
        END IF
    SET Report Successful Packet Delivery
    SET Report Delay
    END IF
    END FOR
END
```

4.4 HARD Protocol Simulation Results

4.4.1 Delay Performance

4.4.1.1 Single Route Multi-Path

In this section we present the simulation results obtained for the delay of delivering packets from random sources to the sink. In this setup, the WSN has a single sink where all packets sent from Device nodes are routed to it. The path is taken according to single route based on location aware routing. At each Midway node forwarding decision, there is a multipath options based in closeness to sink and node availability.

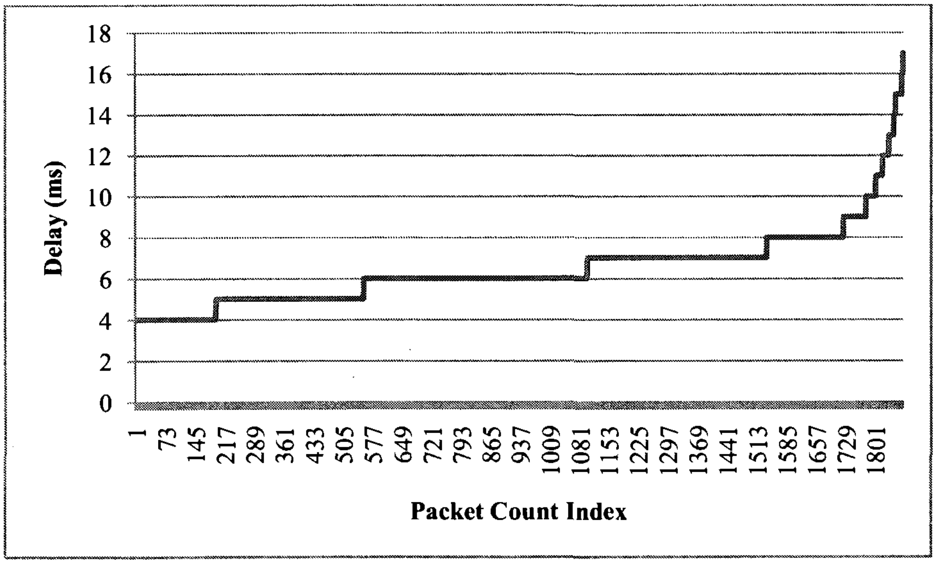


Figure 4.2: Single Route 0% Failure Probability

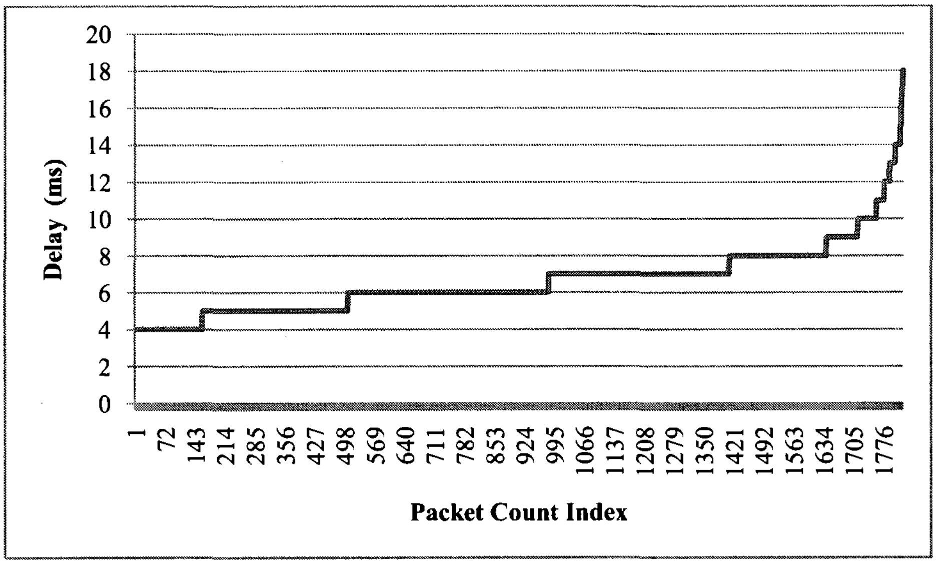


Figure 4.3: Single Route 10% Failure Probability

We can observe from Figures 4.2, 4.3 and 4.4 that more than 90% of the packets end-to-end delivery delay values falls under 8ms. This is an expected result for two main reasons: the node probability of failure is small which make shortest path to sink almost always available. The other reason is that about half of nodes generating traffic is within close proximity to the sink because for uniform distribution function of traffic generation. The distribution values of packet end-to-end delivery delays started to differs when we applied failure probability of 60% and above. In Figures 4.5 and 4.6 about 50% of packets experience end-to-end delivery delays of 8ms and higher. This is because of the higher probability of node failures which force routing to take longer paths.

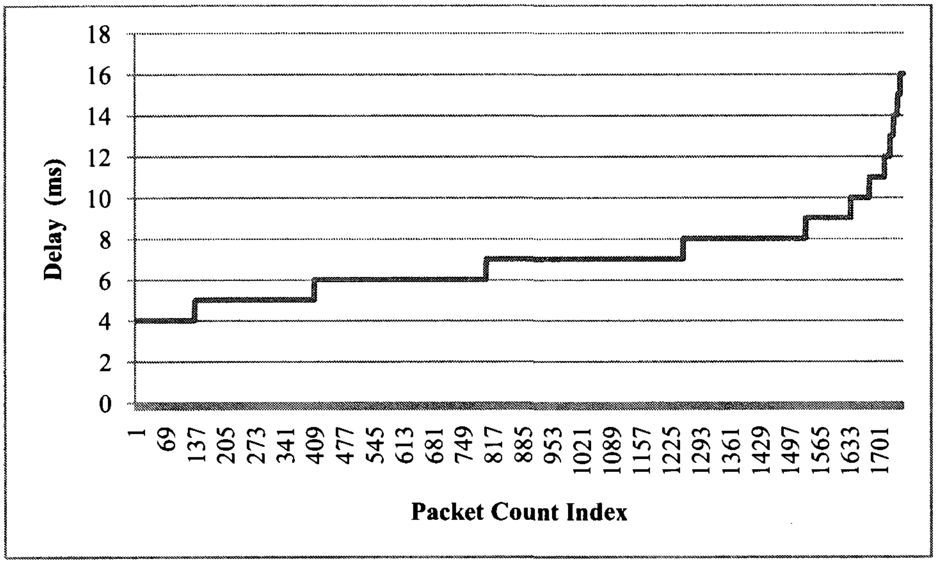


Figure 4.4: Single Route 30% Failure Probability

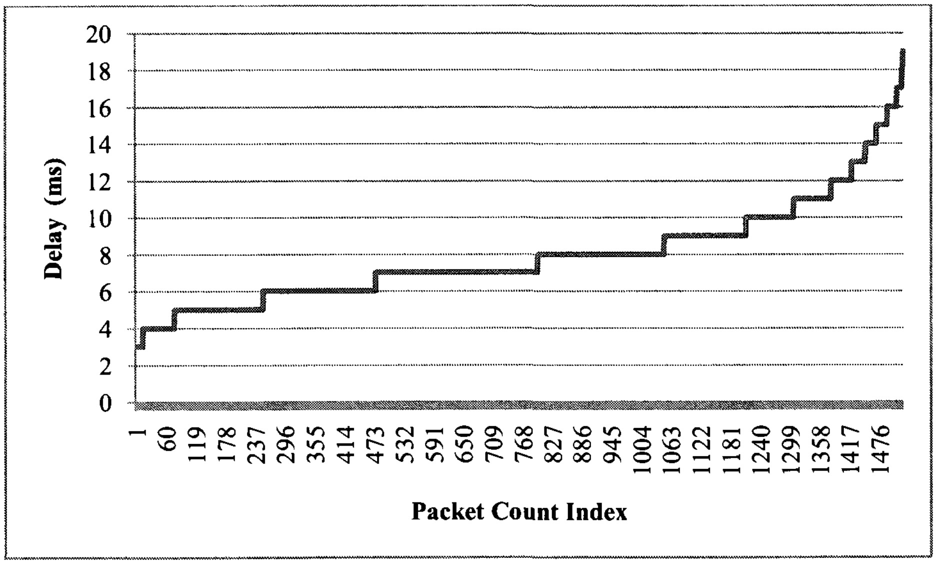


Figure 4.5: Single Route 60% Failure Probability

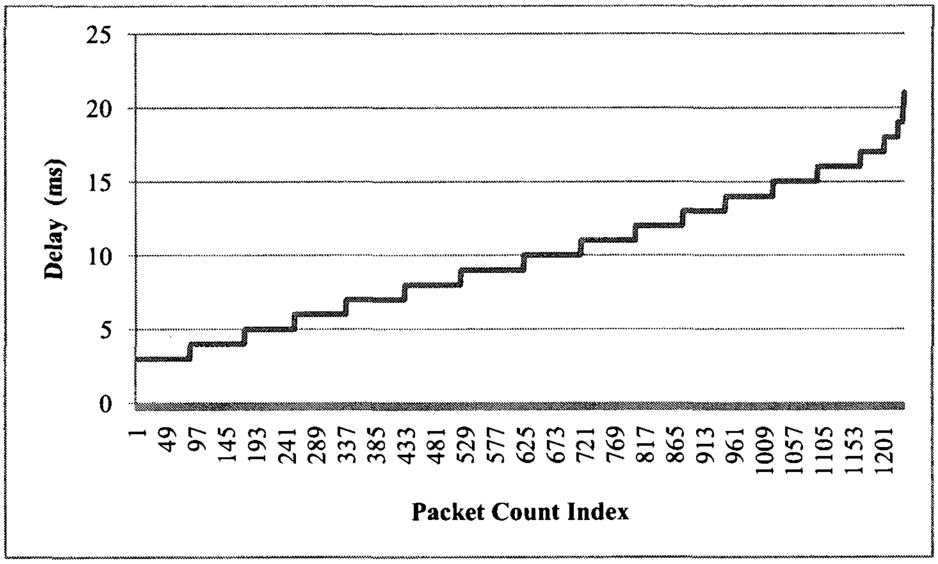


Figure 4.6: Single Route 90% Failure Probability

The above figures show the delay exhibited by delivered packets from random Device nodes to the sink. It is shown that all delivered packets exhibit delay less than 40ms which is the maximum delay allowed by the application. The different figures show different probability of failure applied to Midway nodes. The higher the probability of failures the higher delay exhibited by the delivered packets. However, the maximum delay exhibited still below the maximum delay allowed by the application.

4.4.1.2 Single Route Multi-Path Regional Failure

In this setup, a complete region of the grid network layout exhibit a 50% probability of failure along the Midway nodes. This scenario simulates the case where a region of the plant network exhibit fire, damage or severe interference. In this case, a single sink exists in the network and the forwarding is single route multi-path scheme.

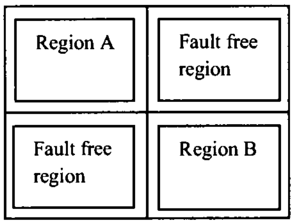


Figure 4.7: Regional Failure Illustration

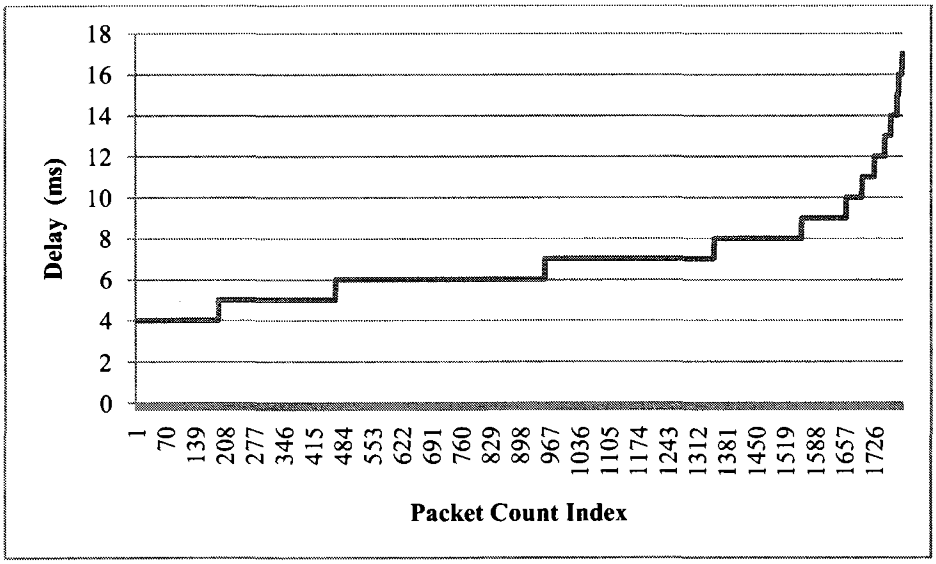


Figure 4.8: Single Route 50% Regional Failure Probability- Region A

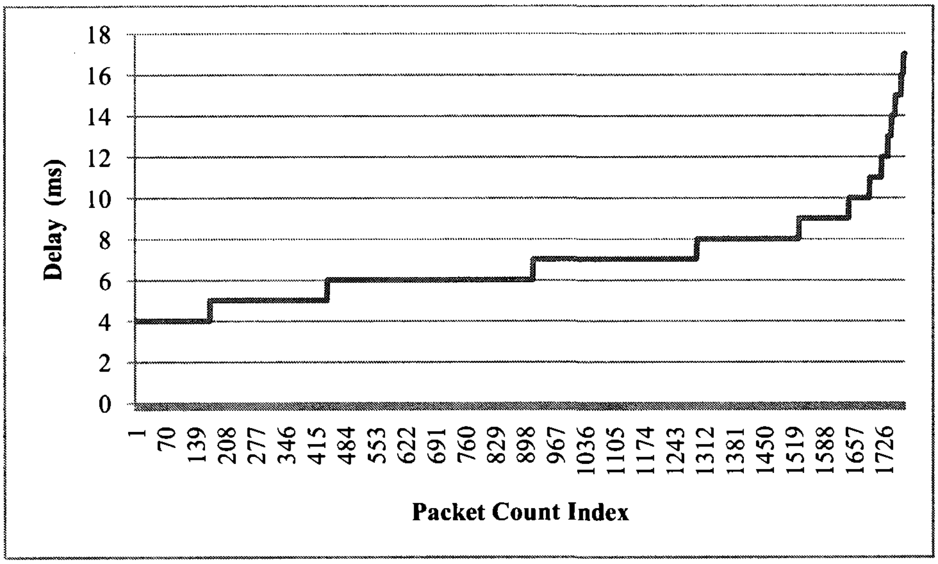


Figure 4.9: Single Route 50% Regional Failure Probability- Region B

The above figures show the delay exhibited by delivered packets from random Device nodes to the sink. It is shown that all delivered packets exhibit delay less than 40ms which is the maximum delay allowed by the application. It can be noted from Figures 4.7 and Figure 4.8 that 90% of packet end-to-end delay values are less than 10ms. Two different quarters of the grid network, Region A & B, injected with 50% random probability of failure for Midway nodes. This failure probability constrained in regions simulate isolated regions of plants hit by fire or sever interference.

4.4.1.3 Dual Route Multi-Path

In this setup, the WSN has dual sinks (primary & Secondary) where all packets sent from Device nodes are routed to either one of them. The path is taken according to dual route based on location aware routing. The dual routes taken from sources to sinks are node and link disjoint paths. At each Midway node forwarding decision, there is a multipath option based in closeness to sink and node availability.

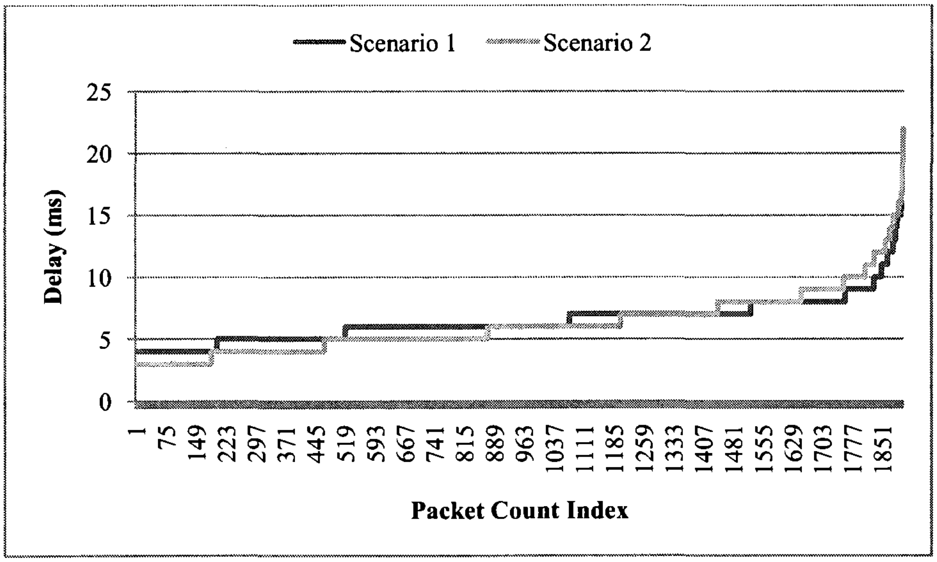


Figure 4.10: Dual Route 0% Failure

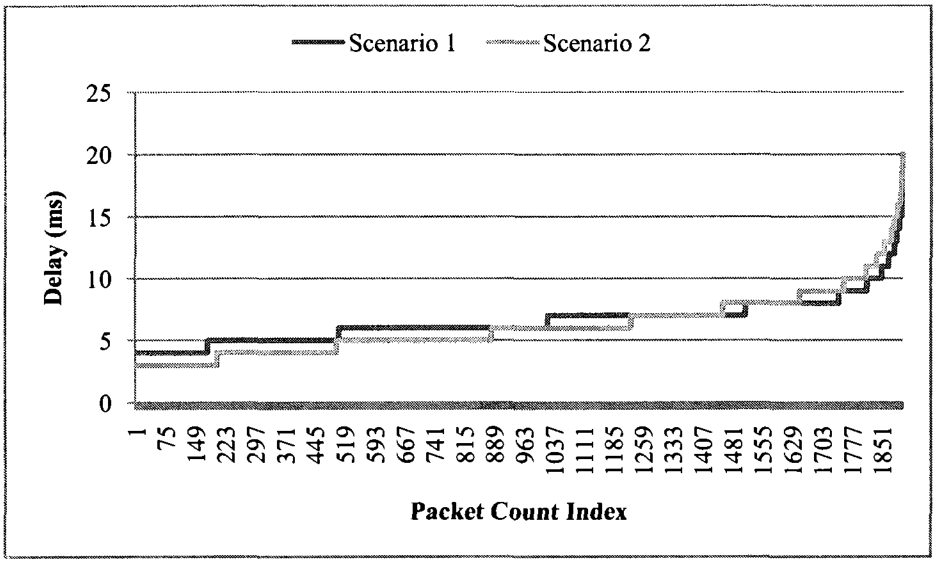


Figure 4.11: Dual Route 10% Percent Failure

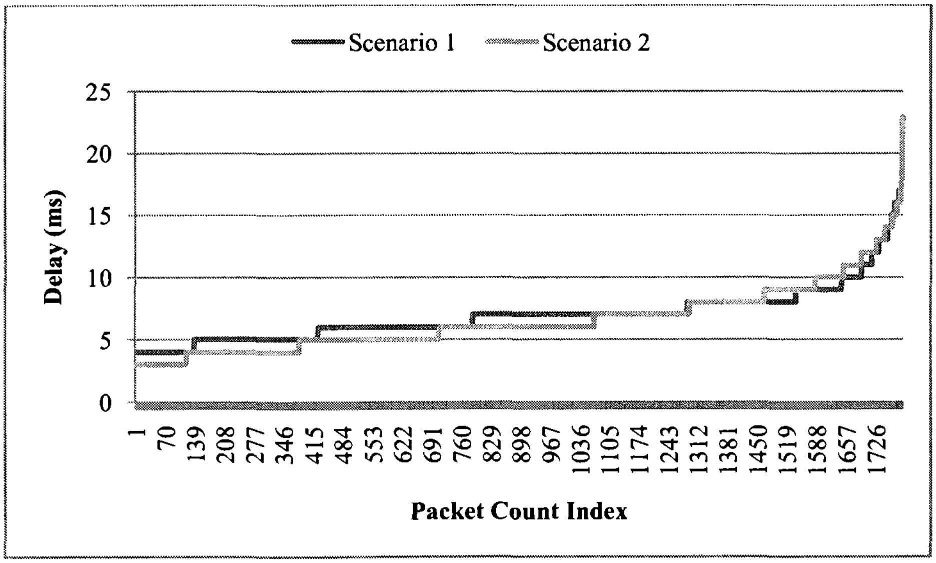


Figure 4.12: Dual Route 30% Percent Failure

The graphs on Figures 4.9, 4.10 and 4.11 show that 90% of packet end-to-end delay values are less than 8ms. This is a similar result obtained from simulation of a single route multipath approach. So we shall conclude that in networks of HARD protocol with failure probability of 30% or less a single route multipath approach is more efficient. Because it affords less overhead and provides the same delay and reliability results of dual route multi path approach. However, the dual route multipath approach provides better end-to-end delay and reliability results in failure probabilities of 60% and more (as can be seen from Figures 4.12 and 4.13).

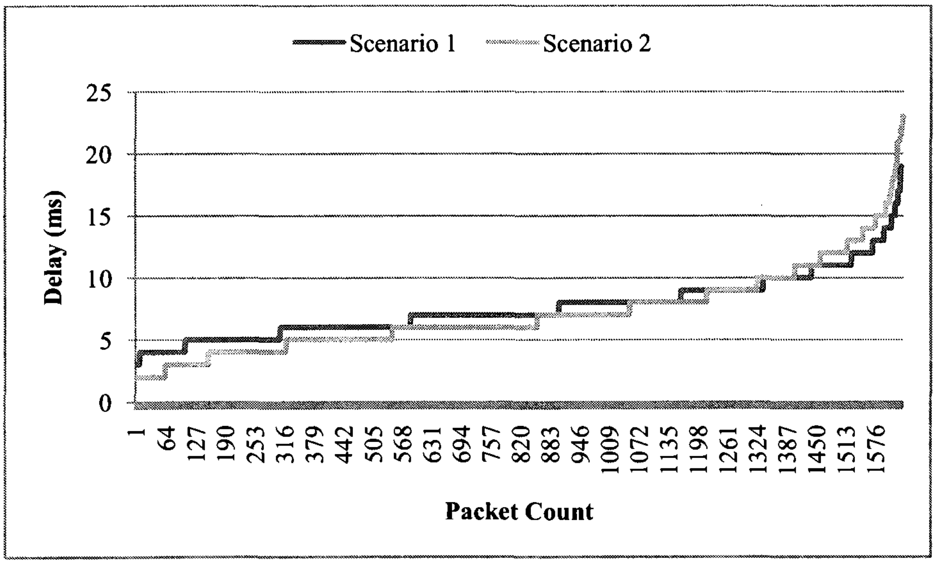


Figure 4.13: Dual Route 60% Percent Failure

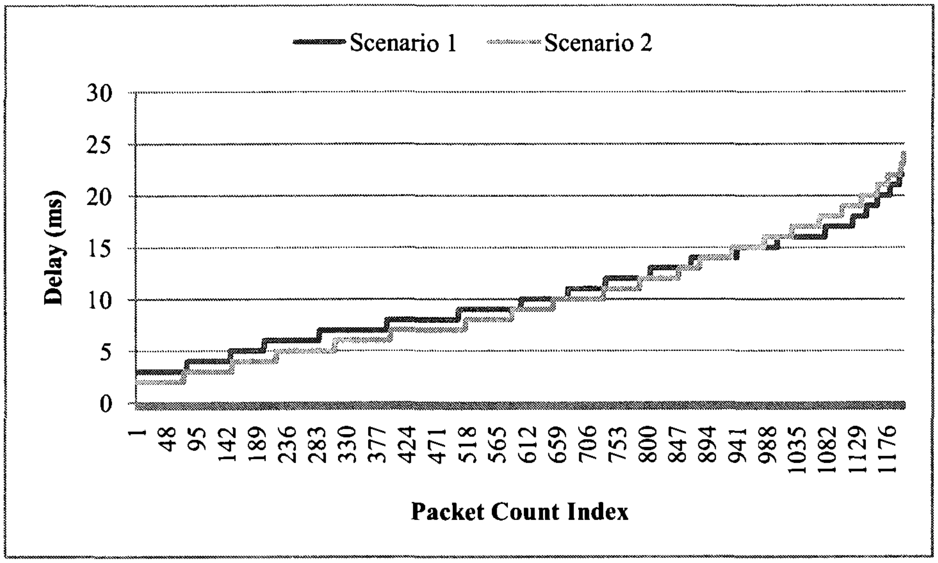


Figure 4.14: Dual Route 90% Percent Failure

The above figures show the delay exhibited by delivered packets from random Device nodes to either the primary sink or the secondary sink. It is shown that all delivered packets exhibit delay less than 40ms which is the maximum delay allowed by the application. The different figures shows different failure probability applied to Midway nodes. The higher the probability of failures the higher delay exhibited by the delivered packets. However, the maximum delay exhibited still below the maximum delay allowed by the application.

4.4.1.4 Dual Route Multi-Path Regional Failure

In this section we present the obtained simulation results for the delay of delivering packets from random sources to the sink. In this setup, a complete region of the grid network layout exhibit a 50% probability of failure along the Midway nodes. This scenario simulates the case where a region of the plant network exhibit fire, damage or severe interference. In this case double sinks exist in the network (primary and secondary) and the forwarding is dual route multi-path scheme.

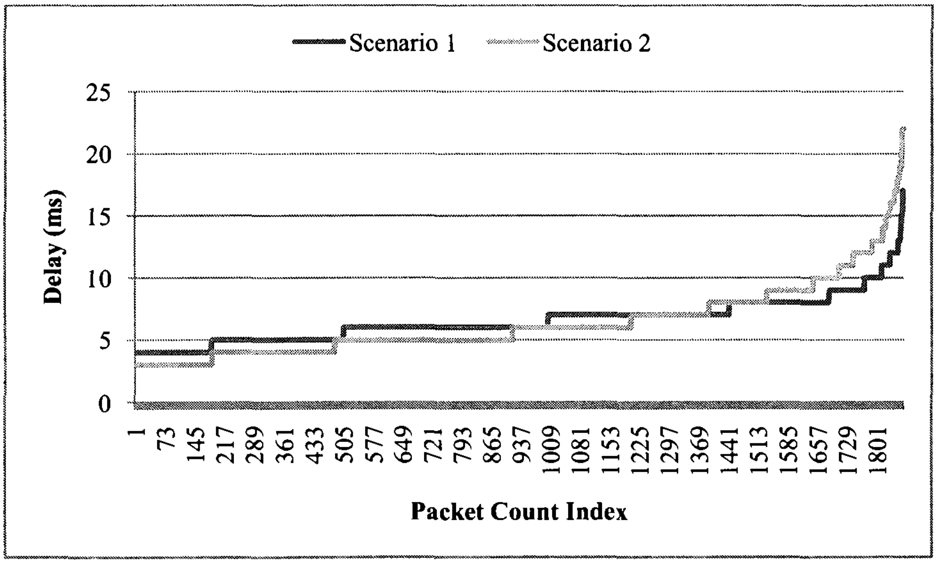


Figure 4.15: Dual Route 50% Regional Failure Probability – Region A

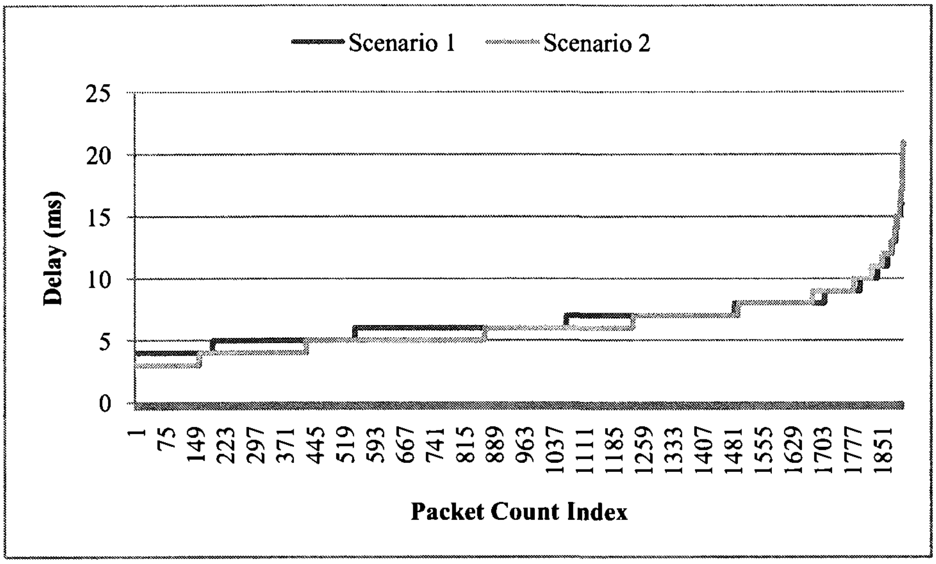


Figure 4.16: Dual Route 50% Regional Failure Probability – Region B

The above figures show the delay exhibited by delivered packets from random Device nodes to the sink. It is shown that all delivered packets exhibit delay less than 40ms delivered to both primary and secondary sinks which is the maximum delay allowed by the application. Two different quarters of the grid network, Region A & B, injected with 50% random probability of failure for Midway nodes.

4.4.2 Reliability Performance

In this section we present the performance of the network reliability resulted from the simulation of HARD protocol. A single route multi-path scheme with different failure probability values performance is presented. Another figures show the different failure probability values performance of dual route multi-path scheme. The dual route scheme performs better as expected on the high failure probability rates of 90%. However, single route and multi route scheme performed similarly for lower failure probability rates.

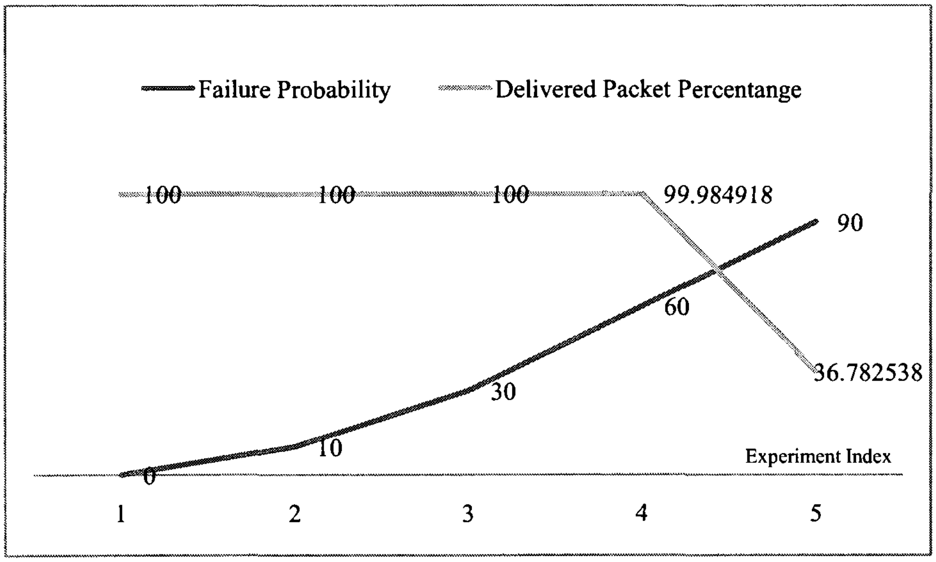


Figure 4.17: Reliability Performance Single Route Multi-Path

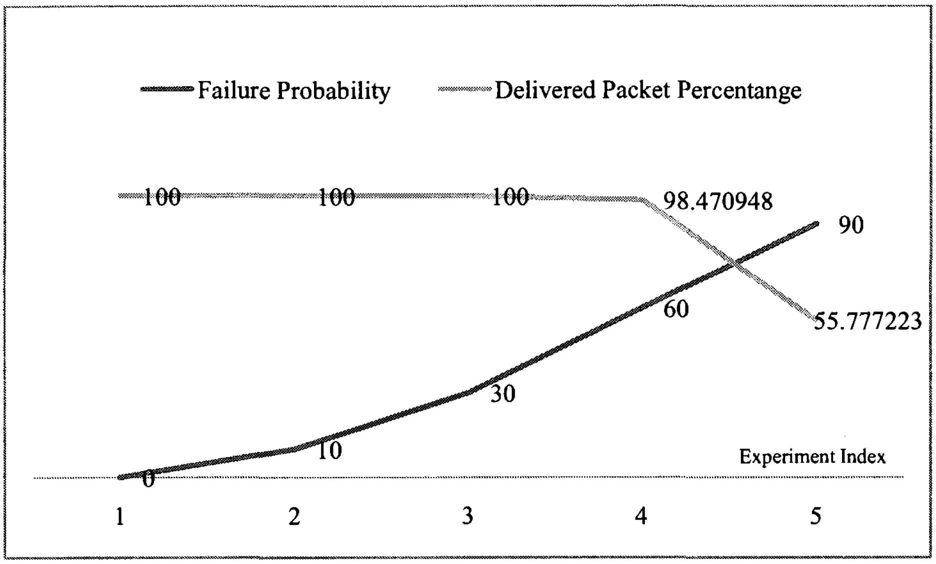


Figure 4.18: Reliability Performance Dual Route Multi-Path

4.5 Summary

The simulation experiment setup has been presented in this chapter. The results of the different scenarios have been analyzed. A number of delay performance scenarios results have been shown. Also results for the network reliability performance have been shown. The confidence interval for the delay results obtained from 10 independent experiment runs found to be very small and thus negligible (see Appendix A).

Chapter 5

5. Conclusion and Future Work

5.1 Concluding Remarks

In this thesis, we have proposed a novel WSN protocol, called HARD, that offers delay bound and reliability performance for oil and gas plants applications. The HARD protocol has a delay bound and reliability high performance requirements that are shown they can be satisfied. The challenges and design issues for designing high performance WSN protocols have been presented at length. Protocol examples with similar objectives to the HARD protocol have been presented. The delay bound of the HARD protocol has been formulated and analyzed. Also the reliability performance of the proposed protocol has been investigated and quantified. The simulation results for delay and reliability performance have been shown and discussed. The HARD protocol assumptions are based on real life reasonable expectation of facilities from oil and gas plants. The protocol HARD consumes low energy, has guaranteed delay bound, shows high reliability, has low overhead and simple operation.

A simulation experiment of the protocol HARD has been performed. Results and analysis of delay performance and reliability performance have been discussed. The results of the simulation experiment have shown near 100% packet delivery reliability for most of fault models. When the fault distribution among Midway nodes exceeds 60%, the packet delivery reliability experience some hits. The dual route multipath scenario has exhibited better resilience to high failure probability of nodes and links. The packet delivery delay results have shown an upper bound of 40ms (worst case) in our simulation experiment as derived through mathematical formulation. Packets delivered to the sink experience higher delays in the case of high probability of failures in nodes and links. The dual route multipath scenario is shown to be more resilient to failures in terms of delay performance. Even with fault probability for Midway nodes near 75%, the packet delivery delay performance results were kept under the upper bound.

5.2 Future Work

The simplicity and low operational cost of HARD protocol are based on the assumptions of exploiting the oil and gas plants environments. For example, the light bulb poles distribution across the plant floor has followed a uniform distribution function which has allowed the protocol to mount super Midway nodes that take the electrical power from the light bulb poles. This has allowed the Midway nodes to be active all the operation time and carry out extra tasks such as time synchronization and location information. The extra tasks performed by Midway nodes alleviate tasks load from the regular nodes and thus prolong their operational lifetime resulted from saved energy. Another important assumption is the use of power grid of light bulb poles to carry power line data communication of Midway nodes. If the above assumptions are changed depending on the plant design, it is interesting to see how the protocol design and operation will adapt. In each grid cell there is a finite number of Device nodes determined based on the upper bound delay target by the protocol design. It is worth studying the scalability of the HARD protocol in terms of the number of sensor nodes allowed in a single cell and thus in the network size while preserving the delay and reliability performance. Also the size of the plant floor is assumed to be deterministic (realistic assumption) which affect the design protocol for delay bound packet delivery. It is worth studying the effect and scalability of geographical area in terms of protocol keeping low delay and low failure rate. Another area of possible exploration is the ability of the HARD protocol carry high volume real time traffic (i.e. video/voice) without affecting the traffic of control and monitoring performance requirements. The effect of introducing mobile Midway and Device nodes in the delay and reliably performance of the protocol is also open for future research.

Bibliography

[1] Holger Karl and Andrreas Willig, *Protocols and Architectures for Wireless Sensor Networks*, 1st ed. West Sussex: John Wiley & Sons Ltd, 2005.

[2] Cordeiro and Agrawal, *Ad Hoc & Sensor Networks*, 1st ed. Singapore: World Scientific, 2006.

[3] Ivan Stojmenovic, Editor, *Handbook of Sensor Networks: Algorithms and Architectures*, 1st ed. John Wiley & Sons Ltd, 2005.

[4] S. Chakrabarti and A. Mishra, "Quality of service challenges for wireless mobile ad hoc networks: Research Articles," *ACM Wireless Communications and Mobile Computing*, vol. 4, Issue 2, pp. 129-153, March 2004.

[5] A. Mishra, *Security and Quality of Service in Ad Hoc Wireless Networks*, Cambridge University Press, 2008.

[6] M. Kuorilehto, M. Kohvakka, J. Suhonen, P. Hämäläinen, M. Hännikäinen, and T.D. Hamalainen, *Ultra-Low Energy Wireless Sensor Networks in Practice: Theory, Realization and Deployment*, Wiley, 2008.

[7] H. Labiod, Editor, *Wireless Ad Hoc and Sensor Networks*, 1st ed. Wiley-ISTE, 2008.

[8] D. Chen and P.K. Varshney, "QoS Support in Wireless Sensor Networks: A Survey," *International Conference on Wireless Networks*, Las Vegas, NV, pp. 227–

233, 2004.

[9] S. Meguerdichian, F. Koushanfar, M. Potkonjak, and M. Srivastava, "Coverage problems in wireless ad-hoc sensor networks," *Twentieth Annual Joint Conference of the IEEE Computer and Communications Societies INFOCOM 2001*, Anchorage, AK, pp. 1380-1387 vol.3, April 2001.

[10] S. Meguerdichian, F. Koushanfar, G. Qu, and M. Potkonjak, "Exposure in wireless Ad-Hoc sensor networks," *Proceedings of the 7th annual international conference on Mobile computing and networking*, Rome, Italy, pp. 139-150, 2001.

[11] W. Bux, "Token-ring local-area networks and their performance," *Proceedings of the IEEE*, vol. 77, Issue 2, pp. 238-256, February 1989.

[12] D.J. Sterling and S.P. Wissler, *The Industrial Ethernet Networking Guide*, 1st ed. Delmar Cengage Learning, 2002.

[13] D. Hristu-Varsakelis, W.S. Levine, R. Alur, K. Arzen, J. Baillieul, and T. Henzinger, *Handbook of Networked and Embedded Control Systems*, Birkhäuser Boston, 2008.

[14] Kris Pister and Greg LaFramboise, "Article: *System Integration: Wired warriors*," Research Triangle Park, NC: International Society of Automation, November 2008, <http://www.isa.org/InTechTemplate.cfm?Section=Article_Index1&template=/ContentManagement/ContentDisplay.cfm&ContentID=72525>.

[15] Control Global, "Article: *Cutting the wires of communications*," Itasca, IL: ControlGlobal.com,2006,<http://www.controlglobal.com/articles/2006/142.html?page=1 >.

[16] S. Petersen, P. Doyle, S. Vatland, C. Aasland, T. tman, and Dag Sjong,

"Requirements, drivers and analysis of wireless sensor network solutions for the Oil & Gas industry," *IEEE Conference on Emerging Technologies & Factory Automation,* Patras, Greece , pp. 219-226, 2007.

[17] D. Chen, M. Nixon, T. Aneweer, R. Shepard, K. Burr, and A.K. Mok, "Wireless Process Control Products from ISA 2004," *International Workshop on Wireless and Industrial Automation, March*, 2005.

[18] Kris Pister, "Video: *Wireless Sensor Networks: Technology and Applications*," Berkley, CA: Center for Information Technology Research in the Interest of Society, November 2007, < http://www.youtube.com/watch?v=PVH1K1Eocz0 >.

[19] Saunders, Simon and Alejandro Zavala. *Antennas and Propagation for Wireless Communication Systems*, Chichester: Wiley, 1999.

[20] D.M. Dobkin, *RF Engineering for Wireless Networks: Hardware, Antennas, and Propagation*, 1^{st} ed. Burlington: Newnes, 2005.

[21] N. Wisitpongphan, G. Ferrari, S. Panichpapiboon, J. Parikh, and O. Tonguz, "QoS provisioning using BER-based routing in ad hoc wireless networks," *IEEE Vehicular Technology Conference, Stockholm, Sweden*, pp. 2483-2487, Vol. 4, 2005.

[22] Dongwoo Kim, Chan-Ho Min, and Sehun Kim, "On-demand SIR and bandwidth-guaranteed routing with transmit power assignment in ad hoc mobile networks," *IEEE Transactions on Vehicular Technology*, vol. 53, Issue 4, pp. 1215-1223, July 2004.

[23] S. Singh, M. Woo, and C.S. Raghavendra, "Power-aware routing in mobile ad hoc networks," *Proceedings of the 4th annual ACM/IEEE international conference on*

Mobile computing and networking, Dallas, Texas, U.S.A, pp. 181-190, 1998.

[24] Jae-Hwan Chang and L. Tassiulas, "Energy conserving routing in wireless ad-hoc networks," *Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies INFOCOM 2000*, Tel-Aviv, Israel, pp. 22-31 vol.1, 2000.

[25] S. Doshi, S. Bhandare, and T.X. Brown, "An on-demand minimum energy routing protocol for a wireless ad hoc network," ACM *SIGMOBILE Mobile Computing and Communications Review*, vol. 6, Issue 3, pp. 50-66, July 2002.

[26] C. Yu, B. Lee, and H. Youn, "Energy efficient routing protocols for mobile ad hoc networks," *Wiley Wireless Communications and Mobile Computing*, vol. 3, Issue 8, pp. 959-973, November 2003.

[27] Yaling Yang and R. Kravets, "Contention-aware admission control for ad hoc networks," *IEEE Transactions on Mobile Computing,* vol. 4, Issue 4, pp. 363-377, July/August 2005.

[28] S.R. Das and C.E. Perkins, "Performance Comparison of Two On-demand Routing Protocols for Ad Hoc Networks," *Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies INFOCOM 2000*, Tel-Aviv, Israel, pp. 3-12, March 2000.

[29] L. Hanzo-II and R. Tafazolli, "A survey of QoS routing solutions for mobile ad hoc networks," IEEE *Communications Surveys & Tutorials*, vol. 9, Issue 2, pp. 50-70, Second Quarter 2007.

[30] Zhong Fan, "QoS routing using lower layer information in ad hoc networks," *15th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Barcelona, Spain, pp. 135-139, Vol.1, September 2004.

[31] A. Misra and S. Banerjee, "MRPC: Maximizing Network Lifetime for Reliable Routing in Wireless Environments," *IEEE Wireless Communications and Networking Conference*, Orlando, FL, U.S.A., Vol. 2, March 2002.

[32] L. Barolli, A. Koyama, and N. Shiratori, "A QoS routing method for ad-hoc networks based on genetic algorithm," *14th International Workshop on Database and Expert Systems Applications,* Prague, Czech Republic, pp. 175-179, September 2003.

[33] N. Nikaein, C. Bonnet, and N. Nikaein, "Harp-hybrid ad hoc routing protocol," *Proceedings of IST: International Symposium on Telecommunications,* Tehran, Iran, September 2001.

[34] I. Rubin and Y. Liu, "Link stability models for QoS ad hoc routing algorithms," *IEEE 58th Vehicular Technology Conference,* Orlando, FL, U.S.A., pp. 3084-3088 Vol.5, October 2003.

[35] Chunhung Richard Lin and Jain-Shing Liu, "QoS routing in ad hoc wireless networks," *IEEE Journal on Selected Areas in Communications,* vol. 17, Issue 8, pp. 1426-1438, August 1999.

[36] Shigang Chen and K. Nahrstedt, "Distributed quality-of-service routing in ad hoc networks," *IEEE Journal on Selected Areas in Communications*, vol. 17, Issue 8, pp. 1488-1505, August 1999.

[37] Min Sheng, Jiandong Li, and Yan Shi, "Routing protocol with QoS guarantees for ad-hoc network," *IEEE Electronics Letters*, vol. 39, Issue 1, pp. 143-145, January 2003.

[38] T. Bheemarjuna, I, B.S, and C.S. Ram, "Quality of service provisioning in ad hoc wireless networks: a survey of issues and solutions," *Elsevier Ad Hoc Networks*,

vol. 4, pp. 83-124, January 2006.

[39] V. Gungor, O. Akan, and I. Akyildiz, "A Real-Time and Reliable Transport $(RT)^2$ Protocol for Wireless Sensor and Actor Networks," *IEEE/ACM Transactions on Networking*, vol. 16, Issue 2, pp. 359-370, April 2008.

[40] Y. Sankarasubramaniam, Ö.B. Akan, and I.F. Akyildiz, "ESRT: event-to-sink reliable transport in wireless sensor networks," *Proceedings of the 4th ACM international symposium on Mobile ad hoc networking and computing*, Annapolis, MD, USA, pp. 177-188, 2003.

[41] C. Wan, A.T. Campbell, and L. Krishnamurthy, "PSFQ: a reliable transport protocol for wireless sensor networks," *Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications*, Atlanta, GA, USA, pp. 1-11, 2002.

[42] F. Stann and J. Heidemann, "RMST: reliable data transport in sensor networks," *IEEE International Workshop on Sensor Network Protocols and Applications,* Vancouver, BC, Canada, pp. 102-112, 2003.

[43] S. Tilak, N.B. Abu-Ghazaleh, and W. Heinzelman, "A taxonomy of wireless micro-sensor network models," *SIGMOBILE Mobile Computing and Communications Review*, vol. 6, No. 2, pp. 28-36, 2002.

[44] S. Mukhopadhyay, D. Panigrahi, and S. Dey, "Data aware, low cost error correction for wireless sensor networks," *IEEE Wireless Communications and Networking Conference,* Atlanta, Georgia, pp. 2492-2497 Vol.4, March 2004.

[45] F. Tobagi and L. Kleinrock, "Packet Switching in Radio Channels: Part II--The Hidden Terminal Problem in Carrier Sense Multiple-Access and the Busy-Tone Solution," *IEEE Transactions on Communications,* vol. 23, No. 12, pp. 1417-1433,

December 1975.

[46] D. Shukla, L. Ch, and S. Iyer, "Mitigating the exposed node problem in IEEE 802.11 ad hoc networks," *The 12th International Conference on Computer Communications and Networks*, Dallas, TX, U.S.A., pp. 157-162, October 2003.

[47] C.E. Perkins, *Ad Hoc Networking*, 1st ed. Reading: Addison-Wesley Professional, 2001.

[48] J. Broch, D.A. Maltz, D.B. Johnson, Y. Hu, and J. Jetcheva, "A Performance Comparison of Multi-Hop Wireless Ad Hoc Network Routing Protocols," *Fourth Annual ACM/IEEE International Conference on Mobile Computing and Networking*, pp. 85—97, 1998.

[49] J. Stine and G. de Veciana, "A paradigm for quality-of-service in wireless ad hoc networks using synchronous signaling and node states," , *IEEE Journal on Selected Areas in Communications*, vol. 22, Issue 7, pp. 1301-1321, September 2004.

[50] M. Neely and E. Modiano, "Capacity and delay tradeoffs for ad hoc mobile networks," *IEEE Transactions on Information Theory,* vol. 51, Issue 6, pp. 1917-1937, June 2005.

[51] M. Grossglauser and D. Tse, "Mobility increases the capacity of ad-hoc wireless networks," *Twentieth Annual Joint Conference of the IEEE Computer and Communications Societies INFOCOM 2001*, Anchorage, AK, U.S.A. pp. 1360-1369, vol.3, April 2001.

[52] L. Galluccio, A. Leonardi, G. Morabito, and S. Palazzo, "Tradeoff between Energy-Efficiency and Timeliness of Neighbor Discovery in Self-Organizing Ad Hoc and

Sensor Networks," *38th Annual Hawaii International Conference on System Sciences,* Big Island, HI, U.S.A., p. 286a, January 2005.

[53] M. Haenggi and D. Puccinelli, "Routing in ad hoc networks: a case for long hops," *IEEE Communications Magazine,* vol. 43, Issue 10, pp. 93-101, October 2005.

[54] Jay Werb and Daniel Sexton, "White Paper: *Improved Quality of Service in IEEE 802.15.4 Mesh Networks,*" Needham, MA: Sensicast Systems, Inc., March 2005,<http://www.sensicast.com/white_paper_form.php?deliver_resource=IWWIA-rev-082906.pdf >.

[55] I.F. Akyildiz, M.C. Vuran, O.B. Akan, and W. Su, "Wireless Sensor Networks: A Survey revisited," *Elsevier Computer Networks Journal*, 2005.

[56] Dust Networks, "White paper: *Technical Overview of Time Synchronizes Mesh Protocol",* Hayward, CA: Dust Networks Inc., 2006, <www.dustnetworks.com/cms/sites/default/files/TSMP_Whitepaper.pdf >.

[57] David Gascon, "Article: *802.15.4 vs. Zigbee,*" Wireless Sensor Networks Research Group,November2008,<http://www.sensornetworks.org/index.php?page=0823123150 >.

[58] HART Communication Foundation, "White Paper: *The HART Protocol – A Solution Enabling Technology*", Austin, TX: HART Communication Foundation, February 2004,<http://www.hartcomm2.org/hart_protocol/applications/white_papers/solution_enabling_technology.html >.

[59] M. Barbeau and E. Kranakis, *Principles of Ad-hoc Networking*, Wiley, 2007.

[60] M. Mauve, A. Widmer, and H. Hartenstein, "A survey on position-based routing in mobile ad hoc networks," IEEE *Network,* vol. 15, Issue 6, pp.30-39,

November/December 2001.

[61] P. Baronti, P. Pillai, V.W.C. Chook, S. Chessa, A. Gotta, and Y.F. Hu, "Wireless sensor networks: A survey on the state of the art and the 802.15.4 and ZigBee standards," *ACM Computer Communications*, vol. 30, Issue 7, pp. 1655-1695, May 2007.

[62] Zigbee Alliance, "Specification paper: *Feature Set. ZigBee PRO",* San Ramon, CA: Zigbee Alliance, October 2007, <www.zigbee.org/imwp/download.asp?ContentID =11900 >.

[63] ISA, *"The ISA100 Standards: Overview & Status*", Research Triangle Park, NC: International Society of Automation: October 2008, <http://www.isa.org/source/ISA100_Overview_Oct_2008.pdf >.

[64] S. Mangold, S. Choi, P. May, O. Klein, G. Hiertz, L.Stibor, "IEEE 802.11e wireless LAN for quality of service," *Proceedings of the European Wireless*, Florence, Italy, vol. 1, pp. 32–39, February 2002.

[65] IEEE 802.11 TGe, *"EDCF proposed draft text,"* TR-01/131r1, March 2001.

[66] IEEE 802.11 TGe, *"Hybrid coordination function (HCF)—proposed updates to normative text of D0.1,"* TR-01/110r1, March 2001.

[67] Y.S. Chen, Y.C. Tseng, J. Sheu, and P. Kuo, "An On-Demand, Link-State, Multi-Path QoS Routing in a Wireless Mobile Ad-Hoc Network y." *The European Wireless*, Florence, Italy, February 2002.

[68] Q. Ni, L. Romdhani, and T. Turletti, "A survey of QoS enhancements for IEEE 802.11 wireless LAN: Research Articles," *ACM Wireless Communications and Mobile Computing.*, vol. 4, Issue 5, pp. 547-566, August 2004.

[69] I. Akyildiz, Weilian Su, Y. Sankarasubramaniam, and E. Cayirci, "A survey on sensor networks," *IEEE Communications Magazine*, vol. 40, Part 8, pp. 102-114, August 2002.

[70] Y. Gao, K. Wu, and F. Li, "Analysis on the redundancy of wireless sensor networks," *Proceedings of the 2nd ACM international conference on Wireless sensor networks and applications*, San Diego, CA, USA, pp. 108-114, 2003.

[71] B. Raman and K. Chebrolu, "Censor networks: a critique of "sensor networks" from a systems perspective," ACM *SIGCOMM Computer Communication Review*, vol. 38, Issue 3, pp. 75-78, July 2008.

[72] V. Kanodia, C. Li, A. Sabharwal, B. Sadeghi, and E. Knightly, "Distributed multi-hop scheduling and medium access with delay and throughput constraints," *ACM Proceedings of the 7th annual international conference on Mobile computing and networking*, Rome, Italy, pp. 200-209, 2001.

[73] Yunfeng Chen and Nidal Nasser, "Energy-Balancing Multipath Routing Protocol for Wireless Sensor Networks", *International Conference on Quality of Service in Heterogeneous Wired/Wireless Networks (QShine)*, Waterloo, ON, Canada, August 2006.

[74] I. Stojmenovic, "Localized network layer protocols in sensor networks based on optimizing cost over progress ratio," IEEE Network, Vol. 20, No. 1, 21-27 January/February 2006.

[75] S. Tilak, N.B. Abu-Ghazaleh, and W. Heinzelman, "Infrastructure tradeoffs for sensor networks," *Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications*, Atlanta, GA, USA, pp. 49-58, 2002.

[76] T. Rasheed, U. Javaid, M. Jerbi, and K. Al Agha, "Scalable Multi-hop Ad Hoc Routing Using Modified OLSR Routing Protocol," *IEEE 18th International Symposium on Personal, Indoor and Mobile Radio Communications*, Athens, Greece, pp. 1-6, 2007.

[77] N. Pavlidou, A. Han Vinck, J. Yazdani, and B. Honary, "Power line communications: state of the art and future trends," IEEE Communications Magazine, vol. 41, Issue 4, pp. 34-40, April 2003.

[78] H. Karl and A. Willig, "A Short Survey of Wireless Sensor Networks," Technical report, Technical University of Berlin, October 2003.

[79] A. Boukerche, Editor, *Handbook of Algorithms for Wireless Networking and Mobile Computing*, 1st ed. Boca Raton: Chapman & Hall/CRC, 2005.

[80] J. Wu, *Handbook on Theoretical and Algorithmic Aspects of Sensor, Ad Hoc Wireless, and Peer-to-Peer Networks*, Auerbach Publications, 2005.

[81] C. Yu, C.R. Das, and Y. Pan, *Performance Analysis of Mobile And AD Hoc Networks*, Nova Science Publishers, 2006.

[82] G.J. Pottie and W.J. Kaiser, *Principles of Embedded Networked Systems Design*, Cambridge University Press, 2009.

[83] J. Sarangapani, *Wireless Ad hoc and Sensor Networks: Protocols, Performance, and Control*, CRC, 2007.

[84] I. Jawhar and J. Wu, "QoS support in TDMA-based mobile ad hoc networks," *Journal of Computer Science and Technology*, vol. 20, Issue 6, pp. 797-810, November 2005.

[85] W. Masri and Z. Mammeri, "QoS Mapping in TDMA Tree Based Clustered WSN

between Accuracy, Density and Bandwidth," *International Conference on Communication Theory, Reliability, and Quality of Service, Bucharest, Romania*, pp. 71-76, 2008.

[86] M. Perillo and W. Heinzelman, "Providing application QoS through intelligent sensor management," *Proceedings of the First IEEE International Workshop on Sensor Network Protocols and Applications,* Rochester University, NY, USA , pp. 93-101, May 2003.

[87] Y. Zou and Krishnendu Chakrabarty, "Sensor deployment and target localization based on virtual forces," *Twenty-Second Annual Joint Conference of the IEEE Computer and Communications Societies INFOCOM 2003,* San Franciso, CA, USA , pp. 1293-1303, 2003.

[88] S. Park and R. Sivakumar, "Sink-to-sensors reliability in sensor networks," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 7, No. 3, pp. 27-28, July 2003.

[89] N. Reijers and K. Langendoen, "Efficient code distribution in wireless sensor networks," *Proceedings of the 2nd ACM international conference on Wireless sensor networks and applications*, San Diego, CA, USA, pp. 60-67, 2003.

[90] K.I. Park, *QoS in Packet Networks*, 1st ed. New York: Springer, 2004.

[91] Engineering Smart Technologies, "The wireless Volture™ Piezoelectric energy harvester," Medford, MA: Mide Technology Corporation, 2008, <http://www.mide.com/products/volture/volture_catalog.php>.

[92] M. Gerla and J.T. Tsai, "Multicluster, mobile, multimedia radio network," *Journal of Wireless Networks*, vol. 1, No. 3, pp. 255-265, September 1995.

[93] X. Li, P. Wan, Y. Wang, and C. Yi, “Fault tolerant deployment and topology control in wireless networks,” *Proceedings of the 4th ACM international symposium on Mobile ad hoc networking and computing,* Annapolis, MD, USA, pp. 117-128, 2003.

Appendix A

Confidence Interval Calculation

The accuracy of the simulation results is normally described in terms of confidence intervals. A confidence interval gives an estimated range of values which is likely to include an unknown population parameter. The estimated range can be calculated from a given set of sample data.

Let X be an unknown population parameter and $X_1, X_2, X_3 \ldots X_N$ be the simulation results of the same experiment but produced by N different runs, and assume these simulation runs are statistically independent.

The sample mean $\overline{X}$ of these results is given by

$$\overline{X} = \frac{\sum_{i=1}^{N} X_i}{N}$$

and the sample variance S_X^2 is defined as follows:

$$S_X^2 = \frac{\sum_{i=1}^{N} \left(X_i - \overline{X}\right)2}{N-1}$$

Appendix A. Confidence Interval

The upper and lower bounds of the confidence interval regarding these simulation results are defined as follows:

$$\text{Upper bound} = \overline{X} + \frac{S_X \times t_{\frac{\alpha}{2},N-1}}{\sqrt{N}}$$

$$\text{Lower bound} = \overline{X} - \frac{S_X \times t_{\frac{\alpha}{2},N-1}}{\sqrt{N}}$$

Where $t_{\frac{\alpha}{2},N-1}$ is the upper $100 \times \frac{\alpha}{2}$ percentage of the t-distribution with $N - 1$ degrees of freedom, and its values can be obtained from tables.

The intervals thus obtained are referred to as the intervals with $100 \times (1 - \alpha)$ percent confidence and $(N - 1)$ degrees of freedom. These confidence intervals can be made as small as desired by increasing the number of independent runs of a single experiment. In this thesis, the 95% confidence intervals for the difference between the simulated and theoretical delays and reliabilities were obtained, based on 10 independent experiments run. The below table shows example confidence intervals of an average of 1600 delay points obtained from 3 different experiment scenarios.

Experiment Scenario	*Single Route 0% Failure Probability Delay*	*Single Route 30% Failure Probability Delay*	*Single Route 90% Failure Probability Delay*
Upper Bound	X + 0.0783	X + 0.0915	X + 0.1230
Lower Bound	X - 0.0798	X - 0.0928	X - 0.1962

Table A.1: Example of calculated confidence intervals