DELAY SENSITIVE ROUTING IN THREE DIMENSIONAL UNDERWATER ACOUSTIC SENSOR NETWORKS

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May 2002

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
May, 2006

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DIMENSIONAL UNDERWATER ACOUSTIC SENSOR

NETWORKS

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CHAPTER I

INTRODUCTION

Sensor network is a collection of large number of sensor nodes which are designed to perform a collaborative monitoring task such as detection, tracking, or classification over a given geographical area. The whole network has a single objective of performing a specific task. Each node in the network contributes to the task by sensing and transmitting the sensed information to the sink or by just forwarding the information sensed by the other node in the network.

The traditional approach in the underwater sensor networks requires deployment of the sensor nodes, collection of data through the sensor nodes and retrieval of the sensor nodes. This is considered to be unsuitable for the underwater sensor networks, because there is no real-time monitoring, failure detection, storage extension, and lack of on-line system configuration. The data recorded cannot be accessed until the sensor nodes are retrieved from the area where they have been deployed. Failure of nodes cannot be detected in order to maintain the connectivity. Once the memory of a sensor node full, it cannot sense further. No inter-action and adaptive sampling can be done here.

Wireless sensor networks are similar to the sensor networks in which sensor nodes communicate without cables and have all the capabilities of a basic sensor network which enables the use of sensor networks in environments which are not user-friendly such as dense forest, military areas and area which cannot be easily reached by humans. Many new technologies in the wireless communications lead the way to the development of low-cost, multi-functional, small sensor nodes. Each sensor node should have a self-organizing capability so that in the case of failure it can place itself in a position such that it is connected to the network. The deployment of sensor nodes is dense and random in the case of terrestrial environment.

1.1 Underwater sensor networks

Underwater sensor networks are a collection of sensor nodes which communicate among them through the emerging underwater acoustic communication technology. In Underwater networks, Acoustic communications is the typical layer technology. There are some reasons that acoustic communication technology was chosen for the communication in underwater. Radio waves propagate through conductive sea water at extra low frequencies (30-300 Hz) which requires large antennae and high transmission power. Scattering is most important factor which made the use of optical waves inefficient. Obviously, acoustic communication technology is the best choice when compared to the radio waves and optical waves. Acoustic modem is the most important technology used by the wireless sensor networks in underwater to communicate among them.

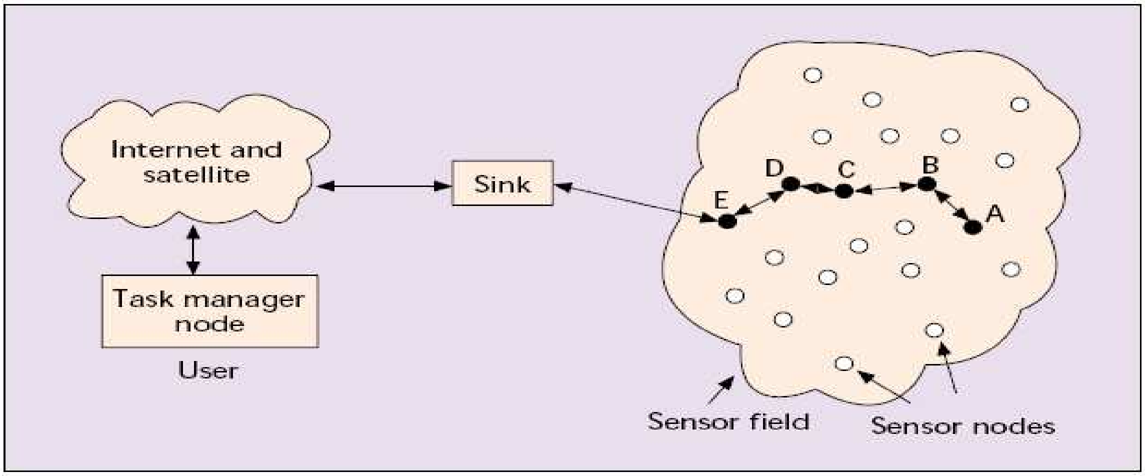

Figure 1 Sensor nodes scattered in a sensor field [1]

1.2 Design Factors

It is believed that the architecture of any kind of sensor network is multi-hop infrastructure-less and it depends on these basic design factors. They are listed below:

Fault tolerance is defined as the capacity of a sensor network to withstand its functionalities without any interruption due to the failure of some sensor nodes.

Scalability is defined as the ability of a sensor network to grow its size in number of nodes or increase its coverage area at any point of time.

Cost of a sensor node is also a main factor in determining the size of a network because a sensor network consists of a large number of sensor nodes and it requires the cost of a sensor node to be very low.

Sensor network topology is a design factor in which the effect of failure of nodes is cancelled by the redeployment of the sensor nodes in that place or by replacing some other sensor nodes in the place of the failed sensor node which helps to maintain the link.

Environment of a sensor network is the one which determines the type of deployment and frequency of maintenance of sensor nodes in a given geographical area.

Transmission media is the most important factor which helps the sensor nodes to communicate between them. It is chosen based on the environment and the functionalities of the sensor network.

Power consumption of a sensor node is important design factor because the charge of the battery in the sensor node cannot be replenished, once it is deployed. So all the protocols, routing algorithms developed for the sensor networks should be developed with the power-aware technology embedded in it.

1.3 Limitations

There are some additional limitations which led to the use of acoustic communication technology. Even though acoustic communication technology is chosen as the best for the underwater communication, there are some limitations which require research in the field of underwater acoustic communication technology. Sensor networks in underwater basically differ from the sensor networks in terrestrial. So this difference imposes some limitations in the underwater sensor networks which use acoustic communication technology. Some of the limitations are listed below,

- Bandwidth is severely limited.
- Propagation delay is larger than RF channel and variable.
- High BER and temporary losses of connectivity.
- Multi-path and fading is present.
- Battery power is limited.

- Failure of nodes due to fouling and corrosion.

The availability of bandwidth varies according to the distance. Propagation delay is five magnitudes larger than the terrestrial RF channel because of the unique characteristics of the underwater acoustic channel and the speed of sound i.e. 1500 m/s. The bit error rate is also comparatively high. The propagation of the signal in multi-path generates ISI (Inter-Symbol Interference) which leads to the degradation of the signal strength. Fading is the term which is used to indicate the decrease in signal strength due to several factors like multi-path, noise etc. Battery power is also limited when compared to the terrestrial sensor network nodes because there is no solar power to replenish the charge of the battery present in the nodes. So, an efficient way is required to use the charge present which makes the life-time of the sensor node longer.

One of the major constraints of the UW-ASN’S is the limited energy supply. The batteries of the wireless modem can be easily replaced in a land-based system, but in the case of underwater sensor networks, it is difficult. Several factors like ship-time, retrieval of the modem, charging the battery, replacing the charged battery makes it more time-consuming and costlier.

1.4 Applications

Some of the applications that have been successfully exploited from the Underwater Acoustic Networks are summarized below:

- Ocean Sampling networks
- Undersea Explorations
- Environmental Monitoring

- Disaster Prevention
- Assisted Navigation
- Distributed Tactical Surveillance
- Mine Reconnaissance

These are the applications that are largely been carried out now-a-days. Several more applications have not yet been explored from the underwater sensor networks.

CHAPTER II

BACKGROUND

Network topology is considered to be a crucial factor that determines the overall lifetime of the network. It is used to determine the energy consumption, reliability and capacity of the network. The capacity of the underwater channel is extremely limited. Care should be taken to increase the lifetime of the network and to utilize the available channel in whole. Failure at a single point should not decrease the lifetime of the network.

2.1 Types of underwater sensor networks

Underwater acoustic sensor networks are basically categorized in to three types.

2.1.1 Static Two-dimensional UASN

Static Two-dimensional UASN is a collection of sensor nodes that are anchored to the bottom of the ocean-bed. By the means of wireless acoustic links the sensor nodes are connected to one or more sinks. These sinks in turn have vertical and horizontal transceivers. The horizontal transceiver is used to collect the data from the sensor nodes. The vertical transceiver is used to send the collected data to the surface station. These nodes and sink are immovable.

2.1.2 Static Three-dimensional UASN

Static Three-dimensional UASN is a collection of sensor nodes that are connected to the bottom of the ocean-bed by tethers. Tethers are used to control the depth of the sensor nodes so that it can adjust their depth in order to sense at different depths and to maintain the connectivity to the network in case of link failures. The two most important features of this type of network are,

Sensing coverage of a given geographical ocean column must be covered by the sensor nodes collaboratively functioning at different depths.

Communication coverage should be achieved by the sensor nodes in order to relay the information sensed to the surface station and to maintain their connectivity to the network always by adjusting their depths.

2.1.3 Three dimensional UASN

Three dimensional UASN (Autonomous Underwater Acoustic Sensor Network vehicles) is a sensor node which is built inside underwater vehicles which are used to enhance the capabilities of the whole sensor network. The two distinct and specific characteristic of this autonomous underwater vehicles are,

Adaptive sampling is a process of controlling and placing the mobile vehicles in places where their data will be more useful and where more sampling rate is needed.

Self-configuration is the process of positioning themselves in order to fulfill the node failure, link failure and to maintain the connectivity in the network.

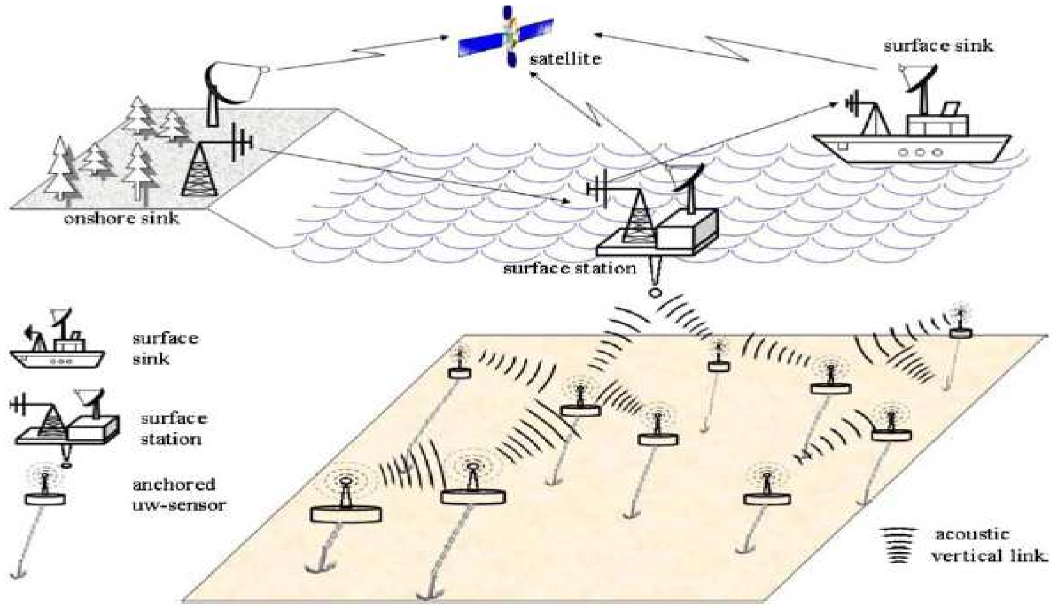

Figure 2 Communication architecture of 3-Dimensional Underwater Acoustic Sensor Network [3]

The main objective of the AUV’S is to rely on its local intelligence rather than relying on the control from online shores. Mobility being the important aspect of AUV’S link failure is most frequent one here. Normally the routing decision which relies on the centralized station is not suitable for AUV’S. So, a different method should be designed in order to make a routing decision as soon as possible or at-least faster than the previous method in case of node failure or link failure.

Different types of AUV’S are small-scale **submarines, drifters, gliders**. The vehicles which drift with local current and move vertically through the water column are called drifters. The vehicles that use hydraulic pumps to vary their volume to generate buoyancy changes that power their forward gliding are gliders. These AUV’S have operating lifetime varying from few weeks to several months. Its depth ranges from 200m to 1500m. As the sensor nodes in the underwater sensor network are different from terrestrial, there are some design challenges peculiar to underwater sensor networks. As the sensor node is expensive than its counterpart the deployment is sparse, distance between nodes is more, power required to transmit is high and there is no chance of spatial correlation here because of sparse population of underwater sensor nodes.

2.2 Network topologies

The network topology is basically divided in three types. They are given below.

2.2.1 Centralized topology

A central station assigned to a network which is responsible for the communication between any source and destination pair. The central station is also called as hub. The main disadvantage in this system is the failure of whole system lies at a single point of failure. If the central station fails, the whole system's communication is affected.

2.2.2 Distributed topology

This topology is similar to peer-to-peer communication. Point-to-point link is maintained from every node to every other node in a peer-to-peer network. Every node has its responsibility in the communication and it eliminates the need for routing.

2.2.3 Multi-hop topology

In this topology, communication links are established by every node with its neighboring nodes only and the communication is done by hopping from node-to-node since the source packets reach the destination. This topology protocols involves the use of intelligent algorithms to adapt the rapidly changing environment.

2.3 Internal architecture

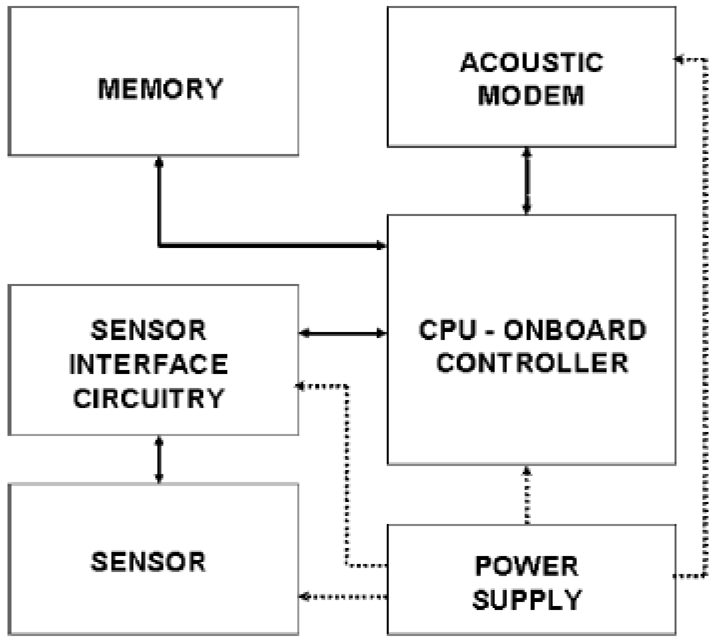

Figure 3 Internal architecture of underwater sensor node [2]

The internal architecture of underwater sensor node consists of six essential components.

CPU Onboard-Controller is used to process the raw data and is connected to the sensor through the sensor interface circuitry.

Sensor is used to sense the actual physical phenomenon for which the sensor node is assigned and sends it to the CPU through the sensor interface circuitry. The sensors included in each sensor node are sensors which are used to measure temperature, salinity, density, acidity, chemicals, conductivity, pH, oxygen, hydrogen, dissolved methane gas, and turbidity.

Memory is used to store the information processed from the raw data in the CPU and it is also used to store and forward the data from other sensor nodes to the sink.

Power supply is used to store the charge (battery) that is used to run the sensor node. The lifetime of the sensor node depends upon the charge in the battery.

Acoustic modem is the device used to send the information collected in a node to another node in the network through acoustic communication technology. As the communication is made through the acoustic modem, there is a need to point out some features of acoustic propagation.

2.4 Basics of acoustic propagation

Acoustic propagation is influenced by the following factors like path-loss, noise, multi-path, Doppler spread, and high and variable propagation delay. Some links are classified as horizontal and vertical according to the direction of the sound ray. The factors mentioned above led to achieve low bit rates i.e. high BER. So the communication is dramatically reduced as compared to the terrestrial radio channel. Underwater acoustic communication links are classified according to their ranges as very long, long, medium, short and very short.

Delay is said to be high and variable in underwater sensor networks. High delays (0.67s/km) will affect the throughput of the system considerably. The variable property of the delay makes the use of some commonly used communication protocols impossible in this environment.

Table 1Available Bandwidth for different ranges in Underwater-Acoustic Channels

DISTANCE	**RANGE [KM]**	**BANDWIDTH [KHZ]**
Very long	1000	<1
Long	10-100	2-5
Medium	1-10	~10
Short	0.1-1	20-50

Very short	<0.1	>100

Path-loss of a signal is characterized by two main factors namely attenuation and geometric spreading. Attenuation is mainly caused due to the absorption of acoustic energy in to heat, which increases with distance and frequency. It is also caused by scattering, reverberation, refraction, and dispersion. The depth of the sensor node in the water plays a vital role in determining the attenuation. Geometric spreading is defined as the spreading of sound energy as a result of expansion of wave-fronts which increases with the propagation distance.

Noise is mainly classified in to man-made noise and ambient noise. Man-made noises are noises made by machinery and shipping activities. Ambient noises are noises caused by tides, currents, storms, wind, and rain, seismic and biological phenomena.

Multi-path is the main cause of ISI (Inter-Symbol Interference) which severely degrades the acoustic communication signal. Multi-path has lower effect on vertical links than the horizontal links.

Doppler spread is one of the most significant factors in underwater channels, because the ISI (Inter-Symbol Interference) causes degradation in the digital communication performance which requires complex signal processing to deal with the produced ISI.

2.5 Cross layer protocol stack

A cross layer protocol stack is proposed for UASN (underwater acoustic sensor networks) is proposed in [2]. This protocol stack consists of five of the seven layers of OSI model namely,

1. Physical layer
2. Data link layer

3. Network layer
4. Transport layer
5. Application layer

In addition to the common responsibilities of these layers, three management planes are included in the protocol stack, which has specials responsibilities. The design imposes the responsibility of each layer for

- Power management
- Task management
- Mobility management

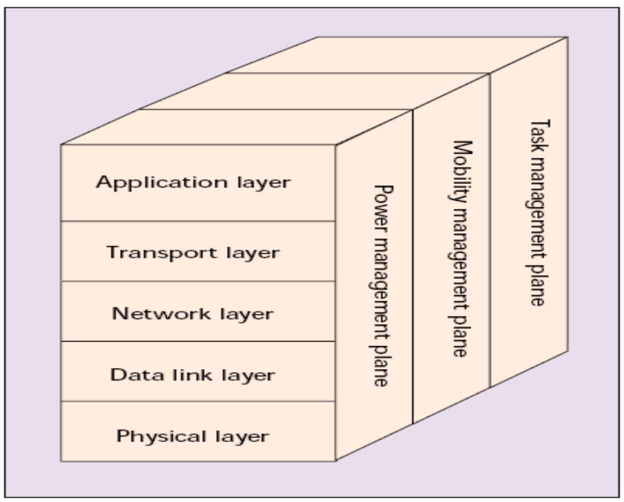

Figure 4 Cross layer protocol stack [2]

The physical layer is responsible for frequency selection, carrier frequency generation, signal detection, modulation, and data encryption. The responsibilities of a data link layer are multiplexing of data streams, medium access, error correction and data frame detection. Network layer has the responsibilities of inter-networking with other sensor networks such as other sensor networks. Transport layer is an unexplored area which still needs a lot of research. When a network has to communicate with other sensor network transport network has to contribute a lot. Application layer is the layer where the exploitation of a sensor network in different areas has to be designed. This application layer is an area where hot research topics are available.

Power management plane is the plane which is responsible for the power consumption, power conservation, power requirement; lifetime of a node has to be monitored. The responsibilities of task management plane are to consider the given task and react in a

fast and efficient way to achieve the result according to the task given. Mobility management plane is used to manage the nodes mobility. It is used to detect and register the movement of a sensor node so that it always knows in which direction it is moving and where it is positioned. It helps to maintain the connectivity to the network always and to update its neighbors list periodically which reduces link failures.

The responsibility of routing the packets falls under the network layer. The node which senses the physical activity has to send the data to the surface station which actually samples the physical phenomenon. A number of ad-hoc routing protocols are available for routing the packets. But, due to the special and unique characteristics of acoustic communication environment, every routing ad-hot routing protocol has some limitations or disadvantages in using it in underwater sensor networks.

2.6 Routing protocols

The two basic methods for routing the packets in a communication network are briefly explained below.

- **Virtual circuit routing** is a method in which the paths are determined at the beginning of the transaction itself.

- **Datagram routing** is a kind of routing in which each node that involved in the transaction takes part in the process of routing.

All the ad-hoc routing protocols are basically classified in to three types. The basic function of all the protocols is to route the packets to specified destination but the way it performs the routing is different. They are listed below.

2.6.1 Pro-active routing protocol

These protocols maintain up-to-date information about the routes to reduce the message latency caused due to route discovery. So the node which contains the route has to broadcast the route packets to all the nodes in the network to maintain the up-to-date information. Due to large node failures, link failures and mobility the network topology keeps on changing every now and then, so the route maintenance causes a lot of signaling overhead and it is required to maintain route from every node to every other node in the sensor network. So, pro-active routing protocol is considered to be un-suitable for the underwater sensor networks.

2.6.2 Re-active routing protocol

Re-active protocols initiate a route discovery process only when a route to destination is required. Then the discovered route is maintained until it is no longer desired. This protocol also relies on flooding of route packets to find the route to a particular destination which leads to higher message latency. Because of reliance on flooding, these protocols also produce a lot of signaling overhead which is not suitable for underwater sensor networks.

2.6.3 Geographic routing protocol

Localization information is used to establish the source-destination path in these protocols. The selection of next hop by each node is based on the position of its neighbor node and the destination node. This technique is considered to be better than the previous two types but the accuracy of localization system has to be studied well in underwater environment with the limited energy expenditure.

2.7 Requirement of a new routing protocol

The topology of the UW-ASN'S is unlikely to vary dynamically on a short time scale. Routing schemes that jointly minimize the signaling overhead and the latency has to be developed. In most of the ad-hot networks, routing protocols are based on packet switching. In UW-ASN'S, virtual circuit routing is believed to develop an efficient and effective protocol. In virtual circuit routing, a path is established priori between a source and destination pair and each packet from that source follows the same path. This is a form of centralized co-ordination which is less flexible but lead to more efficient paths. Furthermore, routing schemes that account for the 3D environment need to be developed. Especially, currents should be taken in to account in the case of 3D environment which cause connectivity holes, especially when the sensor network is deployed in deep waters. The 3D underwater sensor network may consist of 3D sensor nodes combined with AUV'S. So, mobility is a main factor that has to be taken in to consideration which is the main cause of connectivity holes and link failure.

CHAPTER III

REVIEW OF LITERATURE

Several fundamental key aspects of underwater acoustic communications are investigated in [2]. The architecture for a 3D UW-ASN'S is discussed and the characteristics of the underwater channel are explained. The main challenges for the development of efficient networking environment are discussed and a cross-layer approach to the integration of all communication functionalities is suggested. In addition to these, some research issues have been listed for improving the three dimensional underwater sensor networks. The real problems associated with the underwater channel are given and the importance of three dimensional sensor networks is discussed in this paper.

In [7] the different type of network topologies and the best which suits the underwater environment is also given here. The facts about the advantages and disadvantages of a size, charge, capacity of a sensor node are explained in detail. The importance of delay tolerant and real-time applications is discussed. Some surveillance application may need very fast reaction to events and thus networking protocols need to guarantee delay bounded delivery with a delay bound B. The delay-sensitive applications which have a delay bound in which the network has to react to the connectivity holes as possible in order to keep the delay less than the delay bound.

In [2] the responsibilities of the network layer are explained in detail. The routing protocol for ad-hot wireless networks is discussed in [9] and for wireless sensor networks in [10]. This helps to determine the kind of routing protocol needed for an underwater environment. The underwater channel has some special characteristic which makes the routing protocols described in [9] and [10] unsuitable for the wireless sensor network in underwater environment.

Different types of protocols have been explained in [11] and [13]. The ad-hoc nature of the protocols is same but the channel used in underwater is different. We use acoustic communication i.e. sound waves for the communication in UW-WSN. The type of communication and the limitations of the channel are entirely different with respect to the radio channel which we use in terrestrial. [2] Gives the reason why we cannot use the RF channel for the underwater wireless sensor networks and the limitations of the acoustic channel we use in the underwater environment.

In [15], a routing protocol is proposed that autonomously establishes the underwater network topology, controls network resources and establishes network flows. This protocol relies on centralized network manager. The central manager probes the nodes to estimate the channel characteristics. The information is exploited by the central manager to establish efficient data delivery paths in a centralized fashion, which avoids congestion and assures a quality of service guarantee. Even though in terrestrial and ad-hot networks, routing protocols are based on packet switching, virtual circuit routing is preferred for UW-ASN'S. This requires a form of centralized coordination and implies a less flexible architecture, but allows exploiting powerful optimization tools on a centralized manager. It also achieves optimal performance at the network layer like minimum delay paths and energy efficient paths with minimum communication signaling Over-head.

3.1 Channel utilization efficiency and round-trip time

In the underwater environment, the channel is shared by several devices. An analytical model is given in [1] to describe the effects and characteristics of channel utilization efficiency in an underwater environment. In this formulation, length of the payload in the packet, length of the FEC code in the packet, length of the header, length of the ACK packet, the time taken by the node form transmitting to receiving, data transmission rate are all taken in to account. According to the model, the round-trip time taken is given by,

$$Trrt = TtH + TtD + TtF + 2.Tp + Trx\text{-}tx + TtA \; [1] \qquad (3.1)$$

The round-trip time includes the time taken to transmit header, payload, FEC code, ACK and propagation delay for the packet and the ACK packet, the time taken by the node to change it from receiving mode to the transmitting mode.

The concept of packet train is introduced in this paper for the delay-insensitive routing. The solution is based on distributed geographical routing. The concept of packet train seems to be more promising in achieving more channel utilization and low (bit error rate) BER. These two are said to be conflicting objectives. As the size of packet increase, more efficient FEC codes are required to correct the BER which increases the cost. But when the packet is small the channel is used for sending small amount of information for a long time. So, a solution which satisfies these both objectives is packet train concept.

The packet train consists of a number of packets which enables the node to hold the channel to send more information than before and also it consists of smaller packets which do not require complex FEC coding techniques. The packets that were received with high BER or the corrupted packets have to be retransmitted rather than retransmitting the whole packet train again. This concept reduces the T_{rrt} (round-trip time) in a nominal way by reducing the number of ACK packets.

3.2 Selection of next hop based on energy metric

In [1], an algorithm is proposed in which the next hop is selected based on energy metric which gives low BER and maximizes the probability of a successful packet decoding at the receiver. The energy metric depends on the link cost metric and the link cost metric is given by,

$$E_i(j) = E_{ij} \cdot N_{ij}^{t} \cdot N_i^{hop} \text{ [1]} \tag{3.2}$$

$E_i^{(j)}$ - Link cost metric.

E_{ij} - Energy required to transmit one bit from node i to node j.

N_{ij}^{t} - Estimated number of retransmissions according to BER

N_i^{hop} – Estimated number of hops from node i to sink.

Using these constraints, the best next hop can be determined in a delay-insensitive application. The concept of packet train and the selection of best next hop seem to be promising. Both the packet train concept and the selection of best next hop concept can be combined to produce to outstanding result in a delay-sensitive application.

3.3 Establishment of primary and back-up paths

In the case of delay-sensitive application, these concepts can improve the use of network resources but the reduction in delay cannot be made through these techniques. So, another concept has been introduced for the delay-sensitive routing in UW-ASN’S. Virtual circuit routing is chosen as the best for UW-ASN’S already to achieve optimal performance at the network layer. Even though sudden mobility, node failure, link failure causes the 3D routing schemes for delay-sensitive applications a little problematic. So in this paper, they have proposed that finding two multi-hop node disjoint paths from each source to destination will be a solution.

- **Primary data path**
- **Back-up data path**

The secondary path will offer protection against both node failure and link failures in the primary path. This protection scheme is classified as a dedicated back-up scheme.

3.4 Statistical path delay model

A statistical path delay is modeled for the underwater links in this paper. For every link (i, j), the link has a propagation delay p_{ij} , distance d_{ij} , speed of the signal q_{ij}. Because of the multi-path, averages of the above factors are taken in to consideration. So, using the delay for every link, end-to-end delay can be calculated. The path which has the minimum delay is chosen as the primary data path and the path which has the second least end-to-end delay will be chosen as the secondary data path which should be always lower than the maximum delay bound $B_{max.}$

As delay is the main factor to be reduced in delay-sensitive routing, there is a possibility of source blocking. Source block probability increases with time i.e. when both the primary and back-up data paths have at-least one failed node, the source will not be able to transmit. According to the rapidly changing environment in underwater, mobility, and node failure it can happen frequently. So measures should be taken to reduce the source block probability.

CHAPTER IV

PROBLEM STATEMENT

Delay-sensitive routing in 3-Dimensional Under-Water Acoustic Sensor Network's is mainly affected by mobility. Basically a sensor network is assumed to have large collection of sensor nodes which have to communicate among themselves. Even though a centralized controller establishes a prior path between source and destination node, some connectivity holes are created due to mobility and also because of node failures. Therefore, it affects the packet transfer from the source to destination.

If a connectivity hole happens when a packet has just a few hops to reach the sink, a new route must be found. The packets that have been transmitted, but not reached the sink must then be re-transmitted. The number of packets may be small or large based on the size of network. This retransmission consumes time, energy, route update cost. The time taken to find a new route is also considered as wastage. In the mean time the source cannot do anything useful i.e. the source is considered to be temporarily blocked.

Even though virtual circuit routing imposes a centralized topology, it produces efficient paths. How-ever, due to rapidly changing environment, mobility, node failure, link failure, the path produced is not as efficient as when the nodes are stable. Therefore, some functionalities of the datagram routing have to be included in the routing protocols of UW-ASN'S. The nodes in the path that is already established should have the ability to make the routing decision in case of link failure and node failure in order to save time and energy. The solutions for the connectivity holes caused by mobility, node failure should be local to avoid communication with the surface station and global reconfiguration of the network which can minimize the signaling overhead.

CHAPTER V

PROPOSED SOLUTION

The solution to the problem proposed is given in the following way. When there is an importance to energy expenditure in the UW networks, delay sensitive applications has a conflicting objective. So a solution has to be proposed that has to meet both the energy expenditure and the delay variance. Even though centralized form of topology is considered for the UW-ASN'S which is less flexible, it is used to exploit the extremely scarce network resources. At the time of mobility and node failures, the connectivity holes need the global reconfiguration in the centralized form of topology which not only leads to signaling overhead, but also some delay. So if the solutions for this problem become local, there is no need to globally reconfigure or to wait for the surface station to devise a new path to transmit. The wait-time for the devising the new path can be saved.

The proposed solution in [1] gives two paths namely primary and back-up data paths which are otherwise called as dedicated scheme. Based on that solution, a centralized form of topology is used in the initialization phase, but at the time of mobility, node failure, and link failure, the nodes in the path that was chosen by the centralized algorithm must have the responsibility of redirecting the packets they have at that moment. So there will be no retransmission of a packet from source again if it has transmitted a packet successfully once, unless the node containing the packet fails. The way proposed in [1] is to create a two paths i.e. primary path and back-up data paths which may cause source block probability.

One way is to create a primary path as in the centralized form of network topology and also giving the responsibility to the nodes in the path created to take routing decisions in the moment of failures.

So instead of having a back-up data path from source to destination, every node should have a back-up node i.e. for the next hop. By this method, the packets already transmitted need not be re-transmitted, but have to choose a different path to reach the destination (Sink). The time taken to re-transmit the packets and the energy spent in the process of transmitting the packets to that point of failure can be saved. This concept of having a back-up next hop node for every node in the chosen path not only reduces the energy consumption but also reduces the delay.

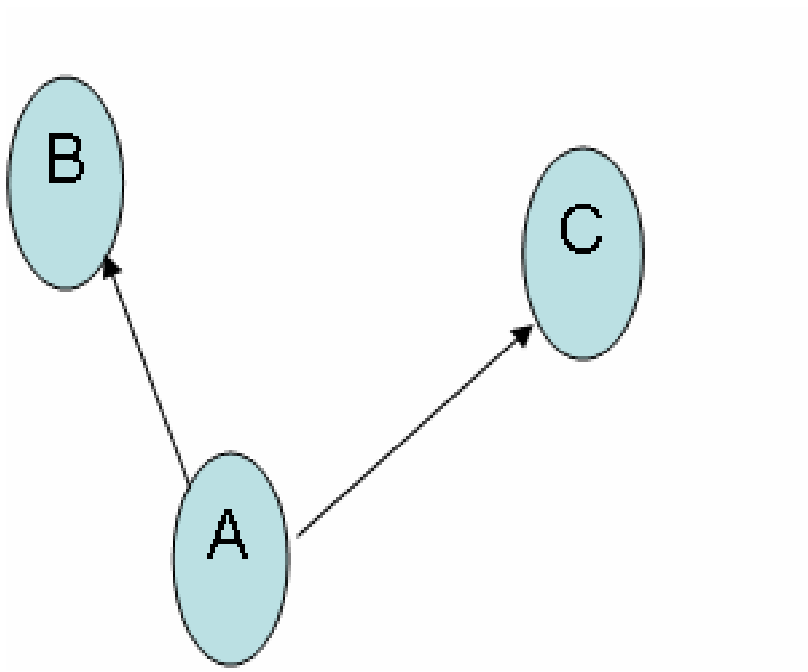

Figure 5 Node connected to its primary and back-up next hop node

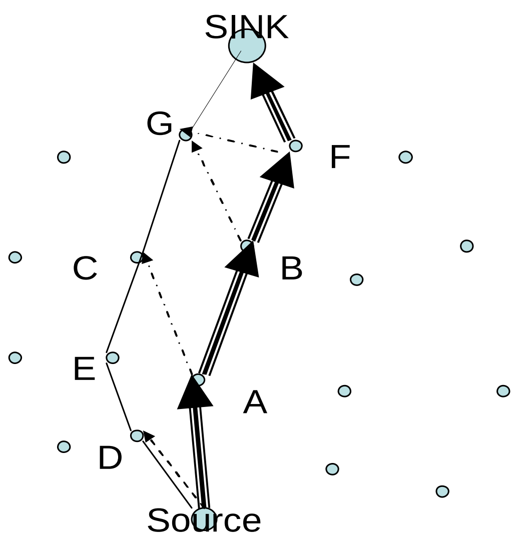

Figure 6 Multihop wire-less sensor network with alternate nodes in the path

During the selection of the primary and back-up nodes in the path selected for the particular source-destination pair, some rules has to be followed. For example, if node A has B as its primary node and C as its back-up node in the network, the rules are,

Node A:

- A cannot be primary for B and C.
- A can be back-up for B or C (worst case).

Node B: (A’s Primary next hop node)

- B cannot be primary for C.
- B can have C as back-up (worst-case).

Node C (A’s Back-up next hop node)

- C cannot be primary for B.
- C cannot have B as back-up.

Each link from source to destination will have a propagation delay P_{ij}. Based on that delay, the end-to-end delay is calculated to find the primary and back-up data paths.

Following the same way, we can use the statistical path delay model to find the maximum delay that can be achieved by the node i.e. $B_{max\ of}$ a link (i, j). So, a node i will have n neighbors. The link which has the least delay $B_{ij\ will}$ choose as the primary node which is already present in the path chosen. The link which has the second least delay $B_{ij\ will\ be}$ as the back-up next hop node j for a node i.

Thick arrow lines – primary path chosen during initialization.

Lines (plain) - Back-up path that the surface station may choose in case of failures

Dotted lines - Proposed back-up next hop node path for every node in the path Chosen at the initialization

5.1 Initialization

During initialization, a primary path will be determined for each source, destination pair. This path is established by the centralized surface station which guarantees quality of service, free of congestion, good utilization of scarce network resources.

5.2 Failures and Recovery

During the link failure, node failure which causes connectivity holes, the following may happen.

Case (i). If the back-up path is chosen to transmit, and if a node fails in the back-up path also, source cannot transmit for a long time which leads to a source block probability until the next path is informed to the source by the surface station.

Case (ii). If the proposed best next hop node is chosen at the point of failure, the transmission from the source can keep on going until the new path from the surface station is informed to the source. The packets transmitted in the mean time need not be re transmitted and it is the responsibility of the nodes in the old path to transmit the packets to the sink. Thus once a node successfully transmitted a packet to its neighbor, the responsibility of transmitting the packet to the sink i.e. surface station is also passed on to that particular neighbor. The surface station should take the responsibility of re-arranging the packets received from that source irrespective of the path.

5.3 Alternate next hop nodes

Alternate nodes are the nodes which are indicated by the dotted lines from the nodes in the main path. These are the nodes which are believed to reduce the delay, energy expenditure, and idle time of source.

Concept of Relay nodes:

Relay nodes can be introduced to reduce the number of retransmissions. As the nodes in the underwater environment are subjected to mobility, the concept of relay nodes will be useful. Relay nodes can also be called as intermediate source nodes. The relay nodes are the nodes which are used to store the packets up to their capacity, and when the need comes instead of re-transmitting from the source node, relay nodes can re-transmit in order to save the time, energy of nodes in between the source node and the relay node. The factors to be considered while selecting the relay node are,

1. Based on the number of paths participating in the path, relay nodes has to be determined.
2. Relay nodes should be determined in order to re-transmit the packets faster than before.
3. Relay nodes should be changed periodically in order to reduce the load imposed on nodes, so that the energy consumption of the nodes will be balanced.

4. The frequency of the change in relay nodes should be based upon the energy consumption, packet size, size of packet train and data transfer rate.

For a delay-insensitive application, the number of hops, energy metric used in the selected path should be the least compared to the other paths available. In the case of delay-sensitive applications, the delay in the selected path should be always low compared to the other paths even though other factors cross the limit.

CHAPTER VI

METHODOLOGY

The working of the proposed solution is briefly explained here. Let us assume there are 100 nodes in the sensor network we deal with. A single node is chosen as the surface station which is responsible for forming the network topology. It is also responsible for the communication between sensor nodes and the terrestrial stations and nodes. When this surface is ready to communicate with the nodes in the underwater, it broadcasts a join message to the sensor nodes which they can reach. When the sensor nodes which are in the range of the surface station receive the message it gets activated and in turn these nodes will broadcast a join message to its neighbor sensor nodes. Likewise, the process will continue till the source (leaf) nodes are reached.

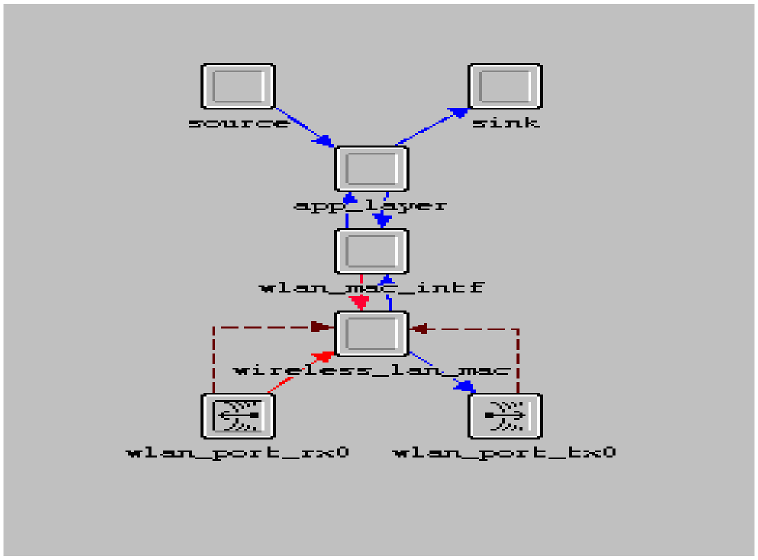

Figure 7 Node model

When a source node is activated by its neighbor it becomes ready to send the data and communicate with the surface station. When all the nodes in the sensor network area are activated, the whole network topology is formed.

6.1 Application interface layer

This is the layer which is introduced in the new proposed design of routing in 3-dimensional underwater sensor networks. This is the layer which is used to build the neighbor (routing) table. The table is built specifically in this layer using the information present in the join/hello packet received from other neighboring nodes. Using the x position and y position the propagation delay is calculated between the node which received the join packet and the node which sent the join packet.

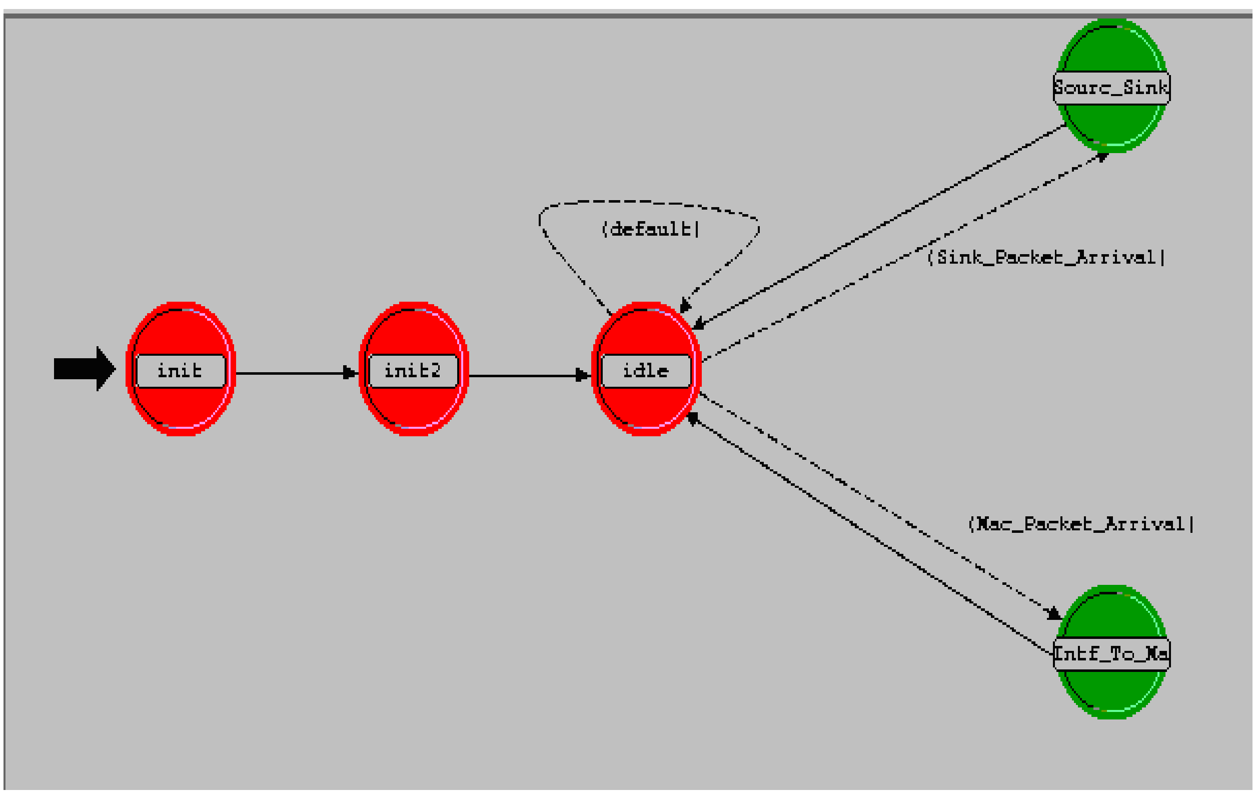

Figure 8 Application interface process model

This application layer interface process model consists of five states. In those, two of them are initial states. The function of these states is to initialize this process and be ready for the other process connected to it. The processes connected to it are the wlan_mac_intf layer, sink, and source. The function of the wlan_mac_intf layer is the interface between the MAC layer and Application layer

6.1.1 Idle module

Apart from the initial states, idle state is the state in which the application interface layer makes important decisions. The main function of the idle state is to determine the type of the packet. According to the type of the packet, appropriate action will be taken on the packet. There are many actions that can be applied on the packet according to the packet header. The attribute in the packet header which determines the type of packet is HC.

If the value of HC is one, then the packet is considered to be HELLO type. If the packet is of HELLO type, then the neighbor table of the node will be updated with the information it received in the HELLO packet.

If the value of HC is zero, then the packet is considered to be a data packet. If the packet is of data packet type, then the final destination is verified. The two actions that can be taken according the attribute called final destination are given below.

Forwarding: If the final destination in the packet does not contain the node identification number of the node which received the packet, then the node should forward the packet to its current next hop. The process goes on with each and every node until the packet reaches the final destination.

Accepting: If the final destination in the packet is the node identification number of the node which received the packet, then the node will send the packet to its own sink to make sure it accepts the packet with its node identification number in its final destination attribute.

The decision to perform these actions will take place in the idle state. When the node is in the idle state, it receives the packet. It determines the type of packet using the command intrpt_type (pkptr), where pkptr is the packet pointer which is pointed to the packet by which we can obtain much information about the packet such as packet creation time, packet node field value, time at which a packet is stamped, packet size, type of packet format.

6.1.2 INTF_TO_MAC_INTF Layer

This is the layer in which the packets are sent to other nodes. Normally, a node has to send its own HELLO packet to other nodes to advertise its existence. Also, if the node is the source node, the node has to send the data packets to other nodes during the ON time. These two objectives can be achieved using the INTF_TO_MAC_INTF layer. The concept of forwarding makes the node energy efficient. By using the next hop nodes to reach the sink, a node can save some energy and the problem of early failures can be prevented. When all the nodes in the path from source to sink contribute some of its energy to the transmission of a packet, the lifetime of the network increases as a whole. The packet's final destination attribute is checked in the packet header and if the packet has to be forwarded, the current next hop node of the node containing the packet is set as the next hop which should be nearer to the sink than itself and must have a least propagation delay among the other neighbor nodes. After the packet is sent, the control automatically returns to the idle state to check whether the node has received a new packet. If a new packet has arrived in the node, the idle state checks the type of the packet and specific action will be taken i.e. the packet may be directed to the INTF_TO_MAC_INTF layer to forward the packets or to send a packet of its own. The intermediate nodes are the nodes which play very important role in the process of forwarding. Other nodes which are different from the intermediate nodes like surface station node and source node will not perform the process of forwarding packets.

6.1.3 Application (source sink) layer

This source sink module in this process is responsible for sending the packets from its own source to other nodes and also to dump the packets received from other nodes in its sink. When a node receives a packet, an appropriate action is taken according to the type of packet. After the packet has been processed, the packet has to be forwarded or sent to the sink. If the packet is destined to the node itself the packet will be dumped in the sink. Otherwise, the packet will be forwarded with the specific destination, the packet has to reach.

6.2 Formation of neighbor table

Every node in the network will have a neighbor table. The neighbor table is built using the join message received from its neighbors.

1. After getting the first join message from its parent node from its parent node during initialization.
2. The status of this link is set to p-primary.
3. This node gossips a join/hello packet for finding its neighbors.

4. After finding the neighbor nodes, one of the node’s statuses is made as s-secondary and the others are b-backup according to the metric followed.
5. After the previous step one or more than one entries will be there for a node in its neighbor table.
6. After reaching a certain limit links are checked for stability and stale links are removed.

Some the attributes are considered to be important in the join message which is used to construct the routing (neighbor) table. They are given below.

1. position
2. type of the packet
3. source address
4. destination address
5. intermediate destination address
6. position of sink
7. packet delay

6.2.1 Format of a join packet

NodeID (32 bits)	
Delay (32 bits)	
Hop_Count (32 bits)	
Destination_Address (32 bits)	
x_position (16 bits)	y_position (16 bits)
ss_x (16 bits)	ss_y (16 bits)
DELAY_SOFAR (32 bits)	

Figure 9 Control packet format

In addition to this, the data packet contains all of this information including the data to be sent. The position of a node plays a vital role in determining the propagation delay between the nodes. The type of the packet is used to differentiate the packet whether it is a join message or the data packet. The source address is used to arrange the packets received from the specified source at the surface station. The destination address is used by the packet to reach the specified destination. The intermediate destination address is used by the packet to inform the nodes which are in the path between the source and the surface station to forward the packet to the surface station. When a node has to forward the packet to the surface station, it has to make sure that the packet is being forwarded to-wards the destination.

6.2.2 Calculation of Propagation Delay

The propagation delay between the nodes depends on the distance between them. Basically, the speed of an acoustic wave in underwater is considered to be 1500 m/s. The delay can be calculated using the formula given below. The formula is given by,

$$\text{Distance} = \text{Delay X Speed} \qquad (3.3)$$

The distance between the nodes can be calculated by the position of the nodes. When the x position and y position of the nodes are known, the distance between two nodes can be calculated using the distance formula.

6.2.3 Failing probability

The sensor network consists of sensor nodes, which are prone to failures. As the time of operation increases, the probability of node failure increases.

Node failure / Time of operation of nodes.

The failure of nodes is based on the time the node is functioning. Nodes are failed randomly in the simulation. The simulation was conducted for different node failure probabilities.

Network failure probability:

The whole network is considered to be failed when all the paths between the source and the sink fails. If k paths exist and if all the k paths have at-least one failed node in it, then the network is said to be failed. So probability of the failure of the whole network can be calculated by multiplying the failure probability of a node present in the single path with the failure probability of each valid path.

Let us assume a sensor network containing N nodes.

$$\{source, surface\_station, remaining.nodes\} \in N$$

If k node-disjoint path exists between source and sink, $n_{1..}n_k$ are the number of nodes present in that paths p1..pk respectively.

Total number of nodes connected to sink and source:

$$\Rightarrow \bigcup_{i=1}^{k} n_i$$

$k \rightarrow$ number of node dis-joint paths
i $\rightarrow$ count of dis-joint paths
n $\rightarrow$ number of nodes present in k_{th} path

Generalized network failure probability:

We can derive a network failure probability based on some assumptions. The assumptions can be varied to get different network failure probabilities. A generalized network failure probability assumptions and derivations are given here.

Assumptions:

$p \Rightarrow Node$ failure probablity
$n \Rightarrow Number$ of nodes in each path
$k \Rightarrow Number$ of paths connecting source and sink

Failure probability based on assumption:

If every path has equal no of nodes then, total no of nodes contributing to connect source and sink can be calculated using the given terms in the assumption.

Total number of nodes connecting (source $\leftrightarrow$ sink) : nk

Failure probability of a node $\rightarrow P$
Probability of randomly selected node in given path $\rightarrow$ 1/k
Working probability of a given path $\rightarrow (1-P) \wedge n$

When we consider a failure probability of a single path with all the conditions, we got the above result. When the same conditions apply to all the paths it results in the whole network failure.

Path failure probability of a given path P_i :

$$P_{i\ Failure\ \Pr} = (1-(1-P) \wedge n)$$

Path failure probability of all K paths:

$$\Rightarrow \langle P_{1\ \text{Failure Pr}} \times P_{2\ \text{Failure Pr}} \times \ldots\ldots \times P_{k\ \text{Failure Pr}} \rangle$$

$$\Rightarrow (1-(1-P) \wedge n) \times (1-(1-P) \wedge n) \times \ldots\ldots\ldots\ldots\ldots \times (1-(1-P) \wedge n)$$

The whole network failure probability can be obtained by multiplying the failure probabilities of each path in network, which is given by

$$\textit{Network}\ \text{Failure Probability} \Rightarrow (1-(1-P) \wedge n) \wedge K$$

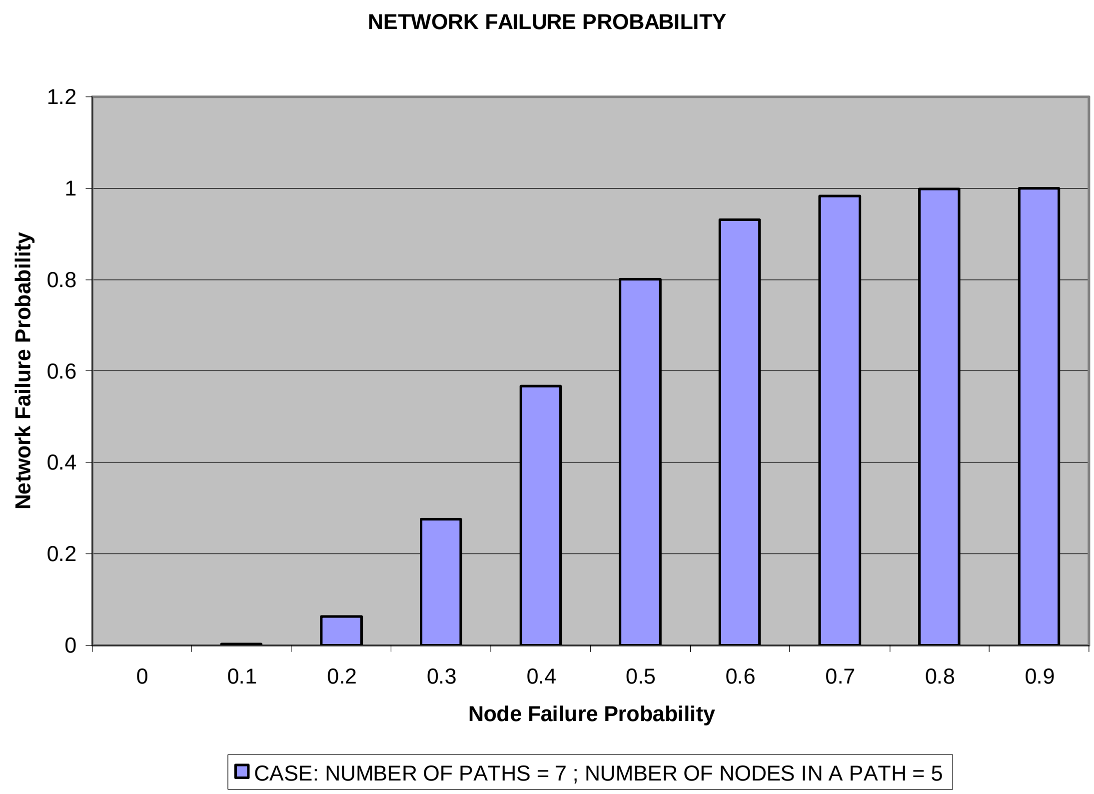

Figure 10 Network Failure Probability

6.2.4 Acoustic propagation speed in underwater

The underwater acoustic propagation speed can be calculated under different operating conditions. The factors which determine the acoustic propagation speed are temperature T, salinity S and depth D. The speed q is determined using the equation,

- T – Temperature in $°c$
- S - Salinity in *ppt*
- D – Depth in *km*

The propagation speed was calculated under different operating conditions, and the value is centered around 1500 m/s. This value is used in our simulation to estimate the propagation delay of the transmission to a particular node. The position of the nodes is also important to calculate the propagation speed because distance formula is involved in calculating the propagation speed between two nodes.

6.2.5 Periodic update of neighbor nodes and failures

The nodes have to update their neighbor tables periodically. The periodic updates are done based on the HELLO packets it receives.

Every node in the sensor network is set to have ON period for 10 seconds and OFF period for 0-60 seconds. A node is supposed to broadcast a HELLO packet to its neighbor every-time it switches from IDLE state to ACTIVE state. So, theoretically a node has to receive a HELLO packet from its neighbor within a time-period.

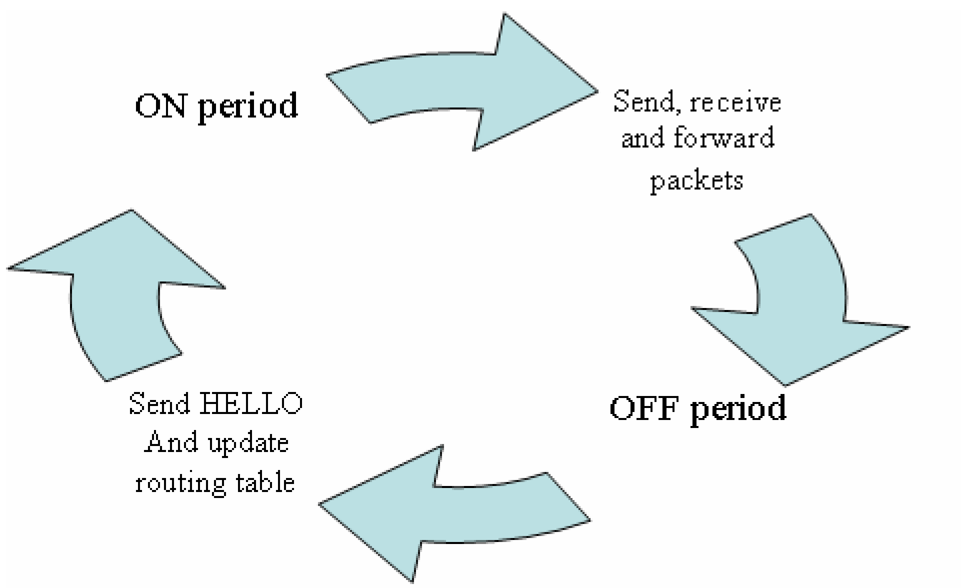

Figure 11 Cyclic nature of a node

The time-period can be calculated using a formula.

$$\text{Time-period} = \text{ON time} + \text{OFF time} + D_{i,j} \quad (3.4)$$

The Delay $D_{i,j}$ is the propagation delay of the node $_i$ to reach node $_j$.

If a node doesn't receive a HELLO packet from its neighbor with this time-period, the node assumes the particular neighbor is no more available and the neighbor table is updated. If the update of the neighbor table is because of movement of the neighbor, the node will receive a HELLO packet with the higher propagation delay than before. Then the neighbor node will be added to the neighbor table with the new delay received.

6.3 Application modules

The source module and the sink module form the application module. These modules plays important role in generating the packets and accepting the packets. Without these modules no packet generation is possible. These modules are summarized below.

6.3.1 Source module

The source module is the one which generates different types of packet. Basically, three types of packet generation is performed in the source. They are,

- Control packets (Hello packets) and
- Data packets.

6.3.1.1 Control packets

The control packets are used to activate its in-active neighboring nodes in the initial stage and also to establish themselves to its neighbor. This type of packet will be generated periodically based on the triangular distribution.

6.3.1.2 Triangular distribution

Triangular distribution is the distribution which finds a subjective description of the population of limited sample data. It is also based on the minimum value, maximum value and the assumption of modal value. It is an alternative for beta distribution. When the limits are known in advance we can use the triangular distribution to keep the generation of results within a range. From the dataset we can determine the ranges of the triangular distribution by which maximum value, minimum value and the modal value can be calculated. In our simulation, we use the triangular distribution to generate the packets. The traffic generation of packets in the source is based upon the triangular distribution.

The triangular distribution is denoted by the notation given below.

$$X \sim \text{Tri}\ (a, b, c) \tag{3.5}$$

The parameters a, b, c present in the notation is upper bound, lower bound and mode respectively. The parameter scale implies that a should be lower than b.

$$Parameter\ scale\ \Rightarrow\ a < b \tag{3.6}$$

The range of the triangular distribution is within the bounds a and b. For example, if a is 10 and b is 50, the value produced in the triangular distribution will be greater than or equal to a and lesser than or equal to b.

$$Range \Rightarrow [a, b] \tag{3.7}$$

These packets will contain the complete information of itself and its neighbor. By receiving this packet, the neighbor nodes identify the nodes that it can reach. The number of control packets is always less then data packets in the network, which maintains the connectivity.

6.3.1.3 Data packets

The data packets can be called as information packets. The raw information is processed in the processor of the source node and it is transformed to data packets. These packets are the packets which determine the throughput of the routing scheme. The amount of data packets received in the sink varies between the routing schemes' which determines the throughput of the routing scheme.

6.3.2 Sink module

The sink module is the module in which all the packets are received and dumped. It can be called as a independent storage area for each node. Each node will have a sink module to receive packets. If a packet is destined to a node, the node will perform appropriate action with respect to the received packet and then the packet will be sent to the sink process. In the sink process, it will keep track of the number of packets received by the sink, the number of bits received by the sink, the time taken by the packet to reach its destination, local media delay and the global media delay through which the packet travels. By using the sink process, the job of handling the packets destined to this node is independent and it improves modular nature of the node architecture.

6.4 States of node

The creation of data packets and the control packets are based on the states of a source process in a node. Normally a node's source can have three stages. They are,

- Disabled
- Active
- Idle

Disabled state of a node is the state in which the node is not functional. In this state, a node cannot generate, receive, transmit and forward the packets.

Active state of a node is the state in which it can generate packets and perform all functions with the packet.

Idle state of a node is the state in which it cannot generate and transmit packets, but the node is able to receive and forward the packets in this state.

Table 2 Node states and its functionalities

	Disabled	**Active**	**Idle**
Control packet generation	*No*	*Yes*	*No*
Data packet generation	*No*	*Yes*	*No*
Switch packet generation	*No*	*Yes*	*No*
Transmit packets	*No*	*Yes*	*No*
Receive packets	*No*	*Yes*	*Yes*
Forward packets	*No*	*Yes*	*Yes*

The functionalities of each node has been compared and tabularized above to differentiate the advantages and disadvantages in each state.

6.4.1 Time span of states

Every state of a node has a time span except the disabled mode. The active state of a node has a time-span which is called as ON time and the time-span which is called as OFF time.

ON time is the time period at which the node is active. This ON time can be calculated using different distributions for nodes. In our simulation, the ON time for a node is designed for 10 Seconds which is a constant.

Table 3 Time-span of states

States\ Time-span	**Type of time-span**	**Time-span**
Disabled	None	1
Active	ON time	10 Seconds
Idle	OFF time	0-60 Seconds

OFF period:

OFF time is the time period at which the node is idle. This OFF time can be calculated using different types of distributions. In our simulation, the OFF time for a node is calculated using triangular distribution. The upper and lower ranges for the triangular distribution are 60 and 0 respectively.

When a node toggles from OFF time to ON time, the first packet generated by the node is HELLO (control) packet. The HELLO packet is generated at the start of ON time each time is to inform the neighbor nodes that the node still exists.

ON period:

The sink node can send the HELLO packets initially and receive the data packets and HELLO packets from other nodes.

The intermediate nodes can send the HELLO packets initially, and it can forward the HELLO packets of other nodes and data packets of the source node to the sink.

6.5 Process of choosing next-hop

The next hop of a node is chosen based on the concept of least distance to the sink and the principle of nearest neighbor. The neighbor table of a node consists of x and y positions of all its neighbors. Using the distance equation and range-based localization algorithms, the distance between the nodes can be estimated using the formula given below.

$$\text{DISTANCE} = \sqrt{(x - x_0)^2 + (y - y_0)^2} \qquad (3.8)$$

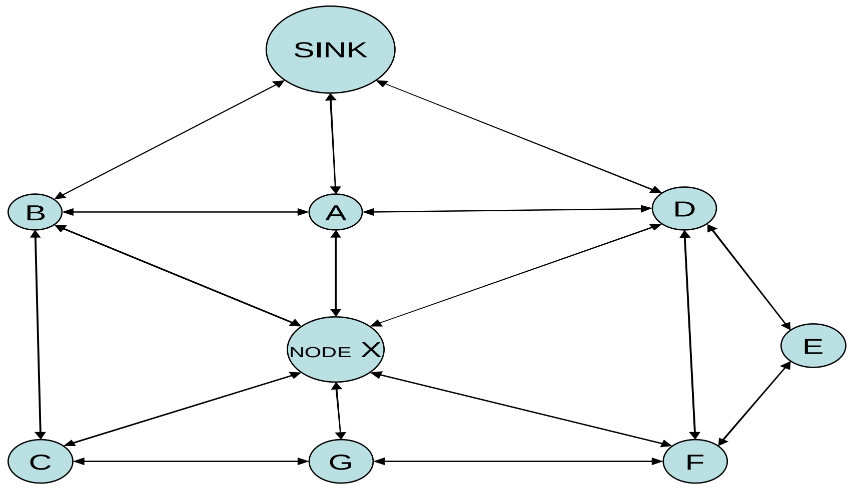

Figure 12 Example of a small area of a sensor network

A node chooses its next hop in step by step process. At first the node is assumed to have no neighbors. It is represented by the equation given below.

$$N - set = \{\varnothing\}; \tag{3.9}$$

6.5.1 Formation of neighbor set

The N-set is the neighbor set of a node through which it can send and receive packets. The set is a empty set at the beginning with no neighbor nodes. After it receives HELLO packets from its neighbor, it updates its neighbor table and have some set of neighbors. A node can choose its next hop from this set of neighbors to send the packets to reach the sink in a effective way. The neighbor set of the node X after it received HELLO packets from its neighbors is given below.

$$N - set = \{A, B, C, D, F, G\} \tag{3.10}$$

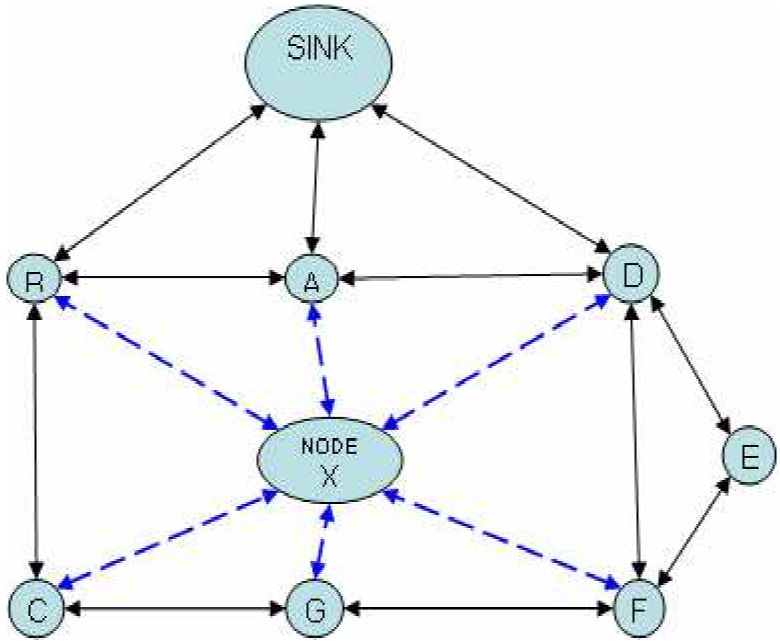

Figure 13 Set of neighbor nodes

6.5.2 Selection of set of valid next hops

After the node has a set of neighbors to choose, a single node will be chosen as its best next-hop. The node will be chosen based on the following conditions.

- The next hop node should be near to the surface station than node X.
- The propagation delay between the node X and the next hop node should be least among the valid neighbor set of nodes.

After the first condition is applied among the set of neighbor nodes of node X, the set of nodes that can be chosen for the next hop are given below.

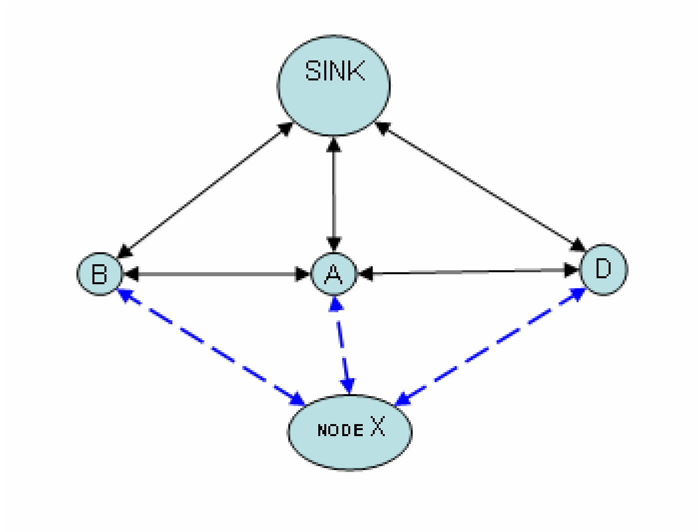

Figure 14 Valid neighbor set of nodes

$$\{A, B, D\} \in Valid\_N-set \tag{3.11}$$

One of the sets in the valid neighbor set should be chosen as a best next-hop node. The node which has the minimum propagation delay between the node X and itself should be chosen. The above condition is given in the equation given below.

$$Next-Hop = \min\{p.d_{i,j}\} \tag{3.12}$$

6.5.3 Choosing the best next hop

The term p.d is used to represent the propagation delay between the nodes.

$$p.d \rightarrow Propagation\ delay \tag{3.13}$$

The term i is used to denote the node X and the term j is used to denote the set of valid neighbor nodes.

$$j \in \{Valid\_N-set\} \tag{3.14}$$

All the nodes in the set are taken under consideration for choosing the best next hop node.

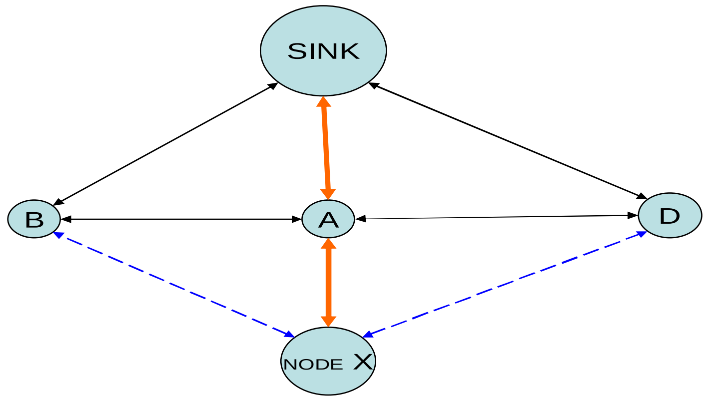

Figure 15 Chosen path from node X to Sink

Comparing the propagation delay between the set of valid nodes in neighbor table and the node X, let us say node A has the least propagation delay than other nodes in the set of valid nodes. So, the node A is chosen as the primary next hop node and the node which has the second least propagation delay is chosen as secondary next hop for the node X to reroute the packets in cases of failure.

6.6 Differences and similarities between routing schemes

Table 4 Differences and similarities between proposes and centralized routing

	PROPOSED DISTRIBUTED ROUTING	**CENTRALIZED ROUTING**
ROUTE INFORMATION PACKETS (JOIN/HELLO PACKETS)	*FROM NEIGHBOR NODES ONLY.*	*FROM ALL NODES TO SINK.*
PACKET FORWARDING	*DATA PACKETS.*	*DATA PACKETS AND ROUTE INFORMATION PACKETS*
CONTROL OVERHEAD	*LOW*	*HIGH*
TRAFFIC	*LOW*	*HIGH*
LINKS AND REPAIR	*CHECK FOR PRIMARY AND SECONDARY LINKS. LOCAL REPAIR.*	*CHECK FOR VALID LINKS. LOCAL REPAIR AND GLOBAL LINK SWITCH.*
NODE-DISJOINT PATHS	*NO*	*YES*
ALTERNATE PATH	*MAY CONTAIN FAILED NODES FOUND IN PRIMARY PATH.*	*DOES NOT CONTAIN FAILED NODES FOUND IN THE PRIMARY PATH.*
FREQUENCY OF SWITCHING TO ALTERNATE LINKS	*HIGH*	*LOW*
ROUTE INFORMATION	*LOCAL*	*GLOBAL*
ENERGY DEPLETION OF NODES	*HIGH (BECAUSE OF FREQUENT SWITCHING)*	*LOW*

Both routing methods have advantages and disadvantages.

6.6.1 Proposed distributed routing

The first four differences show the advantages of proposed distributed routing. Because of this, proposed distributed routing can receive more data packets than centralized routing.

- In this routing method, the sink receives the hello i.e. route information packets only from its neighbor nodes.
- The intermediate nodes are involved in receiving the hello i.e. route information packets and it also forwards the data packets from the source to the sink.
- Because of forwarding only the data packets, the control traffic is low in this type of routing.
- As the control traffic is low, this routing method is able to transmit more data packets.
- The repair of the paths is local in this routing method. Instead of paths, only links are formed and the complete path from source to sink is not obtained in this method.
- As there is not path formation, there is no need to check for node-disjoint paths.
- The secondary path may contain a node that failed in the primary path.
- The frequency of switching to alternate links is high here compared to the other scheme.
- Every node has route information about its local neighbors only. There is no global knowledge of nodes in source or sink.
- The high frequency of switching to alternate links may result in more depletion of energy than the other scheme.

6.6.2 Centralized routing

The next six differenced shows the advantages of centralized routing. Because the chance of occurrence of failed nodes in consecutive paths is less, the node consumes less energy. But the overhead lies in devising a node-disjoint path by the central station.

- The sink (surface station) receives hello packets i.e. route information packets form all the nodes in the network. There is a overhead for all nodes in forwarding the hello packets.
- In the case of packet forwarding, the data packets and the route information packets are forwarded to the sink. So the load in each node in the path from source to sink is high.
- Because of this, there is high control overhead in this method compared to the proposed distributed routing.
- In this method, the data packet that reaches the sink is comparatively low, because of the high control overhead.
- Even though, the link repair is local, two paths are obtained at the instant when the sink receives the hello packet of source. So the source calculates the two shortest paths which are node-disjoint using dijkstras shortest path algorithm.
- Because the two paths are node-disjoint, a node failed node in the primary path will not be present in the secondary path.
- The frequency of switching to secondary link by the nodes is less here because the alternate path is node-disjoint from the primary path.
- The paths are formed by the surface station which has global knowledge about the whole network. Even-though, it is less flexible, this method exploits the scarce network resources by considering the energy level of nodes etc.

- The energy depletion of the nodes in this routing method is comparatively low, because the paths are chosen by the surface station which has the global knowledge of all the nodes.

Chapter VII

SIMULATION

In the simulation, the performance characteristics of centralized controller and the combination of both centralized and distributed controlled routing, which is discussed in the previous chapter were studied. The previously proposed routing method is planned simulated using the OPNET modeler.

7.1 Simulation tool

The OPNET modeler is chosen to simulate the proposed routing model which allows us to design and study communication networks, devices, protocols, and applications with unmatched flexibility and scalability. It supports all types of network types and technologies. Some of the key features which made to choose the OPNET for the simulation are most scalable and efficient simulation engine, hierarchical network models, clear and simple modeling paradigm, finite state machine modeling, total openness, comprehensive support, wireless, point-to-point, multi-point links, advanced modeling platform and integrated debugger. Object-oriented modeling approach and graphical editors in the OPNET modeler mirror the structure of actual networks and network components to design a model which intuitively maps to the model we propose. Geographical and mobile modeling can be done using this modeler which is an important aspect of the model we propose. The OPNET 3DNV (Network Visualizer) is an extended functionality to the core products of OPNET with a ability to visualize mobile network performance, behavior and operations.

The difference in delay, reduction in the number of number of data packets received and the number of control packets received by the sink is compared between the routing model using the centralized controller and the routing model using both centralized control and distributed routing when needed and produced as a final result of simulation.

7.2 Factors influencing the efficiency

The simulation of the routing schemes was carried out in the OPNET simulator. Simulations were performed for different scenarios like node failure probability, number of nodes and size of sensor network. Delay was calculated for different scenarios during the simulation to compare the delay between the two different routing schemes. The number of packets received for different node failure probabilities were recorded to represent the difference in data packet acceptance rate between two routing schemes under different node failure probabilities. The number of HELLO packets received by the sink was also recorded to differentiate the routing schemes control traffic. The different factors that were considered to compare the two routing schemes are given below.

- Delay
- Data packet acceptance rate
- Control traffic

Delay is the factor which represents the average delay of the number of data packets received during the simulation under different scenarios. The average delay may not be optimal in the proposed distributed routing scheme in cases of less node failure probabilities. Some applications require minimum delay during communication. But, there are some cases, where the nodes are prone to failures due to destruction, accidents, etc. So, when we encounter conditions where more nodes are failing in the sensor network, the delay should be compared between the two routing schemes to figure out the delay-effective routing scheme.

Data packet acceptance rate is the rate at which the sink is accepting the data packets. The number of data packets accepted during the simulation run is represented using this factor. Using this factor, one can determine the routing scheme which can receive more number of packets. A graph is drawn using this factor to represent which rouging scheme is best in terms of receiving more number of data packets under different node failure probabilities.

Control traffic is the traffic which represents the amount of HELLO packets in the network. The HELLO packets are the packets which mainly contribute to the control traffic. These packets help the nodes to maintain the neighbor table. When the operation time of the network grows, the nodes in the network are prone to failures. These failures are updated using the HELLO packets. Because of the control traffic, the data acceptance rate will get affected. When a node is involved in handling the control packets it will not be able to generate or handle the data packets, which decreases is data acceptance rate when there is a increase in control traffic.

7.3 Graphs

The graphs are drawn for the factors which are considered as the factors which influence the efficiency of the routing scheme. These graphs represent the advantages and disadvantages in both routing schemes under different conditions. The different node failure probabilities are considered as the main factor to show which routing scheme works well under high node failure probabilities. The factors which we draw graphs for different node/link failure probabilities are delay, data acceptance rate and control traffic.

7.3.1 Comparison of average path delay

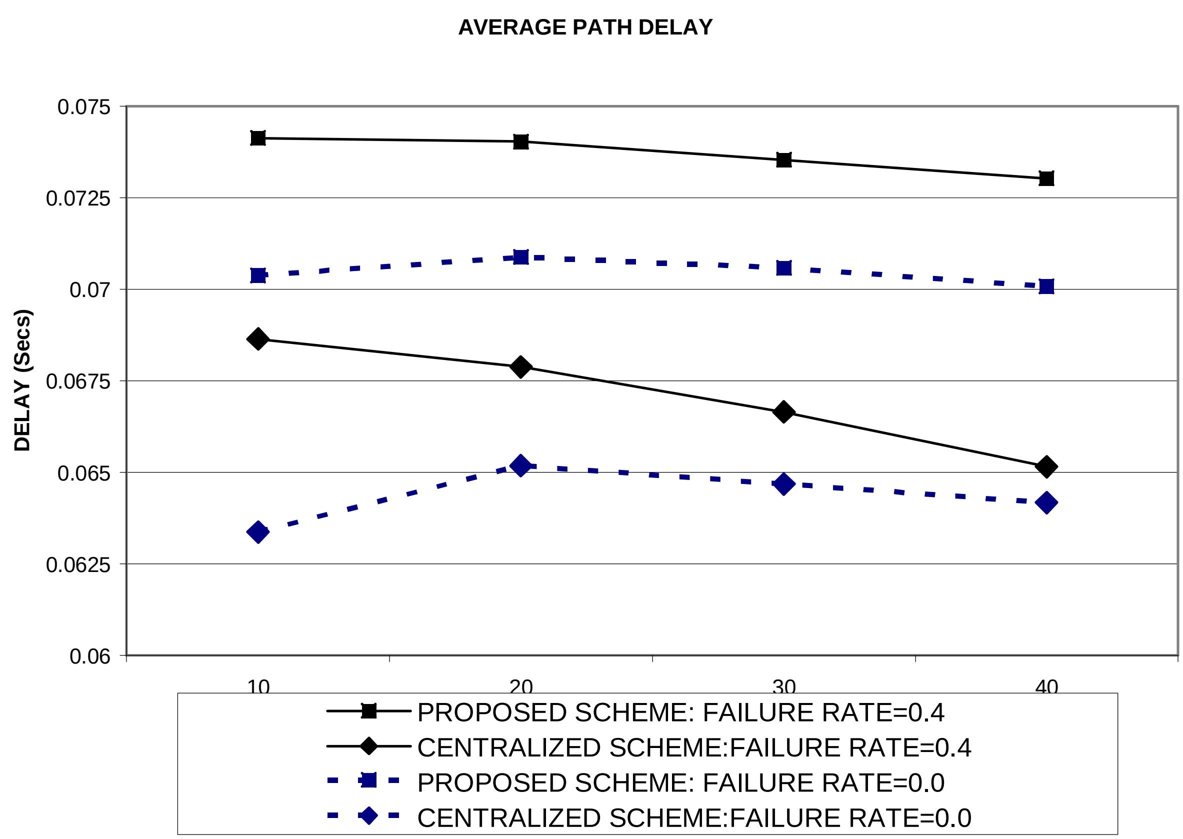

Figure 16 Comparison of average path delay

The path delay is defined as the delay experienced by the data packet which is generated at source and reaches the sink. The two routing schemes have different path delays. The graph shows the centralized routing has a lower delay than the proposed distributed scheme. It is because the centralized rouging scheme follows the shortest path devised by dijkstras shortest path algorithm. Even though the path followed in the proposed distributed routing scheme is not the shortest path, the difference in the delay is negligible, but higher than centralized routing. As the number of nodes in the network decrease, the chance of a packet reaching the sink with minimum delay becomes less. The x-axis is plotted for different node failure probabilities to show the average path delay under different conditions. The delay factor in both the routing schemes seems to increase as there is an increase in node failures.

7.3.2 Comparison of route information (HELLO) packets received

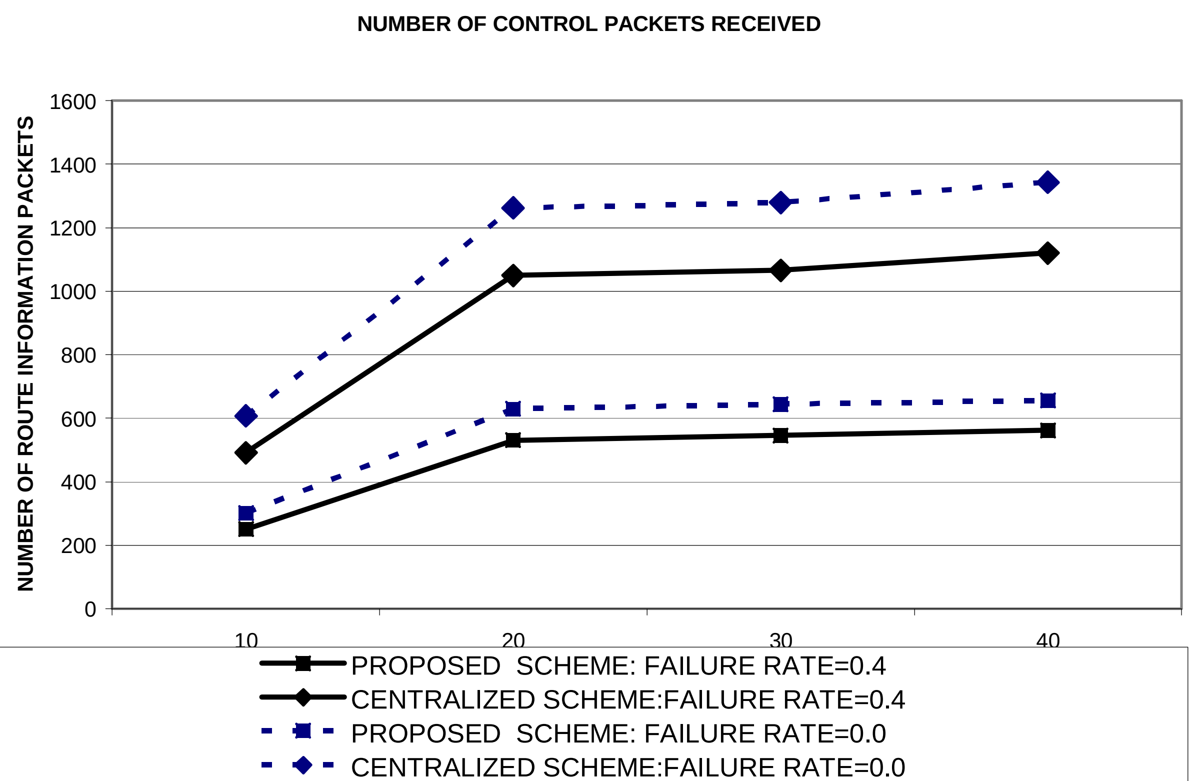

Figure 17 Comparison of route information packets received

Route information is also called as HELLO packets. The route information packets of a node are used to inform its neighbor node about its existence. In this graph, we can see that the number of HELLO packets received by the proposed distributed scheme is very less compared to the centralized routing scheme. In both the schemes, the number of control packets decreases as the node failure probability increases. In the case of centralized routing scheme, a single node failure will affect the number of control packets the sink receives, but the number of control packets received by the sink gets affected only if there is a node failure among one of the neighbors of the sink. There is a huge difference between the proposed distributed routing and the centralized routing which implies that the control overhead is high in the centralized routing compared to the proposed distributed routing.

7.3.3 Comparison of acceptance rate of data packets

This graph depicts the number of data packets received in two routing scheme under different node failure conditions. From the graph, it is clear that the number of data packets received in the centralized routing scheme is high when there the node failure probability is low. But when the node failure probability becomes high, the number of data packets received in the proposed routing scheme becomes high because of the low control overhead. Even-though the average path delay in the centralized routing scheme is low, the proposed distributed routing scheme receives more data packets in the same time.

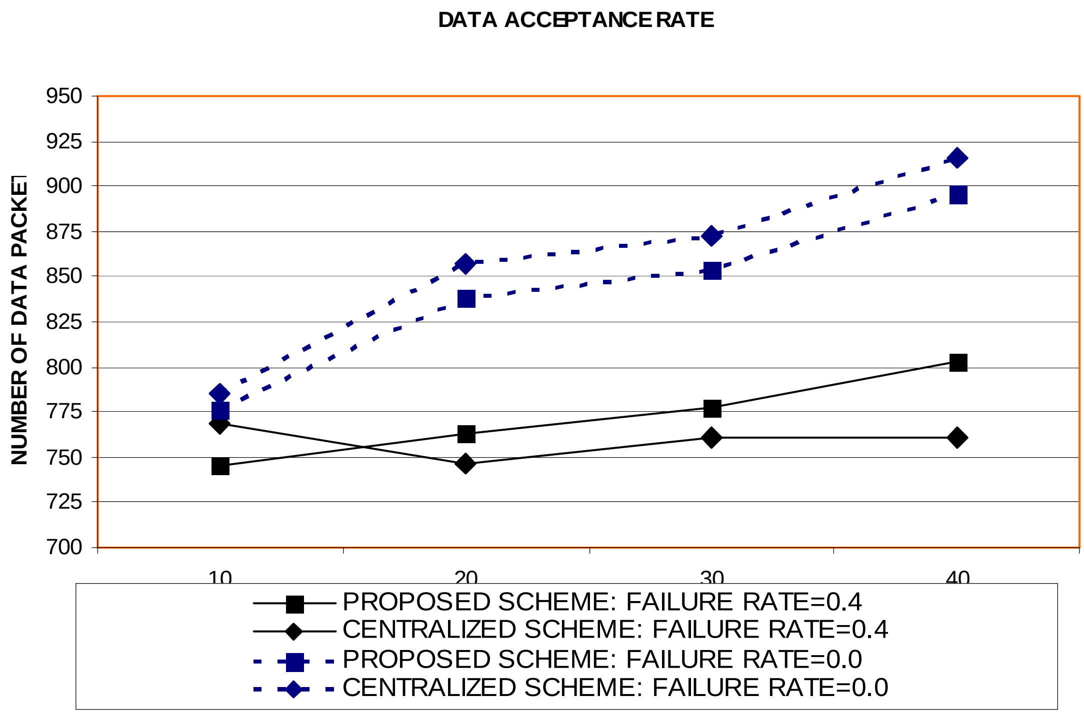

Figure 18 Comparison of acceptance rate of data packets

These three graphs have been analyzed and it is clear that the proposed distributed routing receives more data packets and has less control traffic than centralized routing with increasing node failure probabilities.

Chapter IX

CONCLUSION

In this thesis, the problem of data gathering with minimum delay under different node failure probabilities in underwater acoustic sensor networks is studied. A routing scheme is proposed which is basically a distributed routing scheme but implemented with features of centralized routing. Some features like distributed path repair algorithm helps the scheme to locally repair the links and to withstand in cases of node failures and link failures. Each node in the proposed distributed routing scheme chooses its next hop based on the position of the surface station i.e. sink and the propagation delay with its neighbors. This helps the routing to choose the path faster and also enables a faster recovery in case of failure. The delay is not optimal but when comparing the high data acceptance rate and the low control overhead, the delay difference is negligible. Form the graphs drawn above it is clear that, there is high data acceptance rate, low control overhead and negligible delay difference. The proposed routing scheme was shown to achieve the performance targets of the underwater environment by means of simulation.

Chapter X

FUTURE WORK

The delay encountered in the proposed distributed routing algorithm is not optimal when compared to the routing algorithm which uses a centrally devised shortest path. Because the path is devised by the shortest path algorithm in the central routing scheme, the path delay is low. The path delay in the proposed distributed routing should be lowered to bring its value equal to the centralized scheme, instead of the negligible difference. A new routing scheme must be devised to meet the minimum delay provided by the centralized scheme and the high data acceptance rate feature produced by the proposed distributed scheme.

In the proposed distributed routing, we choose the path based on the propagation delay which chooses the link faster and makes the recovery of the links faster by a local repair algorithm. The lack of global knowledge of nodes makes them unable to produce shortest paths, so a routing method has to be devised to find a shortest path without having global knowledge of all the nodes in the network which might decrease control traffic. The same concept can be used to prevent the failure of nodes due to total energy drain. Instead of choosing the path using the propagation delay, the path can be chosen with energy of the node as a main constraint which can be used in delay-insensitive routing. Using this concept, the lifetime of the whole sensor network can be improved.

The least recently used node can be switched off for a long time than other nodes in order to save the energy. At the time of scarce energy these nodes come in to operation which helps to prevent the slow down of sensor networks traffic due to failure of majority of the nodes.

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VITA

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Abstract:

Recent improvements in wireless communications and acoustic technology have enabled the use of sensor networks in underwater environments. Three dimensional underwater sensor networks is an emerging field which requires research in the field of channel access and routing. Applications like oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation, and tactical surveillance applications use underwater sensor networks. Some applications such as disaster prevention require minimum delay in data gathering. Also care must be taken to make sure that the energy expenditure of an underwater sensor node is minimal because replenishment of a sensor node is not cost-effective.

The routing algorithm proposed in this work for delay-sensitive applications uses a distributed approach. Each node in the proposed distributed rouging chooses its next hop based on the position of surface station and the propagation delay among the set of neighbor nodes. The set of neighbor nodes are chosen which are closer to surface station the node's distance to the surface station. A local path repair algorithm is used to repair the links in a distributed manner. It enables the faster recovery of a failed path which increases the data gathering rate. In cases of link failure and node failure, which is mainly due to mobility and underwater channel characteristics, the nodes in the path are allowed to select their next hops. The best next hop is chosen to minimize delay, retransmissions of the packet already transmitted, idle source time and energy expenditure. Through simulations, the proposed algorithm is shown to achieve a better performance in data gathering when compared to a centralized scheme.

ADVISER'S APPROVAL: Dr. Venkatesh Sarangan