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Self-Organizing and Scalable Routing Protocol (SOSRP) for Underwater Acoustic Sensor Networks

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Protocolo de enrutamiento autoorganizado y escalable (SOSRP) para redes de sensores acústicas submarinas

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Palabras clave: Enrutamiento multihop, rango de transmisión, distancia, autoorganización, energía consumida, retardo de extremo a extremo, tolerancia a fallos, nodo aislado.

Resumen

Las redes de sensores acústicas submarinas (UASN) han ganado mucha importancia en los últimos años porque el 71 por ciento de la superficie de la Tierra está cubierta por océanos, y la mayoría de ellos aún no han sido explorados. Aplicaciones como prospección de yacimientos, prevención de desastres o recopilación de datos para estudios de biología marina se han convertido en el campo de interés para muchos investigadores. Sin embargo, las redes UASN tienen dos limitaciones importantes: un medio muy agresivo (marino) y el uso de señales acústicas. Ello hace que las técnicas para redes de sensores inalámbricas (WSN) terrestres no sean aplicables. Tras realizar un recorrido por el estado del arte en protocolos para redes UASN, se propone en este Trabajo Fin de Máster un protocolo de enrutamiento denominado "Protocolo de enrutamiento autoorganizado y escalable " (SOSRP), descentralizado y basado en tablas que residen en cada nodo. Se usa como criterio para crear rutas una combinación del valor de saltos hasta el nodo recolector y la distancia. Las funciones previstas del protocolo abarcan: autoorganización de las rutas, tolerancia a fallos y detección de nodos aislados. Mediante la implementación en MATLAB de SOSRP así como de un modelo de propagación y energía apropiados para entorno marino, se obtienen resultados de rendimiento en distintos escenarios (variando nº nodos y rango de transmisión) que incluyen parámetros como retardo extremo a extremo de paquetes, consumo de energía o longitud de rutas creadas (con y sin fallo). Los resultados obtenidos muestran una operación estable, fiable y adecuada para el despliegue y operación de los nodos en redes UASN.

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Abstract

Underwater acoustic sensor networks (UASN) have gained much importance in recent years because 71 percent of the Earth's surface is covered by oceans, and most of them have not yet been explored. Applications such as resource discovery, disaster prevention or data collection for marine biology studies have become the field of interest for many researchers. However, UASN networks have two important limitations: a very aggressive (marine) environment and the use of acoustic signals. This means that the techniques for terrestrial wireless sensor networks (WSN) are not applicable. After a brief expose of the state of the art in protocols for UASN networks, this Master's Thesis proposes a routing protocol called "Self-Organizing and Scalable Routing Protocol" (SOSRP), decentralized and based on tables that reside in each node. A combination of the hop value to the collector node and the distance is used as a criterion to create routes. The expected functions of the protocol include: self-organization of the routes, tolerance to failures and detection of isolated nodes. Through the implementation in MATLAB of SOSRP as well as a model of propagation and energy appropriate for marine environment, performance results are obtained in different scenarios (varying nodes and transmission range) that include parameters such as end-to-end packet delay, consumption of energy or length of created routes (with and without failure). The results obtained show a stable, reliable and suitable operation for the deployment and operation of nodes in UASN networks.

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Firstly, I would like to thank Prof. Dr. Miguel-Ángel Luque-Nieto for being my tutor and Supervisor for this Masters' thesis research at E.T.S. de Ingeniería de Telecomunicación Universidad de Málaga. He has always helped me regarding this work, whenever I faced any difficulty.

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Author

Sateesh Kumar Hindu

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Chapter 1. Introduction

1.1 Background

Oceans play a vital role in Earth's atmosphere, weather and climate patterns. More than half of oxygen is produced and most of carbon is absorbed by oceans. Even though 71 percent of earth's surface is covered with water and oceans hold 96.5 percent of it, only 5 percent of total ocean volume has been investigated because traditional techniques for underwater exploration has various constraints and rigorous nature of ocean environment.

Wireless Sensor Networks (WSNs) have emerged as one of leading technologies in industrial, structural and remote monitoring because of their capabilities of computation, spatially distributed architecture provides new possibilities to sense the physical phenomena and monitor the harsh environment (e.g. volcanoes, or underwater ecosystems, among others). Because of its various benefits and features which includes low cost, ease to configure, self-organizing, wireless connectivity, WSNs are implemented in wide range of applications on ground such as industrial automation, healthcare, wild life study, environment change etc.

Above discussed roles, various surveys and studies have proved the importance of oceans and marine life towards the Earth's atmosphere and climate change. Therefore, understanding the oceans environment, marine life and underwater resource discovery have become one of the major research areas of modern-day science. Due to different limitations of traditional techniques of ocean exploration, over the years various researchers have proposed the utilization of sensor networks in underwater scenarios, later emerged as Underwater Wireless Sensor Networks (UWSNs).

Various methods, protocols and systems are proposed to improve the technology which resulted in rapid development in underwater wireless communication. Because of this swift progress, applications such as pollution control, oil seeps discoveries, oceanography, disaster prevention, search and survey mission, defense and marine life study have become the major focus of researchers. Due to this, underwater wireless sensor networks are becoming key technology in the development of ocean observation networks among researchers and industry personnel.

1.2 Underwater Acoustic Sensor Network, Problems and Challenges

UWSNs are the collection of many autonomous sensor nodes, networked together through wireless links, performing collaborating tasks to monitor physical or environment conditions such as pressure, temperature, sound etc. These networks were initially developed using the concept of terrestrial WSN systems. Although, many designs and working principles of underwater networks are derived from terrestrial sensor networks but fundamental challenges of two technologies are different. The early implementation of UWSN with RF and optical links proved that new solutions and approaches are required for underwater environment, which confronts different challenges and limitations in terms of signal propagation, low efficiency of radio wave transmission range of few meters and scattering in case of optical waves. Considering RF and optical waves constraints in underwater environment, acoustic waves prove to be promising communication medium to transmit information because of which underwater sensor networks are also referred as Underwater Acoustic Sensor Networks (UASNs). However, the use of acoustic communication poses several challenges. In underwater environment, the propagation speed of acoustic signal is approximately 1500 m/sec which is five times less than RF. It varies with depth and salinity and results in high end to end delay. Due to multipath fading, path loss, noise and Doppler effect, the underwater channel is affected adversely which results in high bit error rate. Furthermore, because of water currents and various underwater activities the underwater sensors remain mobile which makes traditional routing inefficient since the network topology changes as the time passes. Traditional terrestrial communications are not feasible for UASN because the RF signal suffers high attenuation: it is necessary to use lower frequencies, like in acoustic signals. Due to this fact, the speed of propagation is greatly reduced when comparing both media: speed of light (RF in air) vs. 1500 m / s approximately (sound in the water). In addition, the bandwidth of acoustic signals is limited, leading to a low data bit rate (<300 kbps approx.). Also, parameters such as carrier frequency, attenuation, noise, fading, propagation delay, and limited bandwidth are important to consider during protocol designing for UASNs. Figure (1.1) depicts the example of 3D underwater acoustic sensor network model with static and mobile nodes [8].

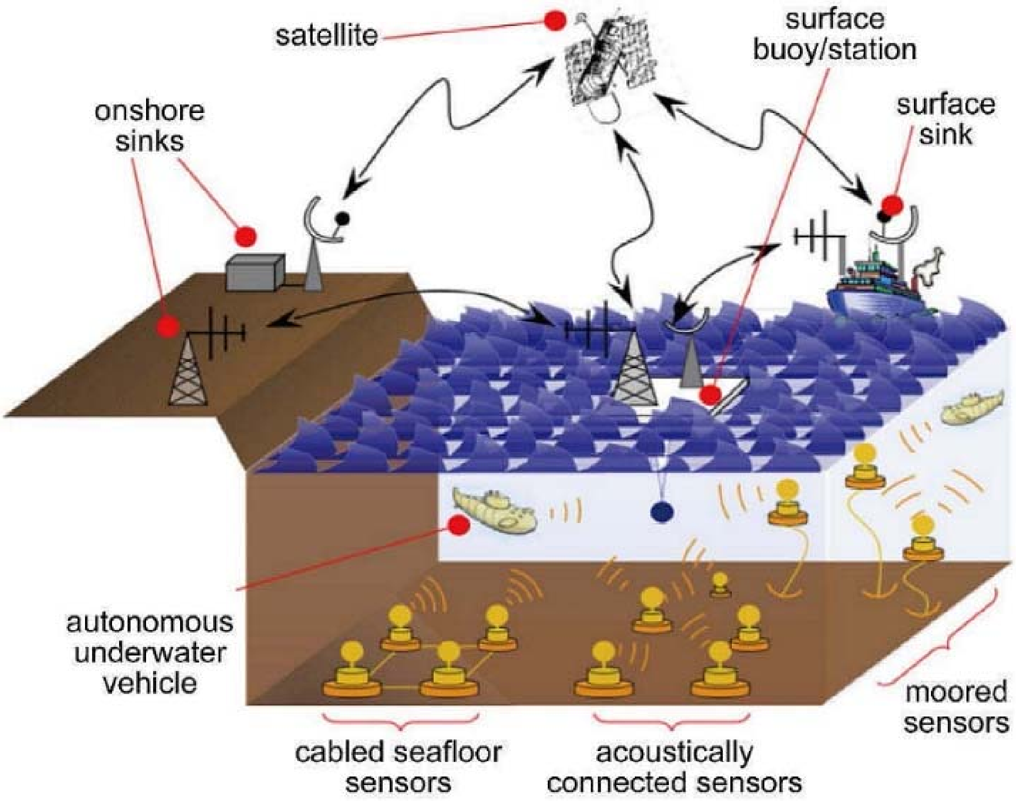


Figure 1.1 Underwater Acoustic Sensor Network Model

Moreover, the energy consumption of underwater sensor nodes will be different compare to terrestrial ones because of different environment, sensor size, data packet length and communication technology. Mostly, the sensor nodes are powered through batteries and it is inconvenient to replace or recharge the batteries of depleted nodes, considering the underwater environment, cost and time required for such operations. The propagation environment also has substantial effect on energy consumption, therefore energy efficiency is one of major concern in designing the protocol for UASN. Network topology is also vital factor to consider for protocol designing. Reliability, Capacity and energy consumption of network are affected and determined through topology control technique. The reliability of underwater network topology is highly important because of high cost of sensor nodes. Therefore, single point topology should be avoided in designing because failure of single node in network could lead to overall network collapse.

1.3 Objectives

The applications related to oceanography and its fields require a large amount of data to be transferred for the purpose of monitoring the underwater environment. This demands a network with high data rate. Further it will affect the energy consumption of underwater sensor nodes adversely because of large data packet transmission over large distances. Considering the bandwidth constraint, energy consumption and various other challenges posed by underwater environment, and high data rate requirement of applications, multihop topology seems to be more favorable solution. Multihop communication is formed by connecting the neighboring nodes with each other. The data packets are transferred from source to Sink (or several sinks) node through transmitting it to intermediate nodes. The communication is governed by routing protocols which establishes the path consists of multiple intermediate nodes between source and destination based on the defined set of rules. Based on the above discuss, following are the objectives of thesis:

1- Simulate a protocol using multihop approach for underwater acoustic sensor network with a single sink on surface.
2- Define the path selection strategy based on the shortest distance between source node and Sink.
3- Calculate the energy consumption, end to end delay, and mean number of hops.

4- Evaluate the optimal transmission range for sensor node to minimize the hops between source and sink.

1.4 Thesis Outline

The reminder of thesis is structured as follow: Chapter 2 begins with the introduction to routing, describing its basic idea and importance in centralized and distributed wireless network. It further discusses competence of distributed approach for UASNs including a literature review which introduce different underwater and current research on routing protocols in the field of UASNs. Chapter 3 is focused on the proposed protocol named "SOS Routing Protocol for UASNs". The simulation details, software, protocol working, deployment criteria, energy model and various parameters for performing measurements such energy consumption are discussed. The chapter further discusses the problems associated with sensing and deployment of nodes in the square area. Chapter 4 discusses the simulation results in terms of energy consumption, delay, path loss etc. Finally, Chapter 5 concludes the thesis by summarizing the proposed work and results, besides proposing some ideas to further enhance the protocol in the future work.

Chapter 2. Literature Review

2.1 Introduction

Routing is the process of finding the path that can forward the messages from source and destination in a network. It involves the hardware deployment such as routers, network topology and protocols to govern the selection criteria of path. Mostly network layer is used to execute the routing of messages in sensor networks [15]. Depending on the application requirement, the routing type is implemented. The two important routing models are centralized and decentralized routing. In centralized routing model, routing process is performed by centrally located database or entity which means a single entity stores a routing table of a network and every time a node needs to transmit the data, the central node is responsible for providing the route details. Centralized routing model is simple because a single entity develops routing table, but if central node fails the entire network will collapse, whereas in decentralized network, routing is performed based on the distributed routing table stored at each node in the network. Nodes make the decision for route selection based on the defined criteria of choosing the next node.

UASNs are formed by large number of sensor nodes linked together using acoustic modems. Each node has capabilities of sensing, storing, processing and wireless communication which enable it to sense, gather application specific information from the surrounding environment and send the data to sink. The centralized routing model in such network is not suitable because single node is responsible for routing decision making and its failure will result in network disintegration. However, decentralized model is an appropriate choice for such networks where each node can make the decision of selecting the next hop to transmit the data. This enhances the robustness of network because node failure will not disrupt the entire network communication.

This chapter covers the literature review where it starts with the introduction in section 2.1, giving the brief idea of routing and its two routing model, evaluating the best approach for UASNs. In Section 2.2 discusses some decentralized networks and highlighting their characteristics. It is followed by section 2.3 where various protocols are discussed which are proposed by researchers for UASNs over the years. Finally, section 2.4 provides the conclusion for chapter 2.

2.2 Decentralized Networks

2.2.1 Mesh Networks

A mesh network is a decentralized infrastructure-based network type in which nodes are linked to possible number of other nodes either directly or dynamically. Unlike centralized model, nodes in mesh network cooperate with each other to route the data efficiently without any centralized node for decision making and management. This enables the network to self-organize and self-configure, which in turn reduces the installation overhead and provide fault tolerance in case of failing of a reduced number of nodes. In mesh network, routing is performed on network layer of OSI model, where each device can act like router and relay data on account of source node such that it provides facility of multihop routing.

The routing protocols used in mesh network are proactive, reactive or hybrid. In proactive routing, each node keeps one or more routing table representing entire network's topology. The tables are updated at regular interval, which updates the node for any possible route changes or link breakages. This makes the network self-healing in case of route failure. The protocol works better in fixed mesh where nodes are stationary and route changes are rare or may never change. In mobile mesh network, the rapid changes in network path because of mobility of nodes, increases the network traffic and collision, reduces bandwidth and utilizes more network resources. Unlike proactive protocol, reactive routing protocol establishes paths on demand. To find the correct route, the protocol conducts a search on entire network. This in turn provides scalability, lesser overhead and high latency because it takes more time to establish path. The hybrid protocol combines reactive and proactive protocol and utilize the characteristics of both. Unlike proactive protocol, the routing information is updated only when there is change in the topology and for determination of best routes to destination, an accurate metrics is generated using distance vectors.

2.2.2 Ad Hoc Networks

An ad hoc network is a type of self-configuring without infrastructure network where nodes use wireless communication to transmit the data packet, without any central administration involvement [16]. In infrastructure based wireless network, node can communicate and send the packet to destination with the aid of access point. The nodes within the transmission range of access point can request to send the packet. Hence malfunctioning of access point can disconnect the nodes from the network [18].

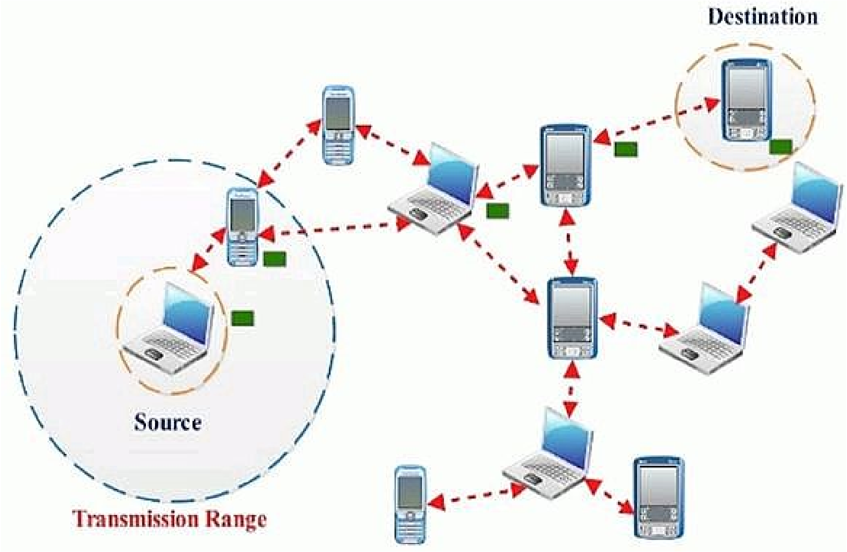


Figure 2.1 An Ad Hoc Network

Figure 2.1 [17] shows an example of ad hoc network where source transmits data to the base station through a chain of connected intermediate hops (marked with green). However, the nodes in the ad hoc network are equipped with transceivers which act like a router, they form an arbitrary topology where they can arrange themselves and communicate with each other without any access point. They are short lived, autonomous, dynamic and function specific networks since the communication links are established when there is need to send the packet to destination. The network supports direct communication between the nodes when they are within transmission range of each other and communication between nodes can be established which are indirectly connected through series of intermediate nodes. These networks were first developed by military forces because of their decentralized networking which is an operative necessity in military applications [17].

2.3 Protocols for UASNs

With the advancement in the field of wireless communication and sensor technology, researchers have proposed numerous routing techniques for WSNs and UASNs. Some of routing protocols are discussed in this section.

2.3.1 Low Energy Algorithm Adaptive Clustering Hierarchy (LEACH)

LEACH [19] is the clustering-based routing protocol and most popular in terrestrial wireless sensor networks. It follows the dynamic clustering approach based on energy consumption. The rotation of cluster head (CH) is random and periodic where each node has same probability to be elected as next cluster head. It is done to distribute the energy load equally among the nodes in the sensor network. The operation in LEACH take place in rounds where each round consists of two phases: setup phase where CH is elected and steady state phase where data is transferred to sink.

In setup phase, cluster heads are selected through election process based on selection probability. The CHs informs other nodes in the network about their election and based on distance each node decides to choose the closest CH for data transmission. In steady state phase, each node with in the clusters transmits the sensed data to respective CH where data aggregation takes place. The CHs after data integration send it to the base station. The process repeats each round and a new CH is selected [19] [20]. Figure 2.2 [22] shows the network architecture of LEACH.

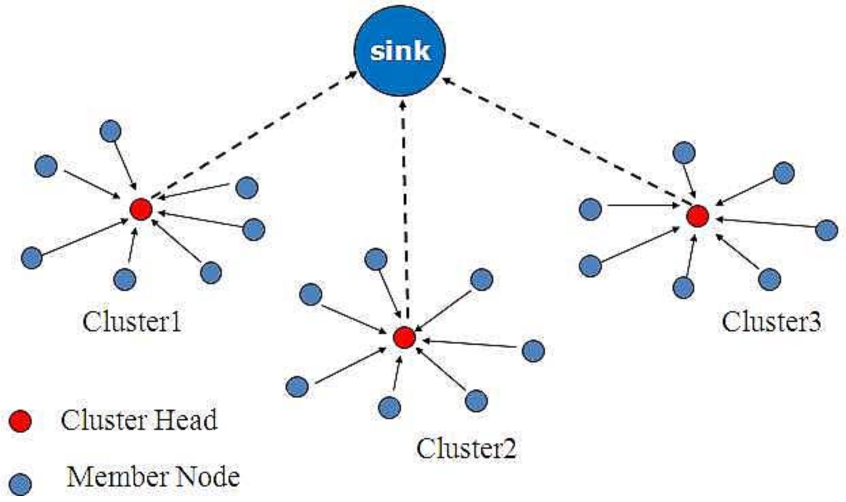


Figure 2.2 LEACH network model

Various researchers have proposed routing protocol for terrestrial and underwater WSNs using LEACH. In [20], a new clustering algorithm is proposed using LEACH protocol to address the problem of large clusters and nodes at the edge consuming more energy. The protocol introduces two criteria to improve the energy efficiency of LEACH in UASNs. In the CH election phase, the position of CH is considered as the cluster center from the points which were uniformly distributed in the network. The node with highest energy level is elected as CH which makes the CH distribution uniform and built stable clusters. For nodes to select the CH, weight factor is introduced in which not only the energy consumption between node and CH but energy dissipation between every CH and BS is also considered for node to join the cluster. The results show that algorithm balances the cluster size and reduce the total network energy consumption. In [19], the author has compared the direct communication in which each node directly sends data to sink with LEACH protocol. Based on the energy consumption and underwater environment, the energy model is implemented. The simulation outcomes show that clustering approach using LEACH consumes less energy compare to direct communication because in direct communication the distance between node and sink may be larger which results in more energy consumption. In [21], the author compared LEACH, LEACH centralized where BS selects the CHs and LEACH using genetic algorithm for terrestrial WSN. The outcomes depict that LEACH GA increases the network lifetime by average of 54% and 47% compare to LEACH and LEACH C respectively. The 2D and 3D configurations for WSN are compared to evaluate the effect on the network lifetime in [22]. In a 3D structure for WSN new parameters have been introduced to consider for energy consumption and other calculations because the 2D energy model can't be used. The analysis is performed by simulating LEACH in both 2D and 3D network model. The results indicate that 3D model for WSN decreases the network lifetime by 21% compare to 2D network model. This fact emphasizes the selection on network model for UASNs because of variable depths of sensor node.

2.3.2 Energy Balanced and Lifetime Extended (EBLE) Routing Protocol

EBLE [28] considers both energy efficiency and balancing in the protocol design. The protocol operates in two phases: candidate forwarding set selection phase and data transmission phase. In first phase, the sink broadcasts a signal so that each node can estimate the relative distance between itself and sink by calculating received signal strength (RSS). Each node further broadcast a packet to its neighbor containing information about its relative distance to the sink and present residual energy level (EL). Each node stores the EL of neighboring node and calculates a cost value using cost function. Using the relatively long effective propagation distance and short actual propagation distance, the cost function calculates the energy consumption per transmission distance which is used to select the next hop.

Three cases are considered in the data transmission phase. In the first case, a subset of neighbors is constructed with larger and equal EL, considering the EL of sending node is smaller or equal to at least one neighbors' EL. The node with the minimal cost value is selected as next hop. In second case, when sink is within the transmission range of the node, the packet is directly delivered to sink. Finally, the third case considers that EL is larger than neighboring node and sink is out of reach. Then a table of nodes with larger EL is built and node with minimal cost is selected as next hop.

The authors tested the protocol for two cases: regular node distribution and random node distribution. The simulation results show that EBLC achieves similar performance as balanced transmission mechanism (BTM) protocol in regular distribution, which is better than direct transmission and balance energy adaptive routing (BEAR). Whereas in random distribution, EBLC displays higher delay and energy efficiency compare to other test protocols.

2.3.3 Energy Aware and Void Avoiding Routing Protocol (EAVARP)

EAVARP operates in two phases: layering and data collection phase [29]. The sensor nodes are distributed in concentric shells built during the layering phase around the sink. Each node constructs and update their routing table based on the layering packet received during this phase. The protocol uses opportunistic directional forward strategy (ODFS) for forwarding the data in data collection phase to avoid the flooding, cyclic transmissions and voids. The simulation results indicate that protocol extends the network lifetime through balancing the energy in the network compare to other routing protocols.

2.3.4 Stateless Opportunistic Routing Protocol (SORP)

In sensor network, void node problem occurs when a node is in void region which means there is no neighboring node to forward the packet leading to the destination. It increases delay and packet drop rate because of long packet detour and timer to reach the destination which significantly affect the packet delivery ratio [30] [31]. To address the problem of void nodes and energy-reliability trade off, SORP is proposed [32]. The protocol performs a depth based stateless routing which can avoid the trapped and void areas, selects the candidate forwarding node through calculating holding time for each node in the forwarding area, using the local information acquired in updating phase from the neighboring nodes. The results demonstrate that SORP decreases the energy consumption, packet loss and end to end delay in sparse to dense scenarios.

2.3.5 Hop by Hop: Power Efficient Routing Protocol (H^n - PERP)

In UWSNs, the efficient data delivering is still a challenge because of limitations of acoustic communication and underwater conditions. To address the packet delivery problem, a hop-based protocol is proposed in [33], known as H^n - PERP. The author proposes a centralized model, providing a mechanism for scheduling and data transmission processing. The protocol enhances the energy efficiency and network throughput through power monitoring solutions. The analysis is performed based on the parameters influencing the scheduling and data transmission such as number of nodes, hop count, energy levels, energy required to forward the packet and congestion to maximize the network lifetime. The results show that when increasing number of nodes, the network performance remains stable, also network productivity is not affected because of difference in energy levels variation.

2.3.6 Balanced Energy Efficient Circular (BEEC) Routing Protocol

In BEEC [34] routing protocol, a circular field is divided into ten sub regions and each region is further divided into eight sectors. The data is collected from the sectors using two mobile sinks, moving in circular patterns; each covers five different sectors in sequence. The protocol increases the performance of network in term of lifetime, energy consumption, throughput and stability. However, sink follow a fixed circular pattern which leads to packet loss and higher delay because of unawareness of network conditions.

2.3.7 Vector based Forwarding (VBF) Protocol

In VBF routing protocols, a routing pipe is created to guide the packet from source node to base station. The routing pipe is defined by a vector from sender to destination, having a certain radius. Nodes which are within the radius of routing pipe can forward the packet. In densely populated sensor network, there might be too many nodes within the radius of pipe, resulting in higher energy consumption. However, in case of small radius size, fewer nodes are within the range of routing pipe, which may increase the packet loss at sink [34]. Figure 2.3[39] shows the example of VBF where W is the radius of routing pipe.

A routing algorithm has been proposed through remodeling VBF in [35]. The protocol considers the routing pipe radius as a function of node range, number of nodes and dimension of environment. The selection of guiding node is based on the residual energy of receiving node, if it is lower than the defined threshold compares to sender, the algorithm reduces the radius of pipe thus decreasing the chances to become guiding node. The results indicate that protocol decreases the energy consumption in network with large number of nodes, by changing the routing pipe's width in proportion to network density. With lower density networks, the protocol exhibits higher packet deliverance compare to VBF, HH-VBF, and VBVA.

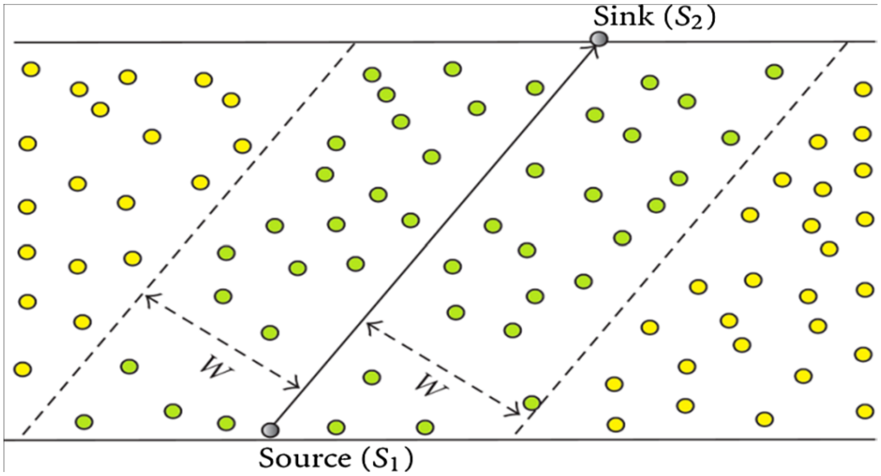


Figure 2.3 Example of VBF routing protocol-based network

2.3.8 Energy Efficient Interference Aware Routing (EEIAR) Protocol

The protocol [36] utilizes the interference aware technique to minimize the packet loss in UASNs using multihop communication to send the data to base station. The selection of next node is done by sender node based on the depth and number of neighbors. The node having the lowest depth and least number of neighbors is selected as forwarder node. The criteria of lowest depth and least neighbors are defined to ensure that packet reach closer to gateway and avoid packet loss and interference during data transmission, respectively. The results indicate that protocol improves the packet delivery ratio by avoiding interference in the network. It also enhances the performance compare to DBR and EEDBR.

2.3.9 Priority based Routing Protocol

In [38], the proposed protocol routes the data based on its priority. The nodes are deployed in a cube considering the underwater scenario. The cube is subdivided into small logical cubes. The algorithm distinguishes the data based on the two traffic classes: high priority and low priority. High priority data requires low delay whereas low priority data can tolerate some delay. In the first phase, the algorithm selects the target cube from one of the logical cubes. For traffic with high priority, the forwarder node is selected based on the minimum distance to base station and residual energy, present in the target cube. This improves the better performance in terms of energy, end to end delay and packet loss.

2.3.10 Clustering Depth based Routing Protocol (cDBR)

In DBR, it is assumed that each node knows its own depth. The next hop is selected based on the depth of the sensor node. The receiving node checks the depth embedded in the packet with its own depth, if it is smaller compare to value in the packet the node will consider itself as a fitting node to forward the packet. The process is continued until packet reaches to destination. Figure 2.4 [40] represents an example of forwarder node selection in DBR. N1 and N2 are the receiving nodes with depths D1 and D2 where S is the sending or source node. The node with least depth will be considered as next forwarder node, that is, N2.

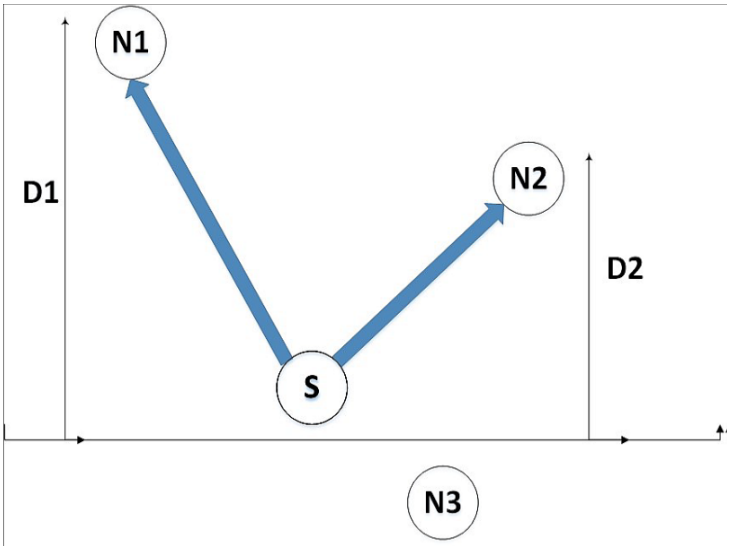


Figure 2.4 Node Selection in Depth based Routing Protocol

In DBR, the nodes are selected based on lowest depth, results in more energy dissipation and nodes nearer to sink are depleted first, causing packet loss and network failure. In [37], proposed protocol combines DBR with clustering approach to minimize the energy consumption and distribute the load among the nodes in the network. The classification of nodes in the network is performed based on the assignment of random number that is from 0 to 1. If the random number is greater than the threshold value, then the node is elected as

CH. If it is zero, the node is considered dead and if it is less than threshold value, it is a normal node. In CH detection, if the residual energy of CH is less than threshold, it is eliminated as CH and a new CH is formed. The approach has improved the energy efficiency through implementing clustering in depth-based routing. In [40], Energy Efficient DBR (EEDBR) is compared with simple DBR and hop by hop dynamic address based (H2-DAB) protocol. The protocol selects the next node based on lowest depth and highest residual energy from the neighboring nodes. The results show path loss and packet delivery ratio is almost same for DBR and EEDBR whereas H2-DAB has higher end to end delay.

2.4 Summary

This chapter discusses some basic concept of routing and recent research work related to UASNs. The failure of master node in centralized network could lead to network disintegration. However, in decentralized approach, node failure doesn't affect the communication of entire network because each node makes its own decision for forwarding packet either directly to sink or through multihop communication. In such networks, routing protocol plays a major role in data delivery through finding and establishing the path from source to destination. It has been emphasized the importance of UASNs and routing issues related to it. Various protocols proposed by researchers using different techniques such clustering, multihop, direct communication, depth and vector-based packet forwarding are discussed in this chapter. They provide different solution based on energy efficiency, end to end delay, and packet delivery. Considering the discussed work, a self-organizing protocol is proposed in this thesis for UASNs, which allow the nodes to form the network through local information and communicate with destination randomly.

Chapter 3. Self-Organizing Scalable Routing Protocol for UASNs

3.1 Introduction

In this chapter, a self-organizing and scalable routing protocol is proposed for UASNs. The chapter discusses the system model in section 3.2, which comprises of two subsections describing the network and energy model for the proposed protocol. Section 3.3 discusses the working methodology of proposed protocol thereby describing the four phases. The section further discusses the characteristics of protocol. The chapter is summarized in section 3.4.

3.2 System Model

The system model is a three-dimensional layout where energy and propagation model for the proposed protocol are implemented considering the underwater conditions and various work proposed by researchers. The 3D model is chosen because of third dimension (depth) involvement and its impact on important parameters in underwater scenario. Moreover, it is worth mentioning that energy consumption is an important parameter to consider in design the protocol for any sensor network. Therefore, the energy and acoustic waves propagation model is implemented in MatLab for measuring the energy dissipation during the network operation. Since the protocol is implemented for shallow water scenario, therefore the propagation model is discussed.

3.2.1 Network Model

Mostly, current wireless sensor protocols are built on 2D design, where nodes are deployed on earth surface, and their transmission range is higher compare to network height. However, in UASNs the nodes' deployment in 3D field and the difference of depth is too large to ignore because with changing depth, the temperature and salinity also vary affecting to important parameters such as propagation delay and path loss in underwater sensor networks. Therefore, the proposed network model is three dimensional because it is much closer to 3D space in underwater environment in real world.

The sensor network is 200 x 200 x 200 (m) cube, the top of cube is considered as surface of water and bottom as a sea bed. The nodes are deployed one by one in 3D space randomly to address the realistic scenario, including a single sink node on surface. The nodes are randomly placed to assure the flexibility of proposed routing protocol. Each node is placed at minimum 40 meters separation from the surrounding nodes. This is done, to avoid nodes sending packets of similar measured event to the sink. The separation between nodes is done through Euclidean metric using eq 1.

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \tag{1}$$

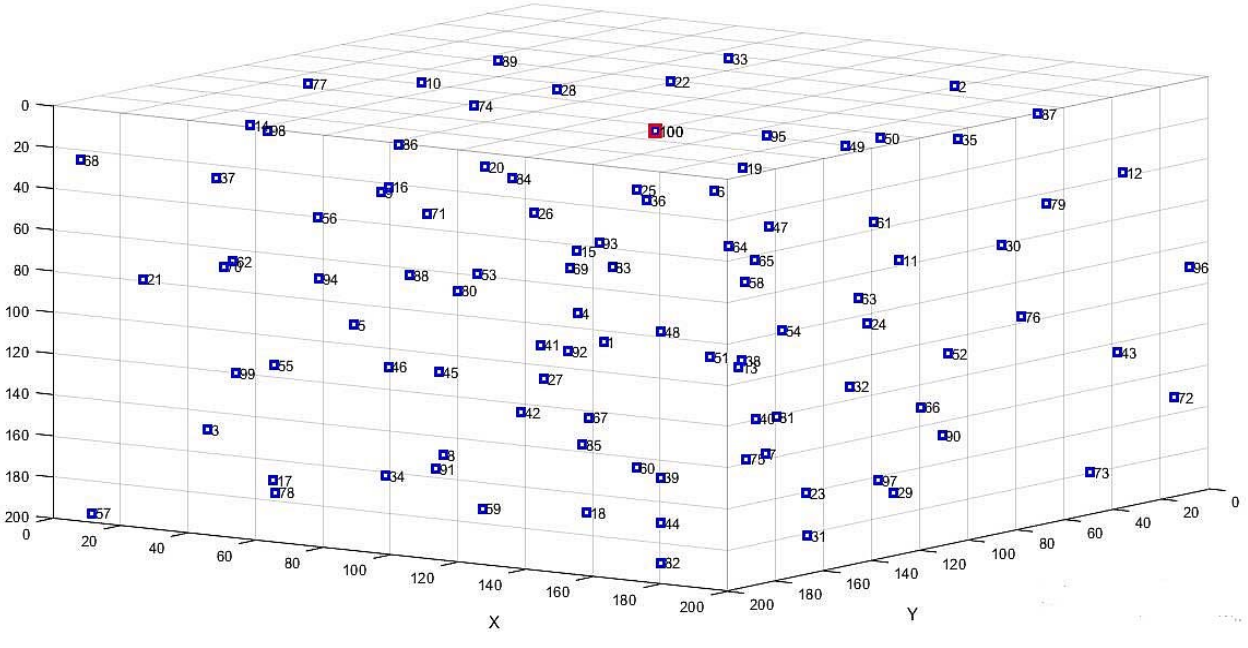


Figure 3.1: Network Model with 99 sensor nodes and a sink node

Figure 3.1 presents the network model where nodes are randomly located in 3D space. The sink is placed at the top of cube i-e surface of water, having depth zero while other sensor nodes are located at random depths. Once the nodes are placed, they are considered to remain static and do not flow because of marine currents and waves. The coverage area of each node is 100 meters, and it is assumed that each node knows their neighboring nodes location within specified transmission radius. Since the nodes are placed randomly, therefore it is assumed that each node uses power control mechanism to alter and save the transmission power based on the distance between two nodes.

3.2.2 Energy Consumption Model

In this section, the energy consumption model is described for the proposed algorithm. It is important to construct the channel model for better understanding of energy consumption in underwater scenarios. The underwater acoustic channels are influenced by many factors, such as Doppler effect, a noise, multipath fading and path loss. Therefore, in UASNs energy to transmit the data from one node to another over distance (d) is given by [9]:

$$Et = P_l * \left(E_{elec} + E_{amp}\right) + P_t * \frac{P_l}{R} \tag{2}$$

Where P_l (bits) is the packet length, E_{elec} (J) is the electronics energy consumed per bit, E_{amp} (J) is the amplifier energy dissipation, P_t (W) is the power transmitted, and Rn (bps) is the transmission rate . The P_t (W) is expressed as [9]

$$P_t = A * I_t = 2\pi r * H * I_t \tag{3}$$

Here, I_t (W) is the Power Intensity, H (m) is the depth of sensor node and r (m) is the distance between two nodes in multipath communication. Similarly, the energy consumed (in J) during reception process is given as [11]:

$$Er = P_l * (E_{elec} + E_{DA}) \tag{4}$$

Where P_r (W) is the reception power, and E_{DA} (J) is the energy consumed during data aggregation process. The transmission rate (R) can be found using Shannon theorem:

$$R = BW * \log_2(1 + SNR) \tag{5}$$

Where BW is the available bandwidth in underwater conditions and SNR is signal to noise ratio which is ratio of signal strength and noise power.

3.2.3 Propagation Model

Many characteristics of underwater environment affect the acoustic communication which makes the propagation channel much more complex compare to terrestrial communication channel. They include temperature, salinity, multipath fading, path loss, depth and Doppler effect. The acoustic signal propagation, network performance and energy dissipation are highly affected by these factors. Equation 5 represents the propagation speed of sound in underwater. It is evident from the equation 5 that speed of sound is a function of temperature, salinity of sea water and depth. Therefore, the variance in acoustic speed is important to consider while estimating the propagation delay because temperature and salinity of sea changes with depth of sensor node, because of which the acoustic speed also varies [8].

$$c = 1448.96 + 4.591T - 5.304 * 0.01T^2 + 2.374 * 0.01T^3 + 1.340(S - 35) + 1.63 * 0.1D + 1.675 * 10^{-7}D - 1.025 * 0.01T(S - 35) - 7.139 * 10^{-13}TD^3 \tag{6}$$

c is the propagation speed of sound in m/sec, T is temperature expressed in Celsius, D is the depth of sensor node in meters and S is the salinity of sea water in parts per thousands (ppt).

In UASNs, the SNR of transmitted signal is given by passive sonar equation which is sum of source level (SL), transmission loss (TL), ambient noise (NL) and directivity index (DL). SNR (dB) is expressed as [9]:

$$SNR = SL\text{-TL-NL+DL} \tag{7}$$

, where SL (source level) is the intensity of sound radiated by source at the distance of 1 meter. The intensity is the sound power transmitted in a specified direction through unit area. Source level in underwater is expressed in dB re µPa as [9]:

$$SL = \log 10\left(\frac{I_t}{0.067 * 10^{-18}}\right) \tag{8}$$

where I_t can be calculated using equation 3.

Considering the sources of noise level in shallow water such as shipping activity, biological noise, seaquakes etc. We consider noise level (NL) to be 70 dB as an ideal for shallow water and since the deep sea is much quiet compare to shallow waters, we take NL to be 50 dB. The SNR is taken as 20 dB for hydrophones [9], where DL is zero considering omnidirectional modems. Thus, using equation 7, SL can be written as:

$$SL_{SH} = TL + 90 \tag{9}$$

$$SL_{DP} = TL + 70 \tag{10}$$

Here SL_{SH} denotes source level in shallow water and SL_{DP} source level for deep waters.

Transmission Loss (TL) is dependent on the absorption coefficient ($\alpha(f)$) and distance (r) between transmitter and receiver measured in dB/Km and meters respectively. It is the collective depletion in acoustic intensity during wave propagation and significantly affects the underwater communication. Another reason for transmission loss is spreading that are cylindrical spreading and spherical spreading which is based on the depth of sensor node that is shallow water (lower than 100 meters) and deep sea (higher than 100m). Since in this work, nodes are deployed with random depth from zero to 200 meters. Therefore, both cylindrical and spherical spreading are considered. Transmission loss is measured in dB and can be estimated as [9] where TL_{CS} and TL_{SS} denotes transmission loss in cylindrical and spherical spreading respectively and 10^{-3} is the conversion factor from meter to km:

$$TL_{CS} = 10\log(r) + \alpha(f) * r * 10^{-3} \tag{11}$$

$$TL_{SS} = 20\log(r) + \alpha(f) * r * 10^{-3} \tag{12}$$

The absorption coefficient is expressed through Thorp's propagation model as equation (10), where frequency (f) is measured in KHz. Equation 10 is valid for frequencies ranging from 100 Hz to 10 KHz.

$$\alpha(f) = 1.094\left(\frac{0.1 * f^2}{1 + f^2} + \frac{40 * f^2}{4100 + f^2}\right) \tag{13}$$

The noise power (W) experienced in underwater scenario can be expressed as equation (14) [8],

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f) \tag{14}$$

where $N_t(f)$ is turbulence noise, $N_s(f)$ is caused by shipping movements, $N_w(f)$ is wave noise and $N_{th}(f)$ is thermal noise. Above mentioned noises can be expressed using equation 15 -18 [12],

$$N_s(f) = 40 + 20 * (s - 0.5) + 26 * log(f) - 60 * log\ (f + 0.03) \tag{15}$$

$$N_t(f) = 17 - 30 * \log(f) \tag{16}$$

$$N_w(f) = 50 + 7.5\sqrt{w} + 20 * \log(f) - 40 * \log(f + 0.4) \tag{17}$$

$$N_{th}(f) = -15 + 20 * \log(f) \tag{18}$$

3.3 Proposed Protocol

UASNs are composed of large number of fixed or mobile nodes, deployed, collaboratively monitoring a specific area and forwarding data to one or more base stations. The nodes are connected through wireless links which are either manually setup prior to node placement or centrally assigned after deployment, also it is necessary to reconfigure the links whenever node is lost or added which requires considerable efforts. Considering the above-mentioned challenges, harsh ocean current and environment, a self-organizing protocol is proposed to achieve scalability, robustness and fault tolerant system known as Self Organizing and Scalable Routing Protocol (SOSRP). The section further discusses working methodology of proposed protocol which consists of four phases which are discussed in section 3.3.1, also characteristics of SOSRP are discussed in section 3.3.2.

3.3.1 Working Methodology

The SOSRP is designed to conserve the energy through power control and hop count-based techniques. The protocol enables a node to find the neighboring nodes and form a connectivity matrix. The packet routing is based on the smallest distance and hop count between the source and sink.

Figure 3.2 depicts the working principle of proposed protocol. The protocol begins with node deployment, followed by neighbor discovery where each node broadcasts a message to announce its presence to neighboring nodes in defined transmission radius. After that, routing table is generated using the distance and hop count from node to destination. As soon as the event is sensed, the source selects the next node based on the routing table. The packet is forwarded to selected node and this operation extends until the packet reaches to base station. The working methodology consists of four phases: Network initialization, Neighbor Discovery, Path Selection Criteria and Packet Transmission.

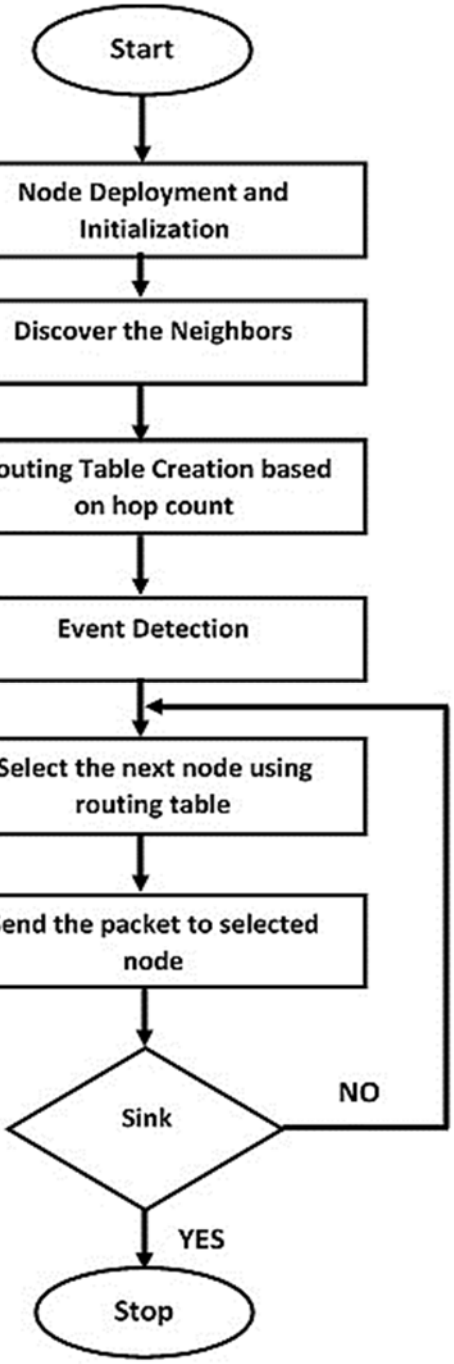


Figure 3.2 Flow chart of SOSRP

3.3.1.1 Network Initialization

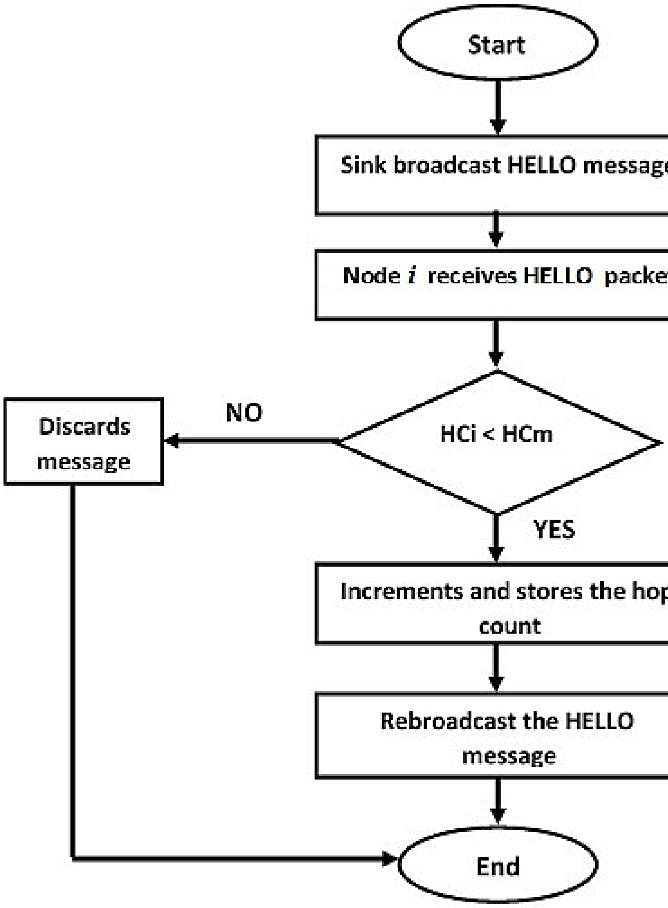
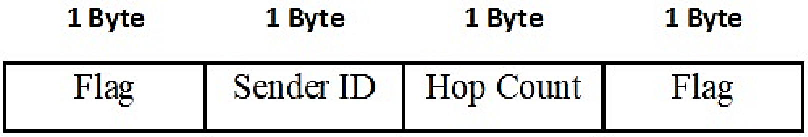


Figure 3.3 Network Initialization Flow Chart, where HCi = Node"*i*" hop count and HCm = hop count in received HELLO message

Figure 3.3 denotes the network initialization process. The nodes are deployed one by one at random depths underwater having random x, y and z coordinates where sink is placed at the surface of sea with zero depth. Initially, after deployment nodes do not have any prior information about the address and location of base station.

In network initialization phase, the sink broadcasts a control packet named "HELLO" packet in a defined transmission radius, containing base station ID and hop count which denotes the address and total number of wireless links from node to sink respectively. After receiving the packet, the node increments the value and stores the hop count if it is not already present or is smaller than the stored hop count and rebroadcast the message with the updated value. In case, the hop count is equal or larger than current value, the node will discard the message.

This process continues until message reaches to every node in the network. Figure 3.4 shows the format of HELLO packet.

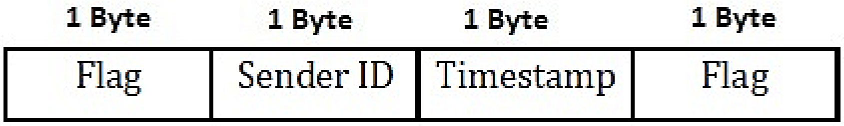


1 Byte	1 Byte	1 Byte	1 Byte
Flag	Sender ID	Hop Count	Flag

Figure 3.4 HELLO Packet

3.3.1.2 Neighbor Discovery

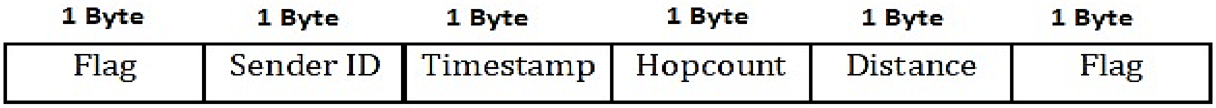
After initialization phase, neighbor discovery phase begins where it is considered that each node broadcast a four bytes request message in defined transmission range to discover the neighboring nodes. The packet encapsulates sender ID and timestamp at which the packet is transmitted. Figure 3.5 displays the format of request packet.



1 Byte	1 Byte	1 Byte	1 Byte
Flag	Sender ID	Timestamp	Flag

Figure 3.5 Request Packet Format

In response, neighboring nodes forwards an INFO message of 6 bytes, containing sender/neighbor ID, timestamp, hop count and distance to sink as shown in figure 3.6 representing the packet format. Upon receiving the packet, the node generates the neighbor table storing neighbor ID, hop count and distance from sink. Time of Arrival technique is considered for calculating the distance between two nodes and it represents the accumulated hop to hop distance from node to destination. To conserve the energy, the neighbor discovery phase is only initiated when change in topology is detected such as node addition or losses. Figure 3.5 shows the neighbor discovery phase and table 3.1 shows the neighbor table constructed for node 5 using figure 3.7.



1 Byte	1 Byte	1 Byte	1 Byte	1 Byte	1 Byte
Flag	Sender ID	Timestamp	Hopcount	Distance	Flag

Figure 3.6 INFO Message Format

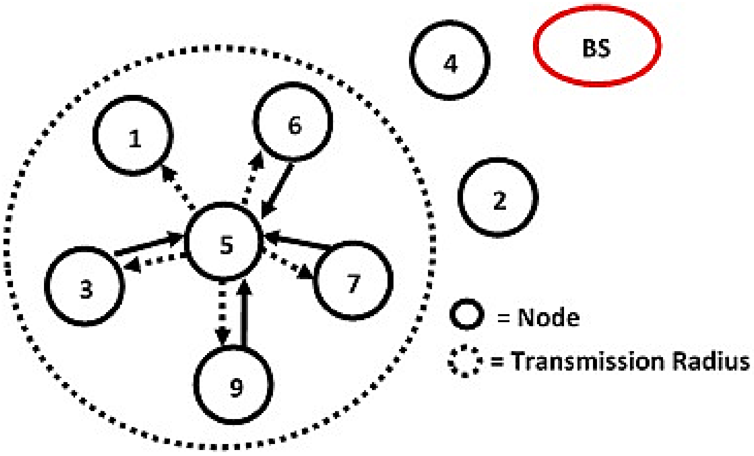


Figure 3.7 Example of Neighbor Discovery for Node 5

Table 3.1 Neighbor Table for Node 5

ID	HopCount	Distance
6	3	130
7	3	150
9	4	190
3	5	250
1	4	198

3.3.1.3 Path Selection Criteria

The path selection criterion for proposed protocol is based on hop count and distance between source and destination. The protocol selects the shortest path between source and sink. On sensing the event, the path formulation begins with the selection of next hop by source node to transmit the data to base station.

To diminish the energy consumption during data transmission, the selection criteria of next node is based on smallest hop count. When source node has data to send, it will look up in its neighbor table to select the next node. The node with the least hop count value will be selected as the next hop. If two neighboring nodes have same hop count value in neighbor table, the node with the shortest hop count distance will be selected as next node. Figure 3.8 depicts the next hop selection criteria and distance between two nodes in calculated using Euclidean distance formula in MatLab, expressed as equation 17. Figure 3.9 shows the example of next node selection where two nodes e.g. node 6 and node 7 have same hop count in the neighbor table of node 5. Here, node 6 is selected as next hop based on the shortest distance between source and destination. The selected entry at each node is shown in respective node's neighbor table: 3.2, 3.3, and 3.4.

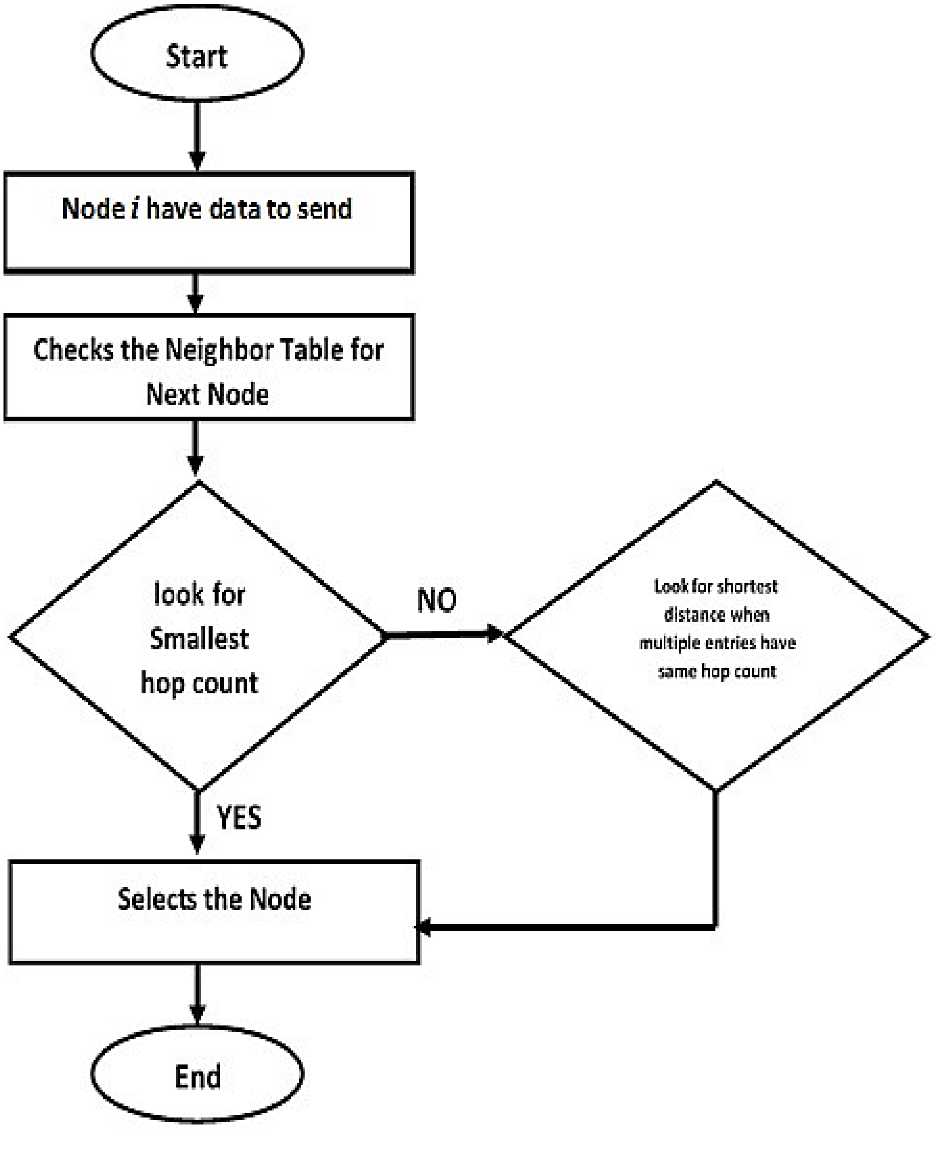


Figure 3.8 Flow chart for Next Node Selection in SOSRP

$$Distance_{hoptohop} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \tag{17}$$

Where (x_1, y_1, z_1) and (x_2, y_2, z_2) are 3D cartesian coordinates of sending and receiving nodes.

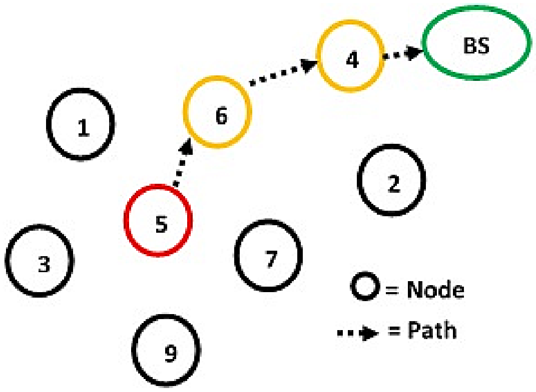


Figure 3.9 Path Selection for Node 5 based on neighboring table

Table 3. 2 Node 5 Neighbor Table, Node 6 is selected as Next Node

ID	HopCount	Distance
6	3	130
7	3	150
9	4	190
3	5	250
1	4	198

Table 3. 3 Node 6 Neighbor Table, Node 4 is selected as Next Node

ID	HopCount	Distance
5	4	170
7	3	150
2	2	75
4	2	65
1	5	230

Table 3. 4 Node 4 Neighbor Table, BS is selected as Final node

ID	HopCount	Distance
BS	1	40
2	2	70
6	3	110

3.3.1.4 Packet Transmission

In proposed protocol, the packet is transmitted from source node to sink using multihop communication where intermediate nodes are selected based on smallest hop count and shortest distance between source and base station.

On acquiring the data, the source node checks the local routing table for the selection of next hop. The selection of node is performed using path selection criteria where hop count and distance are compared among the all the entries stored in the table, based on defined criteria node is selected for packet transmitted. The process repeats at each node until the packet reaches the base station. If a route failure is detected, the algorithm selects an alternate path to transmit the data. The route failure is further discussed in section 3.3.2. Figure 3.9 represents the flow chart for the packet transmission in proposed protocol.

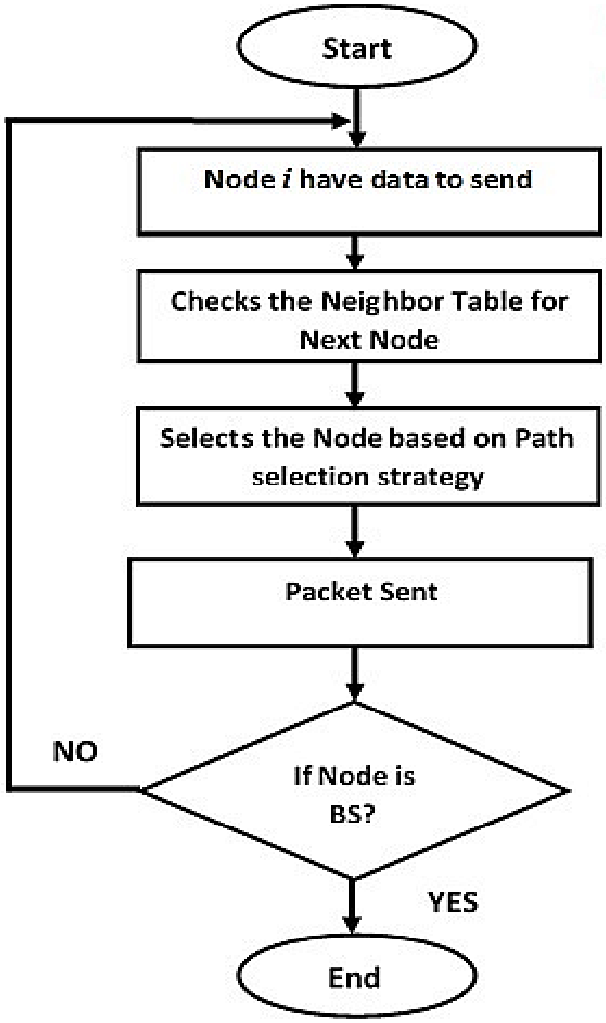


Figure 3.10 Flow chart for packet transmission in SOSRP

3.3.2 Characteristics of Protocol

The proposed protocol is designed considering the hostile environment of underwater, where it becomes essential for nodes to self-organize themselves in the network. SOSRP provides some important features which are vital for proper network functions in underwater. In the following subsections (3.3.2.1-3.3.2.4), a set of characteristics of the proposed protocol are discussed in detail.

3.3.2.1 Self-Organization

To transmit the information to base station, it is important for node to create the routing matrix. A self-organization procedure must form a connectivity matrix with no prior information of network. It should automatically route the data to destination, responds to changes in the network such as addition, losses and deletion of node. SOSRP has an ability to adapt the changes that occur in the network such as route failure or new node deployment. When the fault is detected during data transmission, the protocol enables the node to select the alternate path/node to transmit the data, avoiding the unnecessary data loss and increasing the network performance. Furthermore, when a new node is deployed, it can easily connect to the network through the local information acquired from surrounding neighbors.

Considering above mentioned features, the proposed algorithm starts with nodes having no preprogrammed information about location, total number of neighbors or hop count. The self-organization procedure of proposed protocol mainly depends on two phases: network initialization and neighbor discovery. In network initialization phase, nodes are initialized with hop count information from itself to base station. The information is further used to form a local routing table in the neighbor discovery phase. Both phases are initiated only when there is some change in the topology such as addition or loss of node is detected, conserving most of the network energy. The path selection phase enables the node to select the next hop based on hop count and distance between source and destination. This permit the protocol to automatically respond to any variations detected in the network such route failure, new node deployment or removal with minimum control messages transmission.

3.3.2.2 Route Failure Tolerance

One of the characteristics of SOSRP is path failure tolerance. The path failure may occur because of link hole or node failure which causes data loss. The link hole occurs due to interference, noise, distance or environment conditions while node can fail due to hardware or software failures such as battery discharge, transmission system or application. It is essential to recover the transmission path to increase the probability of data delivery by sending the packet through different paths.

In proposed protocol, since there is a single node chosen to forward packets based on a hop-count and distance criterion, the number of paths available from a source node to the sink is equal to the number of neighbors of that source node.

The path failure is detected through failure of ACK reception from the neighboring node in response of packet received. On recognizing the path failure, the previous node which successfully received the data packet starts the path recovery by selecting new next hop based on path selection criteria (section 3.3.1.4) upon failure of receiving the ACK.

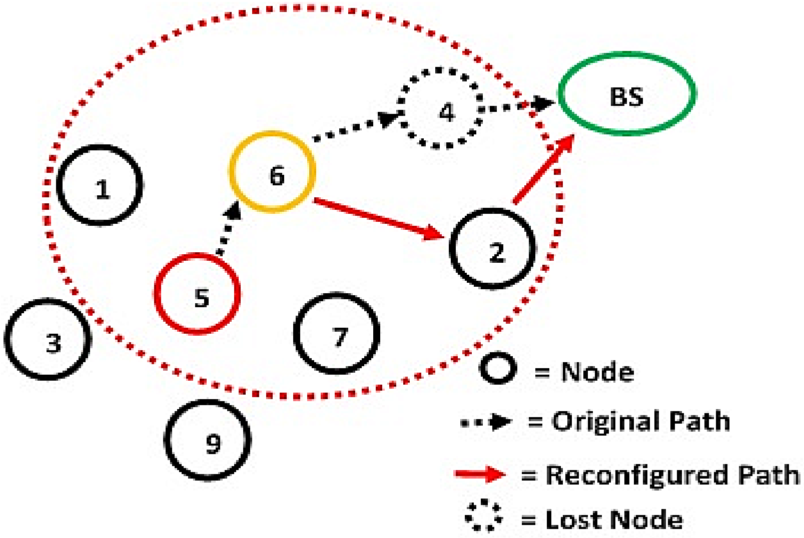


Figure 3.11 Path Recovery example for Node 6

Table 3. 5 Neighbor Table for Node 6

ID	HopCount	Distance
5	4	170
7	3	150
2	2	75
4	2	65
1	5	230

Table 3. 6 Neighbor Table for Node 4

ID	HopCount	Distance
BS	1	40
2	2	70
6	3	110

Table 3. 7 Neighboring Table for Node 2

ID	HopCount	Distance
BS	1	50
4	2	80
6	3	110
7	4	150

Figure 3.6 shows an example of path recovery where 8 nodes are randomly placed and node 4 is lost. Node 6 detours the packet via newly selected node 2 as next hop. The intermediate nodes are selected using table 3.1 (section 3.3.1.2) and table 3.2. Table 3.5, 3.6 and 3.7 denotes the faulty and new entries selected, highlighted with red and yellow colors respectively.

3.3.2.3 Isolation Recognition

Node isolation is defined as a node or group of nodes becomes isolated because of either link holes or located outside the transmission range of other nodes in the network. The isolation results in wastage of resource and energy in transmitting the data. Therefore, it is important to recognize the isolation to save the energy by avoiding the unnecessary transmissions.

In the proposed algorithm, the isolation detection occurs in neighbor discovery phase, where node broadcast a request message in defined transmission radius to find the neighboring nodes. If a node doesn't receive an INFO message in response to its request, it considers that there are no nodes located in its current transmission range and thus node rebroadcast the request message with increasing the transmission power, hence increasing the transmission radius. When the node finds the neighbor, it updates the transmission range and constructs the table accordingly. Figure 3.7 shows the example of isolation recognition where isolation of single node (node 3) is shown as there are no neighboring nodes in its transmission range. Upon not receiving the INFO message, it reconfigures the transmission range by increasing the transmission power and rebroadcasts the request message.

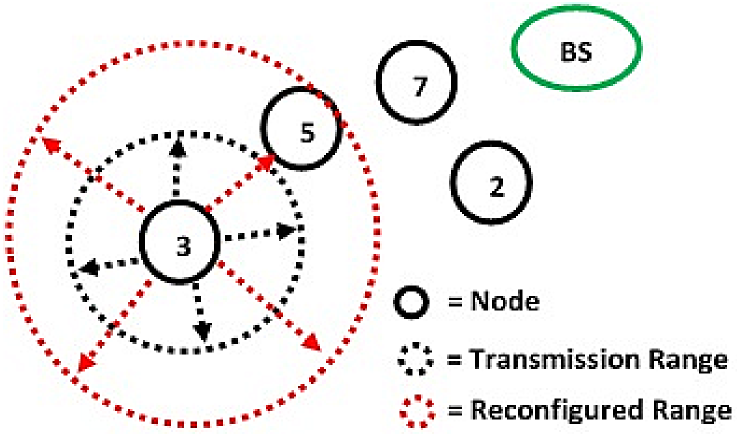


Figure 3.12 Isolation Recognition for Node 3

3.3.2.4 Network Scalability

For routing protocols, scalability is defined in terms of network size. It means network should perform the necessary functions irrespective to the variation of number of nodes in the network. The proposed protocol is scalable since it provides the capability of expanding the network size, thereby adding the new nodes in the network.

3.4 Summary

In the proposed algorithm, 100 nodes (99 sensors and the sink) are randomly deployment in 3D cube with different depths where sink is located at the surface having zero depth. Nodes are placed at minimum separation of 40 meters from each other. To calculate the energy consumption, the mathematical model of energy dissipation and propagation model of acoustic waves in underwater environment are implemented in MatLab. The protocol is implemented to conserve the energy, thereby establishing the shortest path between source and the base station. SOSRP utilizes multihop communication technique to transmit the data, whereas each node participates in the transmission path formation by selecting the next hop based on smallest hop count and shortest distance between two nodes. Further SOSRP is self-organizing routing protocol for UASNs, providing the scalability, adaptivity, fault tolerance and isolation detection which increases the network performance.

Chapter 4. Simulation and Results

4.1 Introduction

In this chapter, the results obtained from simulation are discussed. Initially, chapter begins with section 4.1, discussing the performance metric based on which the evaluation of proposed protocol is performed. The section 4.2 includes the simulation setup using MATLAB, scenarios and various parameters are discussed. Section 4.3 contains the results where effects on network size and transmission range are analyzed. Finally, section 4.4 concludes the chapter.

4.2 Performance Metrics

The performance metrics are parameters which have certain impact on the performance of network. The metrics for the proposed protocol is following:

- Energy consumption: It is the amount of power or energy used in performing the operation.
- End to end delay: It is a time taken to transmit data from source to destination.
- Hop count: It is defined as number of intermediate nodes between source and destination.
- Transmission range: It defines the coverage area of node.

In this work, the protocol is tested with varying different parameters to evaluate the above-mentioned performance metrics.

4.2.1 Energy Consumption

A node dissipates energy in sensor network while performing the operations necessary for the collection of data required by the application. Such operations include processing, listening to the channel, transmitting and receiving the data. Energy consumption is the sum of energy dissipation by a node during performing different operations whereas the accumulation of energy dissipated by each node defines the total energy consumption of network.

4.2.2 End to End Delay

It refers to the time taken to transmit the data packet from source to Sink, irrespective to the number of intermedia nodes. It is sum of transmission, propagation, queuing and processing delay in a network. However, queuing and processing delay are not considered in this work.

4.2.3 Hop Count and Hop Distance

Hop count is the measure of number of intermediate nodes between source and destination. In a multihop approach, higher the hop count higher will be the energy consumption and end to end delay. Therefore, it is essential to keep the hop counter smaller to lower the delay and energy consumption.

Similarly, the hop distance is the distance between two neighboring nodes. It is one of the key parameters used to elect the next node in the path. Depending on hop distance, the energy is dissipated therefore smaller the hop distance, less the energy is consumed in delivering the data.

4.2.4 Transmission Range

In WSNs, transmission range has significant impact on various parameters of network. It defines the coverage area of a sensor node. When the range of sensor nodes are large enough to directly send the data to sink using single hop communication, they consume more energy to communicate due to large distance. However, to converse the energy it is essential to keep the transmission power to minimum for which multihop communication is best technique.

Based on this, transmission power control mechanism is implemented to conserve the energy by calculating the power required to send the packet from hop to hop, considering the changing distance between the nodes and receiver's sensitivity. Different transmission range are tested to evaluate its effects on the performance of network and various parameters.

4.3 Simulation Setup

The simulation is carried out by implementing the sensor network in three-dimensional space in MATLAB to depict the underwater environment. The simulation is tested against different variations in parameters and scenarios. Considering the varying distance between neighboring nodes, the energy and propagation model discussed in chapter 3 are simulated to calculate the required power to transmit the packet from one node to another in order to conserve the energy.

Two scenarios are considered for simulation which are Optimal behavior and Pragmatic behavior. The optimal behavior presents the flawless path selection and data delivery during entire simulation time period. Whereas in pragmatic behavior, a temporary failure is introduced with the probability of 0.2 to test and identify the fault tolerance mechanism and its effects on performance metrics.

Each scenario is further implemented for different and same topology. In different topology, new locations are assigned to nodes with increasing network size whereas in same topology, new nodes are added in existing network keeping the previous node locations same. In each case, network size and transmission range are varied to identify the effects of adding additional nodes in the network and optimal range in the multihop communication respectively. The network size, transmission ranges along with other simulation parameters are discussed in table 4.1.

Table 4. 1 Simulation Parameters

Notation	Parameters	Value
-	Simulation Rounds	50
-	Network Area (m)	200*200*200
-	Network Size	50, 60, 70, 80, 90, 100
Rn	Transmission Range(m)	70, 80, 90, 100
SNR	Signal Noise Ratio	20 dB
NL_{SH}	Noise level (Shallow Waters)	70 dB
NL_{DP}	Noise level (Deep Sea)	50 dB
f	Frequency (KHz)	20
BW	Bandwidth (KHz)	4
E_{elec}	Electronics Energy (nJ)	50
E_{amp}	Amplifier Energy (nJ)	0.0013
E_{idle}	Idle State Energy (nJ)	30
T	Temperature (Celsius)	20
S	Salinity(ppt)	34
P_{dl}	Data Packet Length(bytes)	240
P_{H}	HELLO Packet (bytes)	4
P_{INFO}	INFO Packet (bytes)	6
P_{REQ}	Request Packet	4
R	Transmission rate	26.6 Kbps

Considering the literature review [13] [14], the sources of noise in shallow water are shipping activity, seaquakes, wind level etc. Therefore, we consider the value of noise level 70 dB for shallow water and since the deep sea is much quiet than shallow water therefore noise level for deep sea is 50 dB. Also, targeted SNR is 20 dB. Network area defines the 3D space in which nodes are deployed. Based on the depth of sensor nodes in oceans, values for temperature (20 Celsius) and salinity (34 ppt) are chosen based on different researches [2].

4.4 Results

The results for SOSRP are discussed based on topology size, energy consumption, network fault tolerance, network scalability and network start up.

4.4.1 Topology

In this subsection, the behavior of the SOSRP is tested with different network sizes (from 50 to 100 nodes). The parameter chosen has been the End-to-End delay, in two versions: average and maximum (in the longest path). Moreover, another objective related to was how the transmission range affects to the connectivity in the network, so the transmission range was also swept (from 70 m to 100 m).

For each network size, a new random location for the nodes was set, and consequently the ad-hoc topology is different when changes the number of nodes. That's to say, all the simulations with the same network size has the same location for the nodes (topology), whereas the transmission range is changed from 70 to 100 meters.

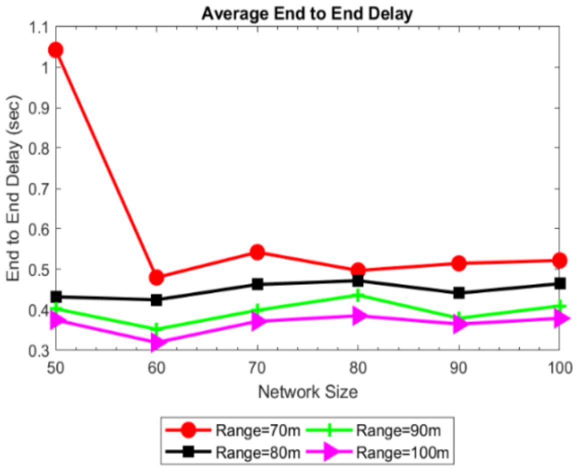


Figure 4.1 Average Delay

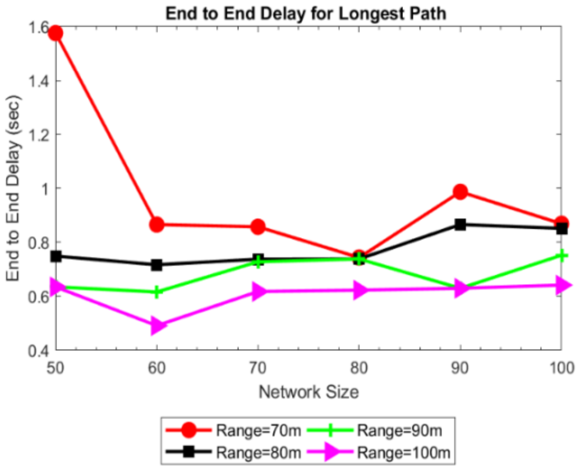


Figure 4.2 End to End Delay for longest Path

The results obtained are shown in Figures 4.1 and 4.2, where a stable operation is kept in the network. In general, when increasing the network size, tends to reduce or keep the end to end delay. This means the new routes are converging to the sink in an efficient way.

Regarding the minimum delay (0.18 sec. approx.) is near constant in every network size because it represents the delay of single hop communication to reach the sink node.

Another evident result is observed when only the transmission range is increased: the delay decreases. The reason is that the coverage area of the nodes is increased which in return decreases the hop count between the source and destination. This effect can be seen in figure 4.2 where delay for longest path is shown: the delay is as high as 1.6 seconds for a network size of 50 nodes and the shortest transmission range (70 meters).

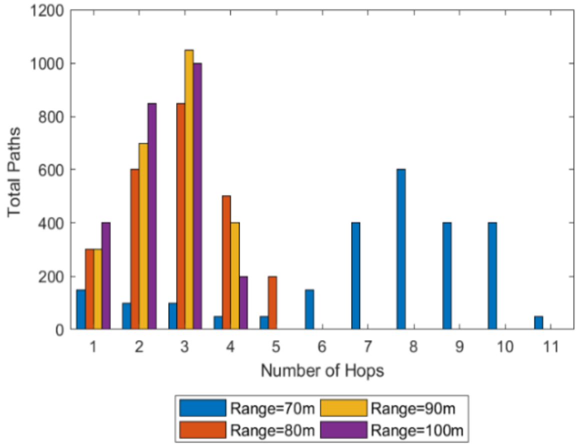


Figure 4.3 Network Size=50 nodes

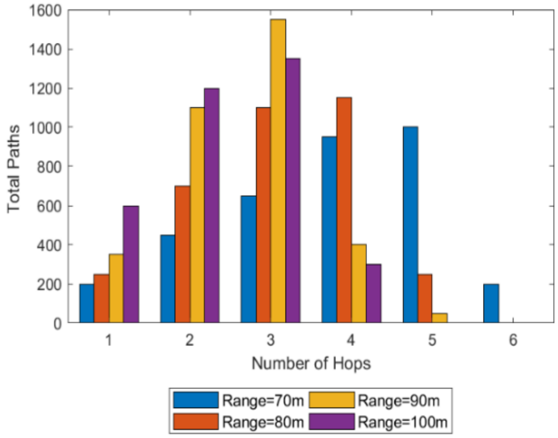


Figure 4.4 Network Size= 70 nodes

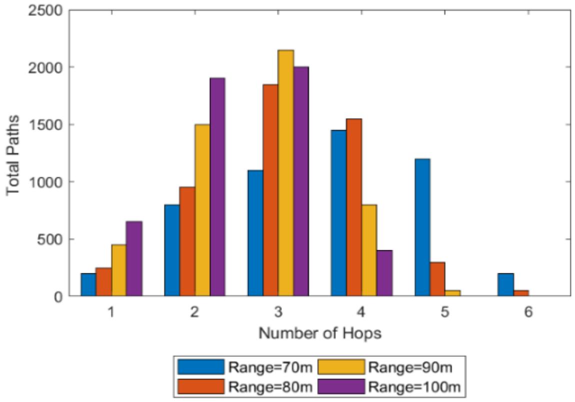


Figure 4.5 Network Size= 100 nodes

Another parameter to measure the efficiency in multi-hop routing protocols is the hop count in a route for packets can reach the sink node. A low number of hops in every route are desirable to keep limited the end to end delay.

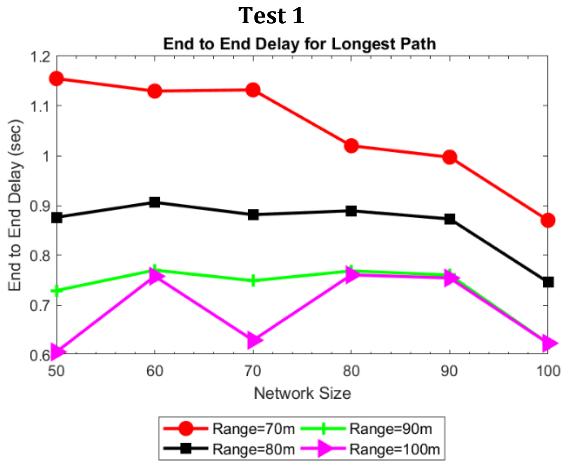


Figure 4.6 E2E delay for Longest path simulation 1

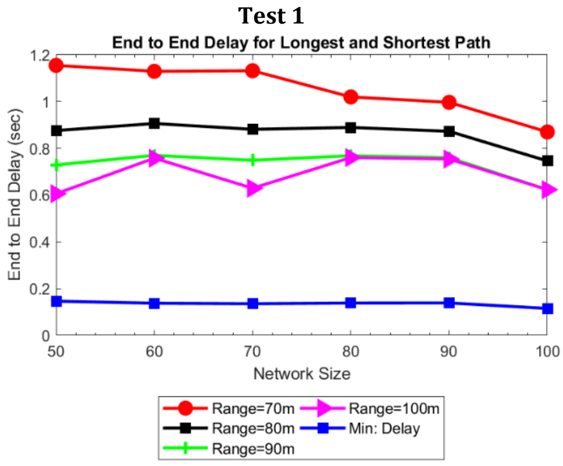


Figure 4.7 E2E for longest and shortest path simulation 1

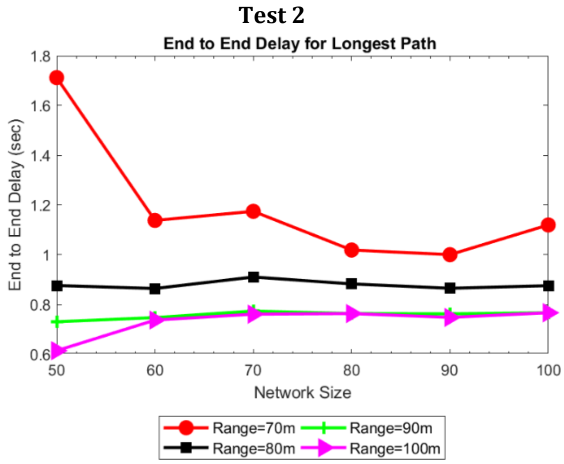


Figure 4.8 E2E delay for Longest path simulation 2

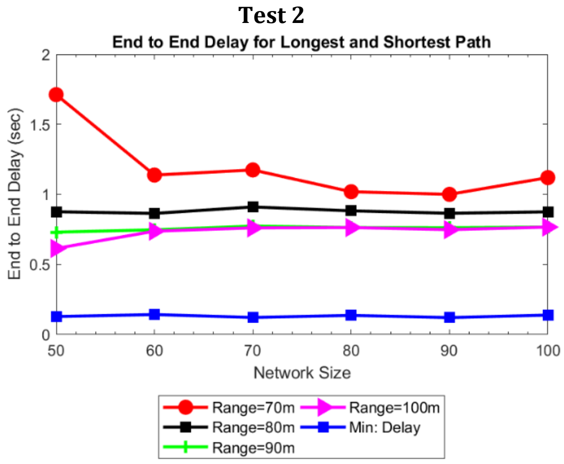


Figure 4.9 E2E for longest and shortest path simulation 2

The results of the simulations are shown in the Figures 4.3 to 4.5. In this set of Figures there is a double interest: to know the number of hops of the routes generated by SOSRP and see the influence of the transmission range in this value. Generally, increasing the transmission range leads to shortest routes (decreasing the hops count). This effect is evident in Figure 4.4.

On the other hand, it must be noted that when the network size changes, new random locations are selected for the nodes, changing the topology. For that reason, the result obtained for one network size is not the same case adding a few nodes. Despite this, the results are consistent with a stable behavior of the SOSRP protocol proposed here.

4.4.2 Energy Consumption

In order to evaluate the results in terms of energy, we must to consider two logical effects. One of them is that as the network size grows, the energy consumption must also increase. The reason is obvious: more nodes are participating in sensing and transmitting data. The second one is related with the transmission range: if increases, the paths to the sink have fewer hops. This fact leads us to reduce the energy employed.

Both effects can be seen in the results presented in Figures 4.10-4.11. The Figure 4.6 calculates the total energy consumption for 50 rounds, in each round 99 nodes send the sensed data to Sink and Figure 4.11 shows energy for only the longest path. The energy consumed for transmit data through longest path in shown in figure 4.11 where maximum energy (2.5 mJ approx.) is consumed for network size 50 nodes and transmission range 70 meters.

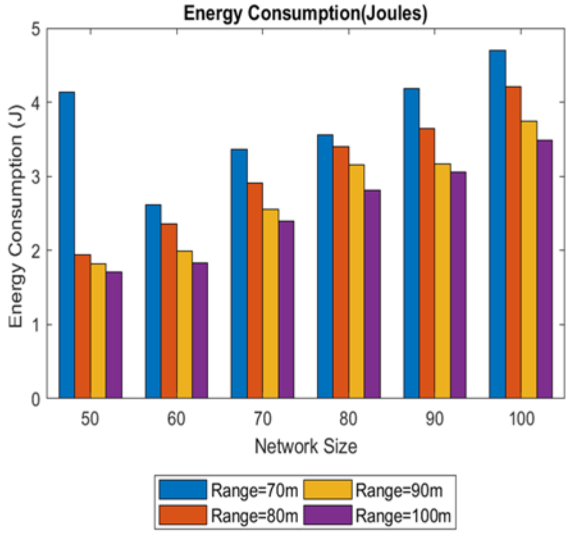


Figure 4.10 Total Energy Consumption in 50 Rounds

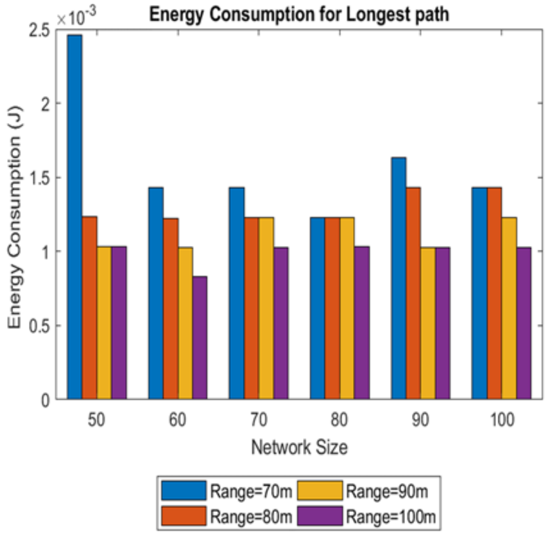


Figure 4.11 Energy Consumption for Longest path

4.4.3 Fault Tolerance

Because of random deployment of nodes, there are N number of neighbors for each node from which source node selects the next forwarder node, thus N number of possible paths leading to Sink. Among the available path, the one with smallest hop count and shortest distance to Sink is consider an optimal path while others are alternate. Alternate path is the best possible route available after optimal path, selected based on the path selection criterion when fault is detected in optimal. To further evaluate the fidelity of SOSRP, a fault probability of 0.2 is realized, to import a fault at random intermediate node in an optimal path. For this purpose, approximately 1000 pragmatic paths were detected with 0.2 probability.

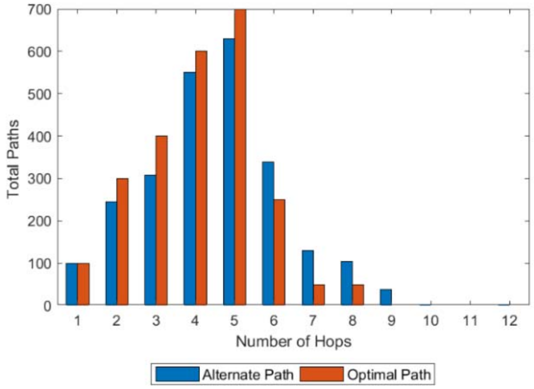


Figure 4.12 Number of hops for network size =50 nodes and Range=70 m in each path

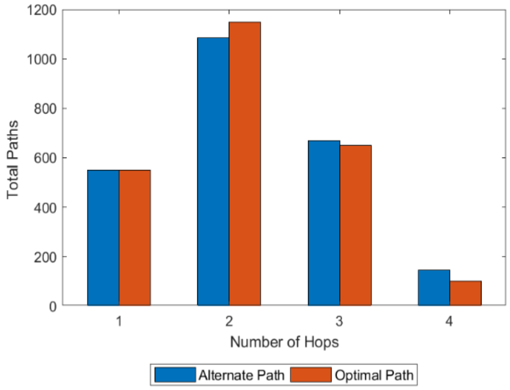


Figure 4.13 Number of hops for network size=50 nodes and Range= 100 m in each path

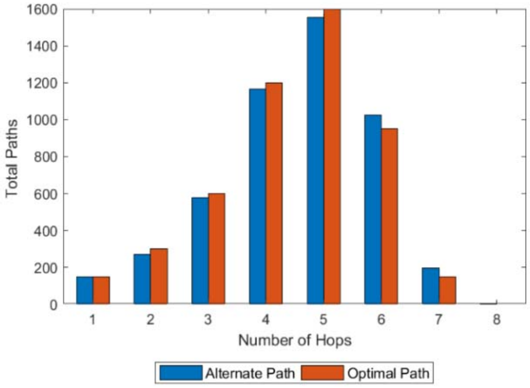


Figure 4.14 Number of hops for network size= 100 nodes and Range= 90 m in each path

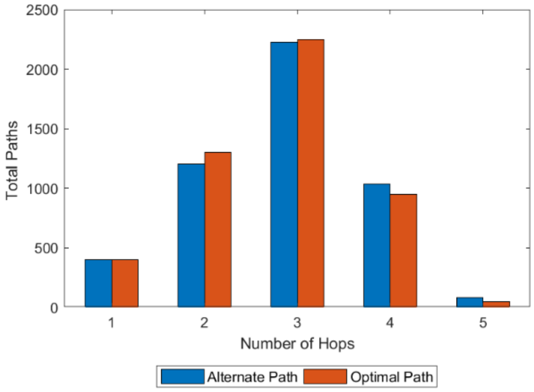


Figure 4.15 Number of hops for network size=100 nodes and Range= 100 m in each path

As previously discussed, in multihop communication it is desirable to keep the hop count minimum in the path to limit the end to end delay and energy consumption. The results obtained compare the total number of paths generated by SOSRP with number of hops in each path for optimal and pragmatic behavior of protocol. The results are shown in Figures 4.12 – 4.15. Figure 4.12 and 4.13 shows the number of hops in the route for network size 50 nodes and Figure 4.14 and 4.15 shows the number of hops for network size 100 nodes, for transmission range of 70 and 100 meters.

It is noticeable from the results, that SOSRP successfully respond to fault detected in the optimal path by selecting a new route to Sink. However, this increases the number of paths with higher hop count thus affecting the end to end delay and energy consumption of network.

This effect can be observed in Figure 4.12 where 50 nodes are deployed with transmission range of 70 meters. The figure shows the influence of transmission range in pragmatic behavior of network, increasing the hops up to 12 in alternate path. Similar, results can be witnessed in Figure 4.14. However, increasing the transmission range to 100 meters eliminated this problem as shown in Figure 4.13 and 4.15 where highest number of hops in both optimal and alternate path is four, where pragmatic behavior causes more routes with higher hop count.

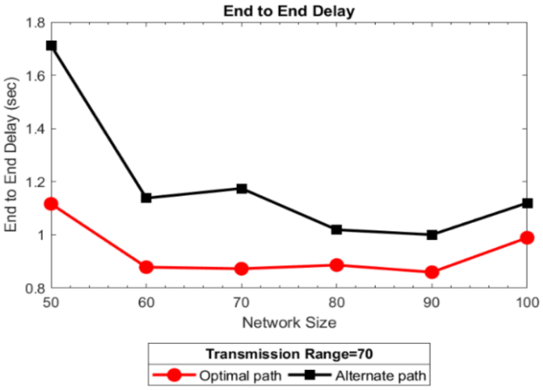


Figure 4.16 End to End Delay for optimal and alternate path, range 70 meters

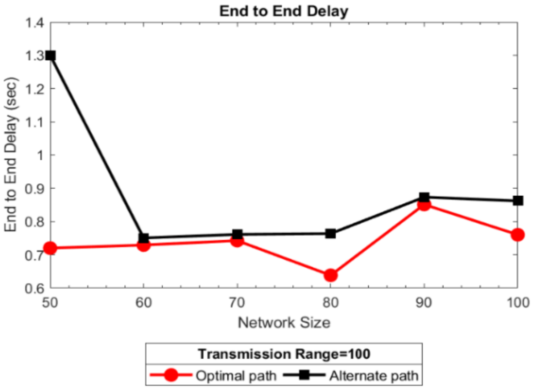


Figure 4.17 E2E for optimal and alternate path, range 100 meters

The results shown in Figures 4.16 and 4.17 depicts end to end delay of optimal and alternate path, for different network size and keeping transmission range 70 and 100 meters respectively. The results show similar behavior of end to end delay in alternate path with respect to optimal path. This effect is evident in Figure 4.16. However, it can be observed that alternate path offers more delay in data transmission compare to optimal path as shown in Figure 4.16 where alternate path offers higher delay (1.7 sec approx.) than optimal path (1.1 sec approx.). Furthermore, increasing the transmission range can mitigate the end to end delay because of reduced number of hops in the newly formed routes. This effect can be observed in Figure 4.17 for transmission range 100 meters, the obtained delay for alternate path is 1.3 sec and 0.7 sec for optimal path approximately which is much lesser than delay observed in Figure 4.16 with transmission range 70 meters.

In order to examine the performance of SOSRP, the percentage of increase for end to end delay and energy consumption is calculated. It is performed by measuring the two parameters for optimal and alternate path. The results obtained are shown in Figures 4.18 and 4.19.

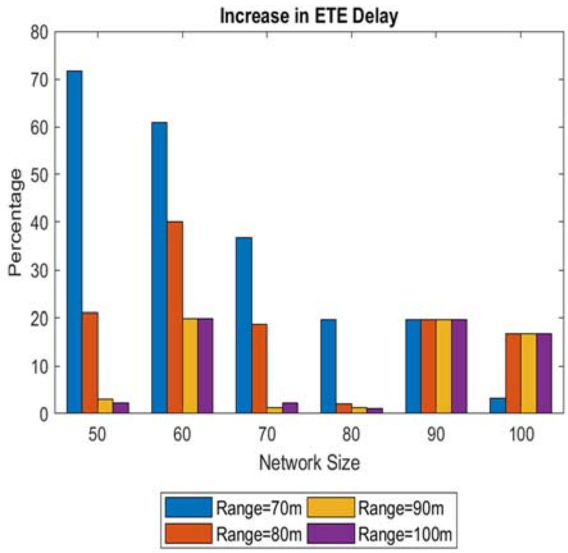


Figure 4.18 Percentage of Increase in Maximum End to End Delay

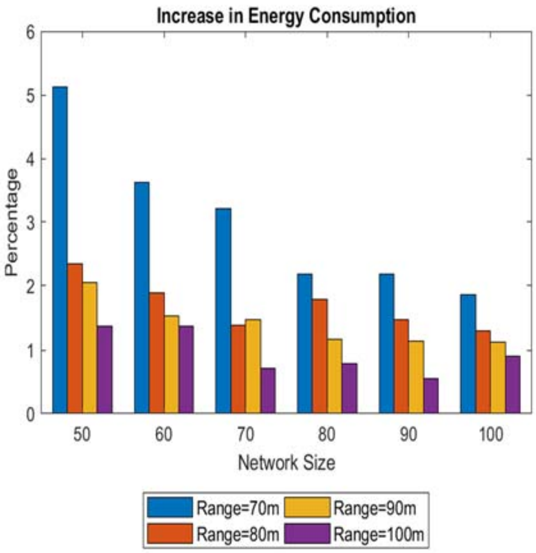


Figure 4.19 Percentage of Increase in Energy Consumption

Figures 4.18 and 4.19 show the percentage of increase in maximum end to end delay and total energy consumption, obtained in pragmatic behavior of protocol. The influence of increasing transmission range and network size is obvious in both figures, considering the reducing percentage of end to end delay and energy consumption. This low increment indicates the proper operation of SOSRP.

4.4.4 Network Scalability

In a real UASN, when it is needed to increase the number of nodes, it would be very expensive and illogical to collect out of water those in service and make a new deployment again one by one until to complete the total number of sensors. Instead of this, a more real task would be to perform a new deployment of only the new nodes needed, keeping the topology of the previous network.

Considering the above discussion, SOSRP is tested for network scalability by deploying the 50 nodes at first and simulated for different ranges (70 to 100 meters). Ten new nodes are randomly added in the network in each simulation, keeping the previous location of deployed nodes. The process repeats until network size reaches 100 nodes. This approach is more realistic and allow each newly deployed node to connect with the network using the local information from neighboring nodes. This decreases the number of operations in the network (e.g. calculating new routes) by keeping the routes stable with minimum changes when few nodes are added in existing network. The stability is noticeable in results shown in Figures 4.20 and 4.21

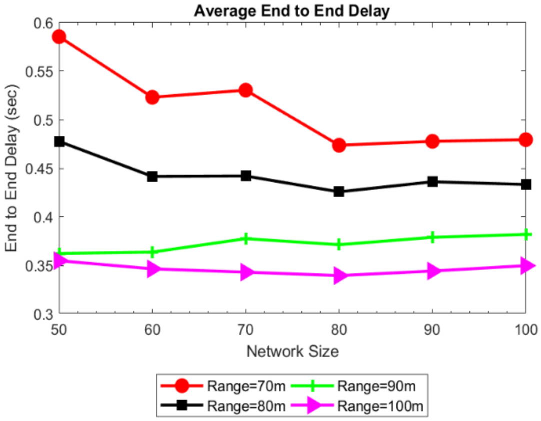


Figure 4. 20 Average Delay

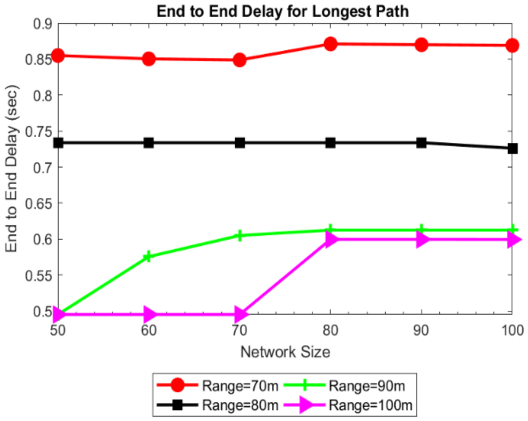


Figure 4. 21 End to End Delay for Longest Path

Figures 4.20 and 4.21 show the outcomes of average and longest path end to end delay. As previously discussed, it is obvious from the figures that with increasing transmission range the end to end delay diminishes because of lower number of hops in the selected route. However, with changing network size there is a slight variation in delay. This stability in delay is observed by preserving the routes stable (previous topology) and newly deployed nodes are within the transmission range of other nodes, keeping the maximum number of hops same as before. This effect can be seen in Figures 4.22 – 4.24.

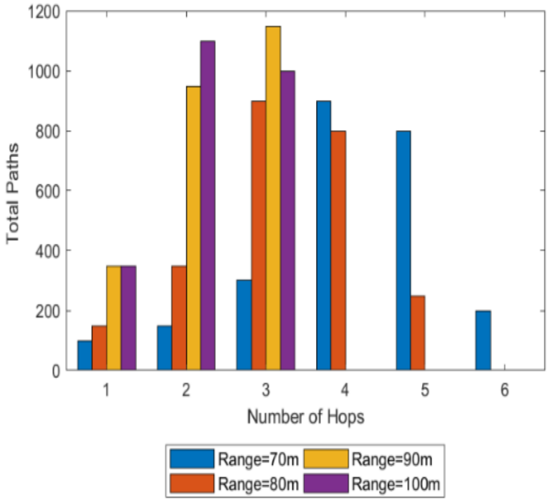


Figure 4.22 Number of hops for network size= 50 nodes in each path for different transmission range.

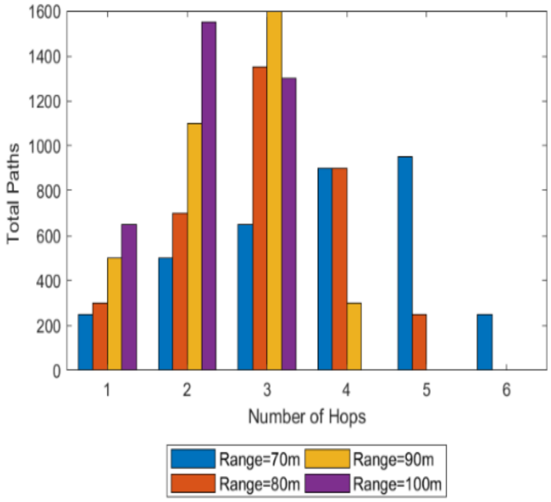


Figure 4. 23 Number of hops for network size= 70 nodes in each path for different transmission range.

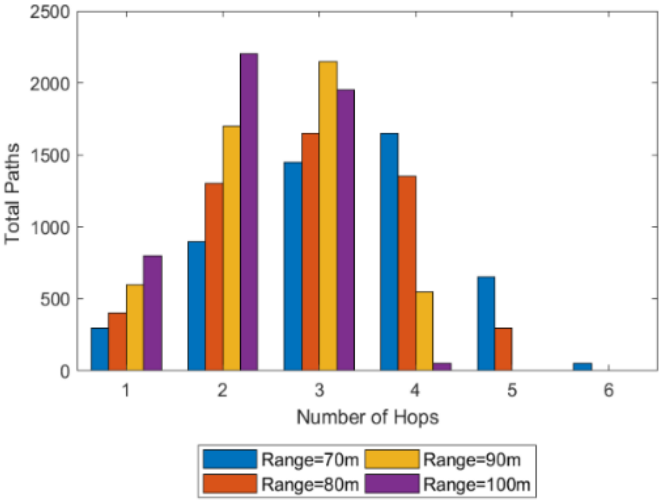


Figure 4. 24 Number of hops for network size= 100 nodes in each path for different transmission range.

The results show the number of hops in all paths generated for different network size (50, 70, 100). It is quite evident from the results that by adding new nodes in the network, the total number of paths is increased because of addition of ten nodes in each run. However, maximum number of hops (max: hops = 6) in any path are same for different network size as shown in Figures 4.22 – 4.24. This proves that performance metrics of SOSRP remains stable irrespective to increasing network size.

Test 1

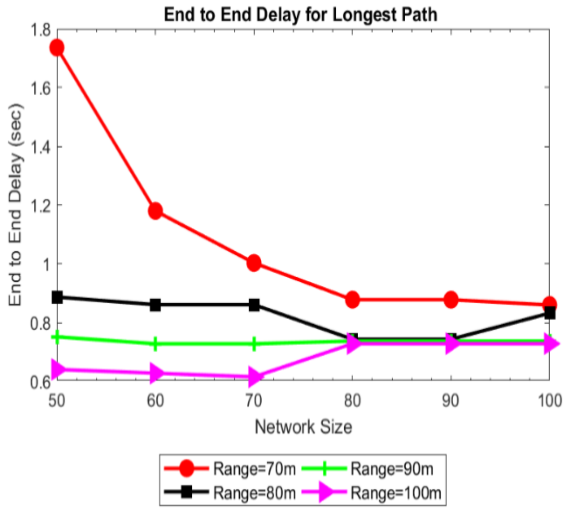


Figure 4. 25 End to End Delay for Longest path simulation 1

Test 2

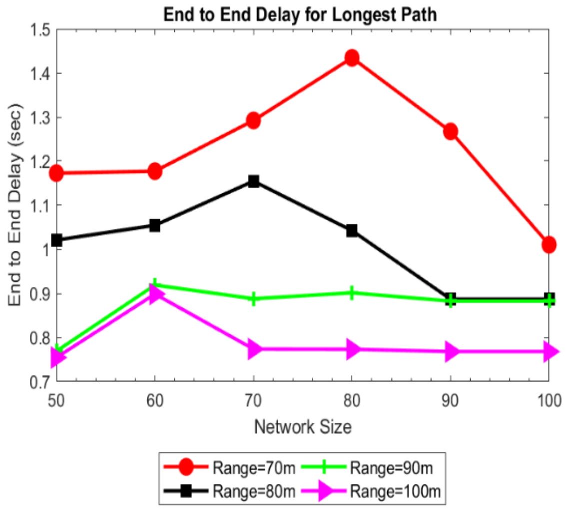


Figure 4. 26 End to End Delay for Longest path simulation 2

In order to validate the observed results, multiple simulations were performed. The result of two simulation: Test 1 and Test 2 are shown in Figures 4.25 and 4.26 for end to end delay obtained in longest path. Comparing the obtained results, it can be seen in figure 4.25 that with increasing network size, the delay for longest path decreases for transmission range 70 meters. An opposite effect can be observed in figure 4.26, where delay is increasing up to network size 80 nodes, keeping the transmission range 70 meters. It is because of random placement of new nodes, increasing the number of hops in the route selected. However, the maximum longest path delay obtained in test 2 (1.5 sec approx.) is still less than maximum delay in test 1. The stability is obtained in longest path delay by increasing the transmission range. The effect is noticeable in results for different transmission ranges (80, 90 and 100).

4.4.5 Network Start up

It is important to consider the energy consumption in network startup operations because a lot of energy is consumed in initialization processes due to higher number of transmissions of control packet by maximum number of nodes. Therefore, it is essential to avoid the unnecessary energy consumption during these processes by controlling the information required in initialization.

To conserve the energy in such phases, SOSRP is designed to connect the nodes with surrounding network with limited local information from neighboring nodes. The SOSRP, nodes are initialized through HELLO packet (contains sender ID, hop count) broadcasted by sink node in the transmission region. The packet is rebroadcasted by each node until it reaches the last node in the network. After initialization, nodes broadcast a request packet in the coverage area, in response each neighboring node send an INFO packet based on which node generates the routing table. To calculate the energy consumption in startup operation of SOSRP, transmission range is kept constant that is 100 meters, packet size for HELLO and Request packet is 4 bytes (32 bits) and INFO packet is 6 bytes (48 bits). The energy consumption is calculated using equation 2 and 4 for transmission and reception respectively and considered as constant for all nodes in the network. The energy consumption for transmission and reception of control packet is shown in Figure 4.27.

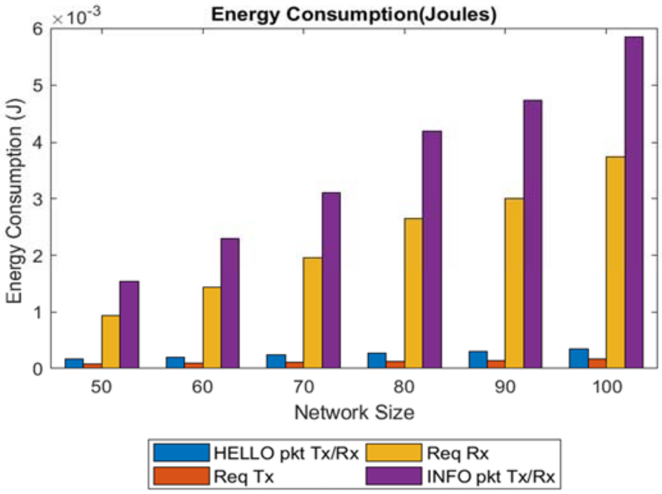


Figure 4.27 Energy Consumption in HELLO, Request message and INFO packet transmission and reception

The results show that more energy is consumed in receiving the request and info packet during neighbor discovery phase because of more nodes receiving the packet upon request of single node.

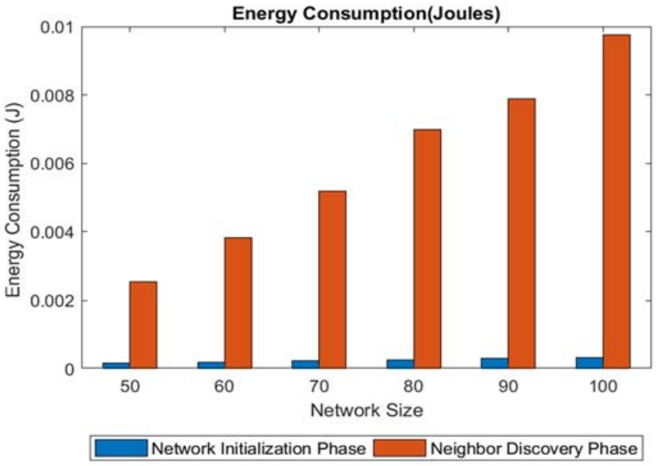


Figure 4. 28 Energy Consumption in Network Initialization and Neighbor Discovery Phase

Figure 4.28 show the energy consumption in network initialization and neighbor discovery phase. It can be observed that neighbor discovery consumes more energy compare to network initialization phase. However, the accumulated energy consumed is in milli joules which is much less compare to flooding mechanism proposed in previous work.

4.5 Summary

To analyze the performance of SOSRP, performance metrics are defined which end to end delay, energy consumption, hop count, hop distance and transmission range. The chosen metrics plays an important in determining the reliability of any protocol. Simulation parameters are discussed (e.g. Target SNR, Noise level, temperature etc.) based on which the results for SOSRP are obtained in MATALB. The protocol is tested against varying network size and transmission range, for optimal and pragmatic behavior to identify their effect on the performance metrics. The obtained results show that performance metrics are improved with increasing transmission range. However, energy consumption is increased with network size because of more nodes participating. In short, the protocol remains stable in optimal and pragmatic nature by providing a balance in performance metrics.

Chapter 5. Conclusion and Future Work

With the advancement in the field of wireless communication and sensor technology, new techniques and protocols are proposed for UASNs. These kinds of networks have become popular among researchers because of applications such as disaster prevention, ocean exploration and resource discovery. Different centralized and distributed network routing approaches are proposed by researchers to make the communication efficient in underwater.

In this thesis, using the concept of decentralized network a Self-organizing and Scalable routing protocol (SOSRP) is proposed where each node form a local connectivity based on the information acquired from the neighboring nodes and performing the data transmission. The protocol utilizes multihop communication technique to transmit the sensed data to the sink node. Each node formulates the routing table using control packets broadcasted in initialization and neighbor discovery phase and path selection is based on the information of hop count and distance to base station (sink node) from the transmitting node. MATLAB platform is used to simulate the protocol along with proper energy and propagation model for acoustic communication to contemplate the undersea conditions. The performance of protocol is measured against end to end delay, energy consumption and number of hops in the path by varying network size and transmission range for optimal and pragmatic behavior of SOSRP. Through different simulations, it is found that an optimal transmission range and network size can improve the performance of protocol by decreasing the number of hops in the generated path. The results show that SOSRP provides stable operation, scalability, fault tolerance and isolation detection for UASNs.

Future Work

Following are some areas for future research:

1. **Clustering:** In WSNs, clustering is most widely used technique to mitigate the energy dissipation. Perhaps, it might be beneficial to examine the clustering in SOSRP.
2. **Multi-path Routing:** As previously discussed, SOSRP selects the optimal path from the various available possibilities in path selection phase based on smallest hop count and shortest distance between source and sink. This feature can further be explored by changing the path selection criteria which will provide source node an opportunity to select the route based on defined routing metric such congestion, residual energy, delay, etc.
3. **Node Mobility:** It is known fact that oceans are not steady, nodes deployed in undersea are in constant motion due to ocean currents and anomality, unless anchored properly. This movement of nodes can lead to link breakage and requires frequent route rediscoveries. Therefore, it is an important parameter to consider in analyzing the performance of SOSRP with mobile nodes.
4. **Throughput:** In a real operation, every node must avoid transmitting at time that can causing interferences to other communications. This effect has not been considered in this work. A scheduling of transmissions and receptions can be added in order to realize interference free communications while increasing the throughput in the network, by means of performing as number of transmissions as possible.

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Self-Organizing and Scalable Routing Protocol for UASNs

Dated: 12 Feb 2019 SUGGESTED CORRECTIONS

PAGE	LINE	READS NOW	SHOULD BE
10	26	Figure 2.2 [22] shows the network architecture of LEACH.	Figure 2.2 [20] shows the network architecture of LEACH.
11	2	In [20], a new clustering algorithm is proposed	In [17], a new clustering algorithm is proposed
11	11	In [19], the author has compared the direct communication	In [16], the author has compared the direct communication
11	16	In [21], the author compared LEACH	In [18], the author compared LEACH
12	8	EBLE [28] considers both energy efficiency and balancing in the protocol design.	EBLE [25] considers both energy efficiency and balancing in the protocol design.
13	4	EAVARP operates in two phases: layering and data collection phase [29].	EAVARP operates in two phases: layering and data collection phase [26].
13	15	which significantly affect the packet delivery ratio [30] [31].	which significantly affect the packet delivery ratio [27] [28].
13	16	energy-reliability trade off, SORP is proposed [32].	energy-reliability trade off, SORP is proposed [29].
13	25	protocol is proposed in [33],	protocol is proposed in [30],
14	8	In BEEC [34] routing protocol, a circular field is divided	In BEEC [7] routing protocol, a circular field is divided
14	20	increase the packet loss at sink [34].	increase the packet loss at sink [32].
14	21	2.3[39] shows the example of VBF	[36] shows the example of VBF
14	22	through remodeling VBF in [35]	through remodeling VBF in [32]
15	6	The protocol [36] utilizes the interference aware technique	The protocol [33] utilizes the interference aware technique
15	15	In [38], the proposed protocol routes the data based on its priority	In [35], the proposed protocol routes the data based on its priority
16	9	Figure 2.4 [40] represents an example of forwarder	Figure 2.4 [37] represents an example of forwarder
16	14	In [37], proposed protocol combines DBR	In [34], proposed protocol combines DBR
17	4	In [40], Energy Efficient DBR (EEDBR) is	In [37], Energy Efficient DBR (EEDBR) is
30	12	The route failure is further discussed in section 3.3.2. Figure 3.9	The route failure is further discussed in section 3.3.2. Figure 3.10
33	7	Figure 3.6 shows an example of path recovery	Figure 3.11 shows an example of path recovery
34	12	Figure 3.7 shows the example of isolation recognition	Figure 3.12 shows the example of isolation recognition
40	2	Considering the literature review [13] [14],	Considering the literature review [12] [13],