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TESIS DOCTORAL

Energy-Efficient Routing Protocols for Ad Hoc Underwater Sensor Networks

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AUTORIZACIÓN DE LOS DIRECTORES DE TESIS DOCTORAL

El alumno del Programa de Doctorado en Ingeniería de Telecomunicación, Jitander Kumar, es primer o segundo autor de las siguientes publicaciones en revistas indexadas en los *Journal Citation Reports* (JCR) del *Web of Science* (WoS):

- **Kumar, J.**; Luque-Nieto, M.-Á.; Hyder, W.; Otero, P. Energy-Efficient Packet Forwarding Scheme Based on Fuzzy Decision-Making in Underwater Sensor Networks. *Sensors* **2021**, *21*, 4368. https://doi.org/10.3390/s21134368.

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Estas publicaciones avalan su tesis doctoral y ninguna otra tesis.

Por todo ello, su tutor y director de tesis Dr. Pablo Otero y su codirector de tesis Dr. Miguel Ángel Luque Nieto autorizan al Sr. Kumar a depositar su tesis doctoral ante las Autoridades académicas de la Universidad de Málaga.

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Abstract

Underwater Wireless Sensor Networks (UWSNs) is emerging technology that includes environmental monitoring, disaster monitoring, underwater search operations, protection of submarines, military applications, tsunamis, man-made disasters, etc. Compared to TWSN (Terrestrial Wireless Sensor Networks) which can be operated using electromagnetic waves (EM waves) for communication, for UWSNs electromagnetic waves are not a suitable choice because of higher absorption rates and EM cannot travel in water more than fewer meters. Thus, acoustic waves are a fitting choice for communication in UWSNs because they can travel a longer distance in the water, but acoustic waves travel slower than EM waves. The speed of acoustic waves in water is around 1500 m/s while the speed of EM waves is approximately 3x108 m/s. In addition, underwater communication suffers from major factors like localization, channel utilization, routing issues, and environmental effects.

The behavior of underwater acoustic channels is affected by multiple factors like sound velocity, multipath fading, channel noise, transmission loss, and bandwidth capacity. Due to the low propagation speeds of acoustic waves, the phenomenon of propagation delay occurs which is a natural phenomenon, but end-to-end (E2E) delay can be reduced. As a result, underwater communication suffers from several delays which can be significant for time-critical applications and can cause increased collisions between the packets and decrease the throughput. In this regard, the routing protocols play an important role in reducing delays and increasing the network lifetime. The node failure requires re-route which can significantly affect the performance of the networks. Hence, several routing protocols are proposed for UWSNs' communication. Some of the routing strategies include opportunistic routing, energy-efficient routing, location-based routing, location-free routing, cluster-based routing protocol, etc. The two types of routing protocols are reactive routing protocols and proactive routing protocols. Reactive routing protocols are on-demand protocols. Reactive routing protocols support dynamic environments but are not suitable for UWSN because of higher delays in route creation. On the other hand, the proactive routing protocols are table driven, these protocols are low latency because nodes already know where a packet must be forwarded based on routing information stored hence forwarding delay is short in proactive routing protocols.

The best routing protocol is chosen based on stability (ability to support stability in varying network conditions), Fault Tolerance (network ability to transfer data in case of failure), Secure route identification (ability to select the optimal routes among available routes), Precision and simplicity (ability to transfer packets productivity), Performance matrices (hops, cost, distance, throughput, and latency). There are multiple design constraints for underwater sensor network routing protocols such as battery lifetime, traffic and security, scalability and integrity, link delays which consist of processing and propagation delays, link reliability, energy consumption, memory, and CPU (Central Processing Unit). Underwater communication uses several network topologies at each layer like the physical layer, medium access layer (responsible for resource sharing), and network layer (responsible for routing and transport). As mentioned earlier that EM waves are not suitable for UWSN communication because water absorbs almost all electromagnetic frequencies which makes acoustic waves a suitable choice for

UWSN. Acoustic wave propagation in the frequency range of interest is depicted in many phases. The first stage is attenuation which occurs due to distance or power loss when a signal travels from one location to another over distance d. The second phase is the surface reflection which includes reflection, and refraction that causes the speed of sound to change with depth. The third stage is large-scale changes in the received signal due to variations in propagation medium e.g. (tides). Multipath propagation causes multiple copies of the same signal to arrive with various delays and delay spreading depends upon the system location. Large-scale variations affect power control at the transmitter, which as a result affects the designing of adaptive signal processing algorithms at the receiver. Therefore, physical layer aspects are essential for acoustic signal processing. The second is the medium access layer The medium access layer is of extreme importance to sharing the communication resources in an efficient manner among the participating nodes. Since the frequency spectrum is shared in wireless networks the need to properly manage interference is very important.

While designing resource-sharing schemes for underwater communication the acoustic channel characteristics need to be considered. Signals can be separated either into time and frequency TDMA (Time Division Multiple Access) and FDMA (Frequency Division Multiple Access) respectively. In FDMA signal division is achieved in the frequency domain but they may overlap in time causing the interference phenomenon to occur. By employing guard bands channel separation can be minimized but FDMA becomes less flexible because of inefficient utilization of the resources. TDMA is a time division where users take the turns to access the medium so that signals do not overlap in time and thus interference is avoided. TDMA is more flexible, but the problem is it requires synchronization so that users can utilize the disjoint time slots. To cope with these medium access techniques, the concept of CDMA (Code division multiple access) was introduced in which signal exists in both time and frequency and can be separated by using unique codes, but it requires bandwidth extension. CDMA with a power control mechanism is proposed for underwater networks. The advantage of CDMA is it does not require synchronization and it is good for multipath fading environments. These media access protocols are designed to lessen energy consumption through sleep modes. Contention-based protocols are used to decide when a node must share the data over a shared medium or channel. Thus, techniques like ALOHA, CSMA (Carrier Sense Multiple Access), and CSMA/CA (Carrier Sense Multiple Access with collision avoidance) are used to avoid collision among nodes. It is particularly important to avoid unnecessary collisions and packet retransmission to avoid delays. In large networks, it is impossible for pair of nodes to communicate directly, and it is called single hop operation. Therefore, the need for intermediate nodes (multi-hop operation) is of utter importance and is used to forward information toward the destination. In this scenario, routing protocols perform a crucial role in deciding the variable route a packet should follow through the network topology. During a node failure phase, the packet takes an alternate route causing the network topology to change.

There is so much research done on energy efficiency in underwater sensor networks to minimize energy consumption. Such methods are available but routing design for underwater networks is still active. The literature focuses on routing protocols which include location-based routing protocols, location-free routing protocols, RSS-based routing protocols, opportunistic routing protocols, cluster-based protocols, energy efficient protocols, reliable data delivery protocols, etc. In this view of routing protocol, we have proposed two energy-efficient packet routing schemes based on fuzzy decision-making in Underwater sensor networks. Fuzzy logic is multi-valued logic that provides an approximate result rather than an exact result like 0 and 1 in Boolean algebra. Fuzzy logic looks like the human decision-making approach, it deals with unprecise and ambiguous information. The ability of fuzzy logic extends over and above conventional networks and can be applied to numerous research areas such as quality control, statistics, and optimization techniques enabling different approaches and performance enhancements.

Fuzzy logic has been employed in UWSNs to improve decision-making, minimize resource consumption, and typically improve performance via efficient deployment, localization, clustering, CH election, routing, data aggregation, security, and so forth. Real-world problems are usually based on truth or false or in other words degree of truth like Boolean logic which works on two outcomes, 0 represents false and 1 represents true. But fuzzy logic works in a different way it considers the degree of truth. Fuzzy logic considers all the values between o and 1. The number which indicates the value is called the truth value in the fuzzy systems. Fuzzy logic also called fuzzy inference system consists of mainly three stages. Fuzzifier, Fuzzy Inference engine, and Defuzzifier. In the first step, the input variable is used to map the values using the membership function to the real interval [0,1]. A fuzzy inference engine provides a basis for decision-making. It is rule-based (IF-THEN). The system output is a real number in the range [0,1] which is obtained by defuzzification techniques to describe the linguistic terms. Linguistic terms or variables consist of a scale that describes chances. E.g., Very good, good, excellent, fair, poor, etc. The advantage of the fuzzy system is it can work with any type of input, precise or unprecise, noisy, or distorted. Fuzzy systems can solve complex problems because they match human decision-making and reasoning. The disadvantage of fuzzy systems is it works on both unprecise and precise types of data making the accuracy of the outcome to be compromised.

Fuzzy logic is used with neural networks for decision-making or how a person would make decisions. It combines data and changes it to expressive data to form partial truths as a fuzzy set. Fuzzy Logic - Decision Making involves various types of decision-making. Individual decision-making, multi-person decision-making, multi-objective decision-making, and multi-attribute decision-making. Since the decision is to be defined as the set of alternatives, the steps for decision-making involve determining the alternatives, evaluating alternatives, comparing between alternatives, and finally choosing one of the alternatives which best suits. Fuzzy logic is chosen because it is widely in applications such as neural networks, aerospace, automotive, defense, business, electronics, finance, industrial sector, manufacturing, marine, medical applications, securities, transportation, pattern classification and recognition, and in psychology for human behavior. Thus, in UWSNs making a decision among sensor nodes to be chosen as relay node or forwarding node is very important and decision-making using fuzzy systems is one of the main components. In the future, neural networks can be used for UWSNs, and they can be augmented with artificial intelligence so that nodes can learn the data patterns and decide automatically which node will have the right to forward the packet.

Keeping in mind the above advantages of the fuzzy systems and their decision-making capabilities, we have used fuzzy logic to select the forwarding node or relay node which can send the data to the GW.

The relay node is chosen based on the crisp value obtained from the defuzzification process and linguistic variable. Multiple variants of the Analytical hierarchy used in the research include Chang's extent analysis method, The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), the cost optimization method, and the Fuzzy extended AHP. Fuzzy AHP is one of the variants of the classical AHP method. AHP is not suitable for some of the decision-making processes for example it is difficult for a decision-maker to choose between numbers 4 and 6 instead of using the number 5. Thus, FAHP functions well and removes imprecision in the AHP method. FAHP is a combination of fuzzy logic with an analytical hierarchy process. The proposed research methods are used to achieve energy efficiency in comparison with several existing research techniques.

The selection of a forwarding node or relay node becomes important in UWSNs because the nodes are close and far from the GW node, The node which is away from the GW will need more power or number of hops to reach the gateway, and due to the fact that sensor node has limited battery capabilities that can cause node failure, delay, retransmissions, re-route and changes in the network topology. the need for the election of a sensor node becomes very important. Not only are the distance parameters taken into account while selecting the relay node, but many input parameters need to be taken into the selection process of a node to be the head node. The main parameters include the distance from the sink node, the number of hops or jump to reach the gateway node, the number of neighbors, transmission range, and node density. The proposed research also takes these parameters as multi-criteria to achieve energy efficiency. There are two major objectives for selecting these parameters because the goal is either for delay-sensitive applications or energy efficiency. For the delay-sensitive application, fewer hops will have much weightage, and if energy conservation is the most important goal, then the fewest number of neighbors and RSS will have much weightage compared to hop count.

Several methods have been considered in the selection of a relay node. Existing research suggests various methods. A node with high residual energy will be considered a relay node. However, the residual energy is not only the parameter to be considered. The node which is closer to the GW node is to be selected as the head node. Some schemes consider both residual energy and distance while selecting the forwarder node. Some consider the location of a node and the remaining energy level.
Some scheme selects Relay Node (RN) by considering node density in the cluster, shortest distance node selection as forwarding node, and RN communication range as threshold distance for the next RN selection. The mechanisms or techniques used are different for the selection of the forwarding node. Research suggests techniques like fuzzy logic, optimization techniques, and if-else decision-making. To select the best relay node, we have used the concept of fuzzy logic with input parameters number of hops, the number of neighbors, and distance (based on RSS). Since distance is not the only parameter that can be used to achieve energy efficiency rather a selection of multiple input parameters will be much more valuable. The fuzzy logic consists of output changes in form of a scale starting from very best, best, far better, better, good, fair, bad, and worse. In the proposed scheme the relay node is selected if the number of hops is less, the number of neighbors is less and the distance is also less from the GW, then the chances of a node being selected as a relay node are very best. These input parameters are defined in linguistic terms like the number of hops (minimum, average, maximum), the number of neighbors (minimum, average, maximum), and distance (near, close, far) as used in the fuzzification

process, the next step is the decision making and finally, the defuzzification value will select the best node. The node with the highest weight or defuzzification score will act as a relay or forwarding node.

The following indicators will be utilized to evaluate the proposed scheme: number of hops, number of neighbors, and RSSI. Furthermore, various transmission ranges have been considered to evaluate the system's energy performance consumption, as well as the average number of hops. UWSNs usually consume energy due to network operations such as data processing, gathering, forwarding, and receiving. As a result, the total energy consumption is the energy dissipated by these node actions. The number of hops refers to intermediate nodes that a packet must visit to reach the destination which is the gateway. This parameter has a direct relationship with the distance, which is the third indicator, obtained from the RSSI. Distance is related to energy consumption. Received Signal Strength (RSS) is measured to estimate the distance between the nodes. When the nodes are close to each other the RSS value is high and when they are far away RSS value is low. Due to the law of transmission power proportional to the square of the distance, multi-hop communication is preferred. Nevertheless, the energy used in a node for receiving and processing a message, and not for transmission, might modify this criterion. However, the larger the number of hops, the larger the end-to-end delay. The Number of neighbors is the second indicator that selects the forwarding node. This indicator is a measure of the priority of selecting the forwarding node. The lower number of neighbors implies a greater chance of a node being selected as a forwarding node. The objective of this thesis is to improve the energy efficiency of a UWSN routing protocol, which also helped to reduce the number of hops and, consequently, the end-to-end delay.

The contributions of the work are (i) the use of fuzzy inference to select the forwarding node to form the path, (ii) the set of rules that form the logic of the fuzzy inference, and (iii) the effect of the transmission range on the number of hops to reach the gateway and on the average energy consumption. The fuzzy inference has been implemented in MATLAB®. The input variables to the fuzzy logic algorithm are the distance (through RSS value), number of neighbors, and number of hops. The introduction of relay nodes in sensor networks results in a prolonged lifetime as they can remove some burden from the overloaded nodes. The relay nodes may also shorten the transmission distance between a pair of distantly located nodes by acting as a hop between them. In general, similar to the sensor nodes, relay nodes are also battery-operated devices capable of wireless communication. On the other hand, some others have suggested that the relay node should be of higher capabilities than the sensor nodes in terms of initial energy provisioning, transmission range, and data processing (data gathering, data aggregation) capability. Higher capability relay nodes are mainly suggested in cluster-based sensor networks, where higher energy provisioned relay nodes take the role of cluster heads. Self-Organized Proactive Routing Protocol for Non-Uniformly Deployed Underwater Networks (SPRINT) is one of the techniques which selects the forwarding node based on weights assigned without any specific method, the weights are just assumed. In the proposed method we find out the weight of the input based on fuzzy logic by using membership functions as discussed above. In this thesis, we have provided an enhancement of the existing SPRINT protocol which does not require any location information which results in reducing the cost of extra hardware or no additional device is needed. SPRINT is meant to accomplish high data throughput whilst using little energy in the nodes. Throughout wireless networks, there is a compromise between throughput and energy consumption. Longer links need more energy to operate. The number of relay nodes or hops between the source node and the final destination node, on the other hand, is an important factor that impacts the throughput. Similarly, every hop adds to the delay in packet forwarding and, accordingly, reduces throughput. As a result, for energy consumption, the closest nodes must be preferred as forwarding nodes, while for throughput, the farthest node must be chosen to minimize the number of hops. SPRINT is a multi-layer, self-organizing, proactive protocol that does not require positioning equipment to determine the location. Considering the facts used in the SPRINT protocol to select the forwarding node, the proposed scheme used relay nodes/intermediate nodes/forwarding nodes to forward the data. Thus, out of many sensors node, the decision is to be made.

In the proposed scheme we have used the concept of fuzzy logic and defuzzification to get the weights of the nodes and the sensor node with the highest weight will be selected as the relay node. The weights are obtained by using hops, neighbors, and distance. These parameters have an impact on the throughput and energy consumption in the UWSN. The usage of the weighting scheme has reduced the delay as compared to SPRINT and RECRP (Reliable Energy-Efficient Cross-Layer Routing Protocol in UWSNs) techniques. The fuzzy inference has been implemented in MATLAB and results show that the energy efficiency obtained from the fuzzy logic scheme finds paths with fewer hops and lower energy consumption compared to the SPRINT protocol which consequently reduces the energy consumed by the sensor node thus battery life can be enhanced by using an appropriate routing scheme. In addition to obtaining energy efficiency using fuzzy logic, a variant of fuzzy logic is used in the form of the FAHP. The new results obtained from FAHP are path length, number of collisions, E2E delay, and energy consumption. When compared to SPRINT-FUZZY with FAHP results it is evident that FAHP performs much better because it is a multi-criteria scheme. The future of the routing scheme and decision-making can be extended using more fuzzy branches like fuzzy neural networks and artificial intelligence so that sensor nodes can make self-decision using the input parameters chosen. Machine learning, AI, and IoUT (Internet of Underwater Things) can be used in future works for better self-decision-making of underwater sensor nodes and networks.

In this thesis, the selection of a relay node is reviewed above. The selection of CH is discussed below. Clustering can be employed in sensor networks to improve scalability and network lifetime. Every cluster generally has a head node identified as the Cluster head. A cluster head can be selected from the cluster nodes. The cluster head may be a member of a large cluster. The cluster heads are responsible for the aggregation of data from the sensor nodes in that cluster and then forwards to the GW node. The lifetime of sensor nodes and cluster heads has a direct impact on network ability therefore the lifetime of a sensor node and a CH must be considered separately. For instance, in case of a sensor node failure, the network deteriorates from the failure of sensing offered by that single node. However, if the CH fails all of the cluster's main sensor nodes become unavailable from the rest of the network. Accordingly, additional measures may be required to ensure the cluster head nodes have a high lifetime. The benefits of clustering are highly energy efficient. The cumulative information is sent directly by CH to BS which reduces the number of broadcast nodes. Thus, CH only connects with the base station and not with any other non-CH nodes. The network becomes highly scalable dissimilar to a traditional network having no clusters. In addition, the use of a TDMA scheme with clustering can reduce the packet collision and thus reduce packet retransmission time which reduces E2E delay thus battery life is extended. If there are numerous contenders for the next forwarding CH, the CH with the highest RSS will be chosen. If the distance is equal, the CH with the fewest hops will be chosen. If there are the same number of hops, the CH with the highest leftover energy will be chosen. In addition to finding the next forwarding CH, the formation of a cluster is another essential process. The formation of a cluster is also a continuous process due to the continuous random movement of the AUV nodes. Since both processes of finding the forwarding CH and cluster formation, are continuous and simultaneous, we need the CHs to be able to communicate with the OSNs and the other CHs simultaneously. This requires the CHs to be equipped with two modems communicating at different frequencies. The BCN packets will be received by the randomly moving OSNs as well and they will estimate their distance from a CH by computing the RSS of the BCN packets. The CH with a larger RSS value will be selected as the CH by an OSN.

The formation of a cluster is another essential process. The creation of a cluster is also a continuous process due to the continuous random movement of the AUV nodes. Since both processes of finding the forwarding CH and cluster formation, are continuous and simultaneous, we need the CHs to be able to communicate with the OSNs and the other CHs simultaneously. This requires the CHs to be equipped with two modems communicating at different frequencies. The BCN packets will be received by the randomly moving OSNs as well and they will estimate their distance from a CH by computing the RSS of the BCN packets. The CH which will have a larger value of the RSS will be selected as the CH by an OSN. The CHs will also indicate to OSNs whether they have established a forwarding path. The OSNs will send their data packets only when they will receive a Ready to Receive (RTR) packet from the CH. This will save the energy of the OSNs by refraining from transmitting the data packets, which will be discarded by the CHs if the forwarding path has not been established. In case of collision, the packet will be lost. Therefore, the OSNs will send the data to the CHs at randomly selected timeslots to avoid collision at the CHs. However, a collision may occur if two nodes have the same timeslot, and are at an equal distance from the CH. There is another possible scenario of data collision where two nodes are at different distances from the CH but send their packets such that the packets arrive at the same time at CH. The results of the SOAM protocol are obtained from MATLAB.

The simulated network is based on autonomous randomly moving sensor nodes and CHs, and a stationary GW node on the surface of the sea. Results show the average throughput for the various number of nodes. There is no clear behavior to predict the throughput with the change in the number of OSNs or CHs. Throughput is higher at few OSNs as compared to more OSNs. This makes sense because the queue delay at cluster heads is low due to a fewer number of packets. Average PDR also has got no clear relationship with the increase in the number of OSNs. In a static network, we expect to have better PDR with the increase in the number of nodes. However, in the case of a fully ad hoc network, this is not the case because of the random movement of the CHs. P-AUV is compared with SOAM in terms of end-to-end delay and packet delivery ratio. It is obtained that SOAM has a larger delay because it is a cluster-based protocol and to avoid collision the nodes select time slots randomly to send the packet. The PDR results of the comparison between SOAM and P-AUV show no clear advantage of SOAM over P-AUV. However, a comparison of the routing methods shows that SOAM has some advantages over P-AUV in two ways. First is that, unlike P-AUV, there is no requirement for location assertion in SOAM. P-AUV nodes must be aware of their location at the time of deployment and during the operation as well. However, SOAM is a location-free routing protocol and requires no additional sensors. Thus, it is evident from the results obtained that energy efficiency and minimum end-end delay are obtained by using proposed schemes as compared to existing routing protocols available in the literature.

Resumen

Las redes de sensores inalámbricos submarinos (UWSN) son tecnologías emergentes que incluyen monitoreo ambiental, monitoreo de desastres, operaciones de búsqueda submarina, protección de submarinos, aplicaciones militares, tsunamis, desastres provocados por el hombre, etc. En comparación con TWSN (redes de sensores inalámbricos terrestres) que pueden operarse utilizando ondas electromagnéticas (ondas EM) para la comunicación, para UWSN las ondas electromagnéticas no son una opción adecuada debido a las tasas de absorción más altas y EM no puede viajar en el agua más de menos metros. Por lo tanto, las ondas acústicas son una opción adecuada para la comunicación en UWSN porque pueden viajar una distancia más larga en el agua, pero el problema con las ondas acústicas es que viajan más lentamente en comparación con las ondas EM. La velocidad de las ondas acústicas en el agua es de alrededor de 1500 m / s, mientras que la velocidad de las ondas EM es de aproximadamente 3x108 m / s. Además, la comunicación submarina sufre de factores importantes como la localización, la utilización del canal, los problemas de enrutamiento y los efectos ambientales. El comportamiento de los canales acústicos submarinos se ve afectado por múltiples factores como la velocidad del sonido, el desvanecimiento multitrayecto, el ruido del canal, la pérdida de transmisión y la capacidad de ancho de banda. Debido a las bajas velocidades de propagación de las ondas acústicas, se produce el fenómeno del retraso de propagación, que es un fenómeno natural, pero el retraso de extremo a extremo (E2E) se puede reducir. Como resultado, la comunicación submarina sufre de varios retrasos que pueden ser significativos para aplicaciones de tiempo crítico y pueden causar un aumento de las colisiones entre los paquetes y disminuir el rendimiento. En este sentido, los protocolos de enrutamiento juegan un papel importante en la reducción de los retrasos y el aumento de la vida útil de la red. La falla del nodo requiere redireccionamiento, lo que puede afectar significativamente el rendimiento de las redes. Por lo tanto, se proponen varios protocolos de enrutamiento para la comunicación de UWSN. Algunas de las estrategias de enrutamiento incluyen enrutamiento oportunista, enrutamiento energéticamente eficiente, enrutamiento basado en la ubicación, enrutamiento sin ubicación, protocolo de enrutamiento basado en clústeres, etc. Los dos tipos de protocolos de enrutamiento son los protocolos de enrutamiento reactivo y los protocolos de enrutamiento proactivo. Los protocolos de enrutamiento reactivo son protocolos bajo demanda. Los protocolos de enrutamiento reactivo admiten entornos dinámicos, pero no son adecuados para UWSN debido a los mayores retrasos en la creación de rutas. Por otro lado, los protocolos de enrutamiento proactivo están controlados por tablas, estos protocolos son de baja latencia porque los nodos ya saben dónde se debe reenviar un paquete en función de la información de enrutamiento almacenada, por lo tanto, el retraso de reenvío es corto en los protocolos de enrutamiento proactivo. El mejor protocolo de enrutamiento se elige en función de la estabilidad (capacidad de admitir estabilidad en condiciones de red variables), tolerancia a fallos (capacidad de la red para transferir datos en caso de falla), identificación de ruta segura (capacidad de seleccionar las rutas óptimas entre las rutas disponibles), precisión y simplicidad (capacidad de transferir paquetes de productividad), matrices de rendimiento (saltos, costo, distancia, rendimiento y latencia). Existen múltiples restricciones de diseño para los protocolos de enrutamiento de redes de sensores submarinos, como la vida útil de la batería, el tráfico y la seguridad, la escalabilidad y la integridad, los retrasos de enlace que consisten en retrasos de procesamiento y propagación, la confiabilidad del enlace, el consumo de energía, la memoria y la CPU

(Unidad Central de Procesamiento). La comunicación subacuática utiliza varias topologías de red en cada capa, como la capa física, la capa de acceso medio (responsable del intercambio de recursos) y la capa de red (responsable del enrutamiento y el transporte). Como se mencionó anteriormente, las ondas EM no son adecuadas para la comunicación UWSN porque el agua absorbe casi todas las frecuencias electromagnéticas, lo que hace que las ondas acústicas sean una opción adecuada para UWSN. La propagación de ondas acústicas en el rango de frecuencia de interés se representa en muchas fases. La primera etapa es la atenuación que ocurre debido a la distancia o pérdida de potencia cuando una señal viaja de un lugar a otro a través de la distancia d. La segunda fase es la reflexión superficial que incluye la reflexión y la refracción que hace que la velocidad del sonido cambie con la profundidad. La tercera etapa son los cambios a gran escala en la señal recibida debido a variaciones en el medio de propagación, por ejemplo, (mareas). La propagación multitrayecto hace que lleguen varias copias de la misma señal con varios retrasos y la propagación del retardo depende de la ubicación del sistema. Las variaciones a gran escala afectan el control de potencia en el transmisor, lo que como resultado afecta el diseño de algoritmos de procesamiento de señal adaptativos en el receptor. Por lo tanto, los aspectos de la capa física son esenciales para el procesamiento de señales acústicas. La segunda es la capa de acceso medio La capa de acceso medio es de extrema importancia para compartir los recursos de comunicación de manera eficiente entre los nodos participantes. Dado que el espectro de frecuencias se comparte en las redes inalámbricas, la necesidad de gestionar adecuadamente la interferencia es muy importante. Al diseñar esquemas de intercambio de recursos para la comunicación submarina, se deben considerar las características del canal acústico. Las señales se pueden separar en tiempo y frecuencia TDMA (*Time Division Multiple Access*) y FDMA (*Frequency Division Multiple Access*) respectivamente. En FDMA la división de señales se logra en el dominio de la frecuencia, pero pueden superponerse en el tiempo causando que ocurra el fenómeno de interferencia. Mediante el empleo de bandas de protección, se puede minimizar la separación de canales, pero FDMA se vuelve menos flexible debido a la utilización ineficiente de los recursos. TDMA es una división de tiempo donde los usuarios se turnan para acceder al medio para que las señales no se superpongan en el tiempo y así se evite la interferencia. TDMA es más flexible, pero el problema es que requiere sincronización para que los usuarios puedan utilizar las franjas horarias disjuntas. Para hacer frente a estas técnicas de acceso al medio, se introdujo el concepto de CDMA (acceso múltiple por división de código) en el que la señal existe tanto en tiempo como en frecuencia y se puede separar mediante el uso de códigos únicos, pero requiere extensión de ancho de banda. Se propone CDMA con un mecanismo de control de potencia para redes submarinas. La ventaja de CDMA es que no requiere sincronización y es bueno para entornos de desvanecimiento de múltiples rutas. Estos protocolos de acceso a medios están diseñados para disminuir el consumo de energía a través de los modos de suspensión. Los protocolos basados en contención se utilizan para decidir cuándo un nodo debe compartir los datos a través de un medio o canal compartido. Por lo tanto, se utilizan técnicas como ALOHA, CSMA (*Carrier Sense Multiple Access*) y CSMA / CA (*Carrier Sense Multiple Access* con prevención de colisiones) para evitar la colisión entre nodos. Es particularmente importante evitar colisiones innecesarias y la retransmisión de paquetes para evitar retrasos. En redes grandes, es imposible que un par de nodos se comuniquen directamente, y se llama operación de salto único. Por lo tanto, la necesidad de nodos intermedios (operación multisalto) es de suma importancia y se utiliza para enviar información hacia el destino. En este escenario, los protocolos de enrutamiento desempeñan un papel crucial para decidir la ruta variable que debe seguir un paquete a través de la topología de red.

Durante una fase de error de nodo, el paquete toma una ruta alternativa que hace que la topología de red cambie.

Se han realizado muchas investigaciones sobre la eficiencia energética en redes de sensores submarinos para minimizar el consumo de energía. Tales métodos están disponibles, pero el diseño de enrutamiento para redes submarinas todavía está activo. La literatura se centra en los protocolos de enrutamiento que incluyen protocolos de enrutamiento basados en la ubicación, protocolos de enrutamiento sin ubicación, protocolos de enrutamiento basados en RSS, protocolos de enrutamiento oportunistas, protocolos basados en clústeres, protocolos de eficiencia energética, protocolos de entrega de datos confiables, etc. En esta visión del protocolo de enrutamiento, hemos propuesto dos esquemas de enrutamiento de paquetes energéticamente eficientes basados en la toma de decisiones difusa en redes de sensores submarinos. La lógica difusa es una lógica multivalor que proporciona un resultado aproximado en lugar de un resultado exacto como 0 y 1 en álgebra booleana. La lógica difusa se parece al enfoque humano de toma de decisiones, trata con información imprecisa y ambigua. La capacidad de la lógica difusa se extiende más allá de las redes convencionales y se puede aplicar a numerosas áreas de investigación, como el control de calidad, las estadísticas y las técnicas de optimización que permiten diferentes enfoques y mejoras de rendimiento. La lógica difusa se ha empleado en las UWSN para mejorar la toma de decisiones, minimizar el consumo de recursos y, por lo general, mejorar el rendimiento a través de una implementación eficiente, localización, agrupación en clústeres, elección de CH, enrutamiento, agregación de datos, seguridad, etc. Los problemas del mundo real generalmente se basan en la verdad o falso o, en otras palabras, en el grado de verdad como la lógica booleana que funciona en dos resultados, 0 representa falso y 1 representa verdadero. Pero la lógica difusa funciona de una manera diferente, considera el grado de verdad. La lógica difusa considera todos los valores entre o y 1. El número que indica el valor se llama valor de verdad en los sistemas difusos. La lógica difusa también llamada sistema de inferencia difusa consta principalmente de tres etapas. *Fuzzifier*, motor de inferencia difusa y *defuzzifier*. En el primer paso, la variable de entrada se utiliza para asignar los valores utilizando la función de pertenencia al intervalo real [0,1]. Un motor de inferencia difusa proporciona una base para la toma de decisiones. Se basa en reglas (IF-THEN). La salida del sistema es un número real en el rango [0,1] que se obtiene mediante técnicas de *desfuzzificación* para describir los términos lingüísticos. Los términos o variables lingüísticas consisten en una escala que describe las posibilidades. Por ejemplo, muy bueno, bueno, excelente, regular, pobre, etc. La ventaja del sistema difuso es que puede trabajar con cualquier tipo de entrada, precisa o imprecisa, ruidosa o distorsionada. Los sistemas difusos pueden resolver problemas complejos porque coinciden con la toma de decisiones y el razonamiento humanos. La desventaja de los sistemas difusos es que funciona tanto en tipos de datos imprecisos como precisos, lo que compromete la precisión del resultado. La lógica difusa se utiliza con redes neuronales para la toma de decisiones o cómo una persona tomaría decisiones. Combina datos y los cambia a datos expresivos para formar verdades parciales como un conjunto difuso. Lógica difusa - La toma de decisiones implica varios tipos de toma de decisiones. Toma de decisiones individual, toma de decisiones de múltiples personas, toma de decisiones multiobjetivo y toma de decisiones de múltiples atributos. Dado que la decisión debe definirse como el conjunto de alternativas, los pasos para la toma de decisiones implican determinar las alternativas, evaluar alternativas, comparar entre alternativas y, finalmente, elegir una de las alternativas que mejor se adapte. La lógica difusa se elige porque es ampliamente en aplicaciones tales como redes neuronales, aeroespacial, automotriz, defensa, negocios, electrónica, finanzas, sector industrial, fabricación, marina, aplicaciones médicas, valores, transporte, clasificación y reconocimiento de patrones, y en psicología para el comportamiento humano. Por lo tanto, en los UWSN tomar una decisión entre los nodos sensores para ser elegidos como nodo de retransmisión o nodo de reenvío es muy importante y la toma de decisiones utilizando sistemas difusos es uno de los componentes principales. En el futuro, las redes neuronales se pueden usar para UWSN, y se pueden aumentar con inteligencia artificial para que los nodos puedan aprender los patrones de datos y decidir automáticamente qué nodo tendrá derecho a reenviar el paquete. Teniendo en cuenta las ventajas anteriores de los sistemas difusos y sus capacidades de toma de decisiones, hemos utilizado la lógica difusa para seleccionar el nodo de reenvío o nodo de retransmisión que puede enviar los datos al GW. El nodo de relé se elige en función del valor nítido obtenido del proceso de *defuzzificación* y la variable lingüística. Las múltiples variantes de la jerarquía analítica utilizadas en la investigación incluyen el método de análisis de extensión de Chang, la técnica para el orden de preferencia por similitud con la solución ideal (TOPSIS), el método de optimización de costos y el AHP extendido difuso. El AHP difuso es una de las variantes del método clásico del AHP. AHP no es adecuado para algunos de los procesos de toma de decisiones, por ejemplo, es difícil para un tomador de decisiones elegir entre los números 4 y 6 en lugar de usar el número 5. Por lo tanto, FAHP funciona bien y elimina la imprecisión en el método AHP. FAHP es una combinación de lógica difusa con un proceso de jerarquía analítica. Los métodos de investigación propuestos se utilizan para lograr la eficiencia energética en comparación con varias técnicas de investigación existentes.

La selección de un nodo de reenvío o nodo de retransmisión se vuelve importante en los UWSN porque los nodos están cerca y lejos del nodo GW, El nodo que está lejos del GW necesitará más potencia o número de saltos para llegar a la puerta de enlace, y debido al hecho de que el nodo sensor tiene capacidades limitadas de batería que pueden causar fallas en el nodo, Retraso, retransmisiones, redireccionamiento y cambios en la topología de la red. La necesidad de la elección de un nodo sensor se vuelve muy importante. No solo se tienen en cuenta los parámetros de distancia al seleccionar el nodo de retransmisión, sino que muchos parámetros de entrada deben tenerse en cuenta en el proceso de selección de un nodo para que sea el nodo principal. Los parámetros principales incluyen la distancia desde el nodo receptor, el número de saltos o saltos para llegar al nodo de puerta de enlace, el número de vecinos, el rango de transmisión y la densidad del nodo. La investigación propuesta también toma estos parámetros como criterios múltiples para lograr la eficiencia energética. Hay dos objetivos principales para seleccionar estos parámetros porque el objetivo es para aplicaciones sensibles al retraso o eficiencia energética. Para la aplicación sensible al retraso, menos lúpulos tendrán mucho peso, y si la conservación de energía es el objetivo más importante, entonces el menor número de vecinos y RSS tendrá mucho peso en comparación con el recuento de lúpulo.

Se han considerado varios métodos en la selección de un nodo de retransmisión. La investigación existente sugiere varios métodos. Un nodo con alta energía residual se considerará un nodo de retransmisión. Sin embargo, la energía residual no es el único parámetro a considerar. El nodo que está más cerca del nodo GW debe seleccionarse como nodo principal. Algunos esquemas consideran tanto la energía residual como la distancia al seleccionar el nodo reenviador. Algunos consideran la ubicación de un nodo y el nivel de energía restante.

Algunos esquemas seleccionan el nodo de retransmisión (RN) considerando la densidad de nodos en el clúster, la selección de nodo de distancia más corta como nodo de reenvío y el rango de comunicación RN como distancia umbral para la siguiente selección de RN. Los mecanismos o técnicas utilizados son diferentes para la selección del nodo de reenvío. La investigación sugiere técnicas como lógica difusa, técnicas de optimización y toma de decisiones si-no. Para seleccionar el mejor nodo de retransmisión, hemos utilizado el concepto de lógica difusa con parámetros de entrada, número de saltos, número de vecinos y distancia (basado en RSS). Dado que la distancia no es el único parámetro que se puede utilizar para lograr la eficiencia energética, una selección de múltiples parámetros de entrada será mucho más valiosa. La lógica difusa consiste en cambios de salida en forma de una escala que comienza desde "lo mejor" y sigue "mucho mejor", "mejor", "bueno", "justo", "malo" y "peor". En el esquema propuesto, el nodo de retransmisión se selecciona si el número de saltos es menor, el número de vecinos es menor y la distancia también es menor desde el GW, entonces las posibilidades de que un nodo sea seleccionado como nodo de retransmisión son muy buenas. Estos parámetros de entrada se definen en términos lingüísticos como el número de saltos (mínimo, promedio, máximo), el número de vecinos (mínimo, promedio, máximo) y la distancia (cerca, cerca, lejos) como se usa en el proceso de *fuzzificación*, el siguiente paso es la toma de decisiones y, finalmente, el valor de *defuzzificación* seleccionará el mejor nodo. El nodo con el peso más alto o puntuación de desactivación actuará como un nodo de relé o reenvío. Se utilizarán los siguientes indicadores para evaluar el esquema propuesto: número de saltos, número de vecinos y RSSI. Además, se han considerado varios rangos de transmisión para evaluar el consumo de rendimiento energético del sistema, así como el número promedio de saltos. Los UWSN generalmente consumen energía debido a las operaciones de red, como el procesamiento, la recopilación, el reenvío y la recepción de datos. Como resultado, el consumo total de energía es la energía disipada por estas acciones de nodo. El número de saltos se refiere a los nodos intermedios que un paquete debe visitar para llegar al destino que es la puerta de enlace. Este parámetro tiene una relación directa con la distancia, que es el tercer indicador, obtenido del RSSI. La distancia está relacionada con el consumo de energía. La intensidad de la señal recibida (RSS) se mide para estimar la distancia entre los nodos. Cuando los nodos están cerca uno del otro, el valor RSS es alto y cuando están lejos, el valor RSS es bajo. Debido a la ley de potencia de transmisión proporcional al cuadrado de la distancia, se prefiere la comunicación multisalto. Sin embargo, la energía utilizada en un nodo para recibir y procesar un mensaje, y no para la transmisión, podría modificar este criterio. Sin embargo, cuanto mayor sea el número de saltos, mayor será el retraso de extremo a extremo. El Número de vecinos es el segundo indicador que selecciona el nodo de reenvío. Este indicador es una medida de la prioridad de seleccionar el nodo de reenvío. El menor número de vecinos implica una mayor probabilidad de que un nodo sea seleccionado como nodo de reenvío. El objetivo de esta tesis es mejorar la eficiencia energética de un protocolo de enrutamiento UWSN, que también ayudó a reducir el número de saltos y, en consecuencia, el retraso de extremo a extremo. Las contribuciones del trabajo son (i) el uso de inferencia difusa para seleccionar el nodo de reenvío para formar la ruta, (ii) el conjunto de reglas que forman la lógica de la inferencia difusa, y (iii) el efecto del rango de transmisión en el número de saltos para llegar a la puerta de enlace y en el consumo promedio de energía. La inferencia difusa se ha implementado en MATLAB. ® Las variables de entrada al algoritmo de lógica difusa son la distancia (a través del valor RSS), el número de vecinos y el número de saltos. La introducción de nodos de retransmisión en las redes de sensores da como resultado una vida útil prolongada, ya que pueden eliminar parte de la carga de los nodos sobrecargados. Los nodos de retransmisión también pueden acortar la distancia de transmisión entre un par de nodos ubicados a distancia actuando como un salto entre ellos. En general, al igual que los nodos sensores, los nodos de relé también son dispositivos que funcionan con baterías capaces de comunicarse de forma inalámbrica. Por otro lado, algunos otros han sugerido que el nodo de retransmisión debería tener capacidades más altas que los nodos del sensor en términos de aprovisionamiento inicial de energía, rango de transmisión y capacidad de procesamiento de datos (recopilación de datos, agregación de datos). Los nodos de relé de mayor capacidad se sugieren principalmente en redes de sensores basadas en clústeres, donde los nodos de relé con mayor aprovisionamiento de energía desempeñan el papel de cabezas de clúster. El protocolo de enrutamiento proactivo autoorganizado para redes submarinas desplegadas de manera no uniforme (SPRINT) es una de las técnicas que selecciona el nodo de reenvío en función de los pesos asignados sin ningún método específico, los pesos se asumen. En el método propuesto descubrimos el peso de la entrada basado en lógica difusa mediante el uso de funciones de membresía como se discutió anteriormente. En esta tesis, hemos proporcionado una mejora del protocolo SPRINT existente que no requiere ninguna información de ubicación, lo que resulta en la reducción del costo de hardware adicional o no se necesita ningún dispositivo adicional. SPRINT está destinado a lograr un alto rendimiento de datos mientras usa poca energía en los nodos. A través de las redes inalámbricas, existe un compromiso entre el rendimiento y el consumo de energía. Los enlaces más largos necesitan más energía para funcionar. El número de nodos de retransmisión o saltos entre el nodo de origen y el nodo de destino final, por otro lado, es un factor importante que afecta el rendimiento. Del mismo modo, cada salto aumenta el retraso en el reenvío de paquetes y, en consecuencia, reduce el rendimiento. Como resultado, para el consumo de energía, se deben preferir los nodos más cercanos como nodos de reenvío, mientras que, para el rendimiento, se debe elegir el nodo más lejano para minimizar el número de saltos. SPRINT es un protocolo multicapa, autoorganizado y proactivo que no requiere equipo de posicionamiento para determinar la ubicación. Teniendo en cuenta los hechos utilizados en el protocolo SPRINT para seleccionar el nodo de reenvío, el esquema propuesto utilizó nodos de retransmisión/nodos intermedios/nodos de reenvío para reenviar los datos. Por lo tanto, de muchos sensores nodo, la decisión debe tomarse. En el esquema propuesto hemos utilizado el concepto de lógica difusa y *desfuzzificación* para obtener los pesos de los nodos y el nodo sensor con el mayor peso será seleccionado como nodo de relé. Los pesos se obtienen mediante el uso de lúpulo, vecinos y distancia. Estos parámetros tienen un impacto en el rendimiento y el consumo de energía en el UWSN. El uso del esquema de ponderación ha reducido el retraso en comparación con las técnicas SPRINT y RECRP (*Reliable Energy-Efficient Cross-Layer Routing Protocol in UWSNs*). La inferencia difusa se ha implementado en MATLAB y los resultados muestran que la eficiencia energética obtenida del esquema de lógica difusa encuentra rutas con menos saltos y menor consumo de energía en comparación con el protocolo SPRINT, lo que reduce la energía consumida por el nodo sensor, por lo que la duración de la batería se puede mejorar mediante el uso de un esquema de enrutamiento adecuado. Además de obtener eficiencia energética utilizando lógica difusa, se utiliza una variante de lógica difusa en forma de FAHP. Los nuevos resultados obtenidos de FAHP son la longitud de la trayectoria, el número de colisiones, el retardo E2E y el consumo de energía. Cuando se compara con SPRINT-FUZZY con los resultados de FAHP, es evidente que FAHP funciona mucho mejor porque es un esquema multicriterio. El futuro del esquema de enrutamiento y la toma de decisiones se puede ampliar utilizando ramas más difusas como redes neuronales difusas e inteligencia artificial para que los nodos de sensores puedan tomar decisiones por sí mismos utilizando los parámetros de entrada elegidos. El aprendizaje automático, la IA y IoUT (*Internet of Underwater Things*) se pueden utilizar en trabajos futuros para una mejor toma de decisiones de nodos y redes de sensores submarinos.

En esta tesis, la selección de un nodo de retransmisión se revisa anteriormente. La selección de CH se discute a continuación. La agrupación en clústeres se puede emplear en redes de sensores para mejorar la escalabilidad y la vida útil de la red. Cada clúster generalmente tiene un nodo principal identificado como el jefe del clúster. Se puede seleccionar un cabezal de clúster de los nodos del clúster. La cabeza del clúster puede ser miembro de un clúster grande. Los cabezales de clúster son responsables de la agregación de datos de los nodos de sensores en ese clúster y luego los reenvían al nodo GW. La vida útil de los nodos sensores y los cabezales de clúster tiene un impacto directo en la capacidad de la red, por lo tanto, la vida útil de un nodo sensor y un CH debe considerarse por separado. Por ejemplo, en caso de falla de un nodo sensor, la red se deteriora por la falla de detección ofrecida por ese único nodo. Sin embargo, si el CH falla, todos los nodos principales del sensor del clúster dejan de estar disponibles en el resto de la red. En consecuencia, es posible que se requieran medidas adicionales para garantizar que los nodos principales del clúster tengan una vida útil alta. Los beneficios de la agrupación son altamente eficientes energéticamente. La información acumulada es enviada directamente por CH a BS, lo que reduce el número de nodos de difusión. Por lo tanto, CH solo se conecta con la estación base y no con ningún otro nodo que no sea CH. La red se vuelve altamente escalable a diferencia de una red tradicional que no tiene clústeres. Además, el uso de un esquema TDMA con agrupamiento puede reducir la colisión de paquetes y, por lo tanto, reducir el tiempo de retransmisión de paquetes, lo que reduce el retraso de E2E, por lo que se extiende la vida útil de la batería. Si hay numerosos contendientes para el próximo CH de reenvío, se elegirá el CH con el RSS más alto. Si la distancia es igual, se elegirá el CH con menos saltos. Si hay el mismo número de lúpulos, se elegirá el CH con la mayor energía sobrante. Además de encontrar el siguiente CH de reenvío, la formación de un clúster es otro proceso esencial. La formación de un clúster también es un proceso continuo debido al movimiento aleatorio continuo de los nodos AUV. Dado que ambos procesos de búsqueda del CH de reenvío y formación de clústeres son continuos y simultáneos, necesitamos que los CH puedan comunicarse con los OSN y los otros CH simultáneamente. Esto requiere que los CH estén equipados con dos módems que se comuniquen a diferentes frecuencias. Los paquetes BCN también serán recibidos por los OSN que se mueven aleatoriamente y estimarán su distancia desde un CH calculando el RSS de los paquetes BCN. El CH con un valor RSS mayor será seleccionado como CH por un OSN.

La formación de un clúster es otro proceso esencial. La creación de un clúster también es un proceso continuo debido al movimiento aleatorio continuo de los nodos AUV. Dado que ambos procesos de búsqueda del CH de reenvío y formación de clústeres son continuos y simultáneos, necesitamos que los CH puedan comunicarse con los OSN y los otros CH simultáneamente. Esto requiere que los CH estén equipados con dos módems que se comuniquen a diferentes frecuencias. Los paquetes BCN también serán recibidos por los OSN que se mueven aleatoriamente y estimarán su distancia desde un CH calculando el RSS de los paquetes BCN. El CH que tendrá un valor mayor del RSS será seleccionado como CH por un OSN. Los CH también indicarán a los OSN si han establecido una ruta de reenvío. Los OSN enviarán sus paquetes de datos solo cuando reciban un paquete listo para recibir (RTR) del

CH. Esto ahorrará la energía de los OSN al abstenerse de transmitir los paquetes de datos, que serán descartados por los CH si no se ha establecido la ruta de reenvío. En caso de colisión, el paquete se perderá. Por lo tanto, los OSN enviarán los datos a los CH en intervalos de tiempo seleccionados al azar para evitar colisiones en los CH. Sin embargo, una colisión puede ocurrir si dos nodos tienen el mismo intervalo de tiempo, y están a la misma distancia del CH. Existe otro posible escenario de colisión de datos donde dos nodos están a diferentes distancias del CH pero envían sus paquetes de tal manera que los paquetes llegan al mismo tiempo al CH. Los resultados del protocolo SOAM se obtienen de MATLAB. La red simulada se basa en nodos sensores y CH autónomos que se mueven aleatoriamente, y un nodo GW estacionario en la superficie del mar. Los resultados muestran el rendimiento promedio para el número de nodos. No hay un comportamiento claro para predecir el rendimiento con el cambio en el número de OSN o CH. El rendimiento es mayor en algunos OSN en comparación con más OSN. Esto tiene sentido porque el retraso de la cola en los cabezales de clúster es bajo debido a un menor número de paquetes. El valor medio de PDR tampoco tiene una relación clara con el aumento en el número de OSN. En una red estática, esperamos tener un mejor PDR con el aumento en el número de nodos. Sin embargo, en el caso de una red totalmente ad hoc, este no es el caso debido al movimiento aleatorio de los CH. P-AUV se compara con SOAM en términos de retraso de extremo a extremo y relación de entrega de paquetes. Se obtiene que SOAM tiene un retraso mayor porque es un protocolo basado en clúster y para evitar colisiones los nodos seleccionan franjas horarias aleatoriamente para enviar el paquete. Los resultados PDR de la comparación entre SOAM y P-AUV no muestran una ventaja clara de SOAM sobre P-AUV. Sin embargo, una comparación de los métodos de enrutamiento muestra que SOAM tiene algunas ventajas sobre P-AUV de dos maneras. La primera es que, a diferencia de P-AUV, no hay ningún requisito para la afirmación de ubicación en SOAM. Los nodos P-AUV deben ser conscientes de su ubicación en el momento de la implementación y también durante la operación. Sin embargo, SOAM es un protocolo de enrutamiento sin ubicación y no requiere sensores adicionales. Por lo tanto, es evidente a partir de los resultados obtenidos que la eficiencia energética y el retraso final mínimo se obtienen mediante el uso de esquemas propuestos en comparación con los protocolos de enrutamiento existentes disponibles en la literatura.

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“No tengas miedo a la perfección, nunca la alcanzarás”.

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List of Abbreviations

4D	Four-dimensional
AHP	Analytical Hierarchy Process
AMUWSN	Ad hoc mobile UWSN
ANFIS	Adaptive Neural Fuzzy Inference System
ANP	Analytical Network Process
AoA	Angle of Arrival
AUV	Autonomous Underwater Vehicle
BCN	Beacon Nodes
BS	Base Station
CDMA	Code Division Multiple Access
CH	Cluster Head
CPU	Central Processing Unit
DARPA	Defense advanced research projects agency
DL	Directivity index
E2E	End-to-End Delay
EM	Electromagnetic Waves.
EN	Elementary node
FAHP	Fuzzy Analytical Hierarchy Process
FDMA	Frequency Division Multiple Access
GNSS	Global Navigation Satellite System
GW	Gateway node
HH-VBF	Hop by Hop VBF
IoT	Internet of Things
ISI	Intersymbol interference
LEACH	Low energy adaptive clustering hierarchy
MAC	Medium Access Control
MADM	Multiple-attribute decision making
MANETs	Mobile Ad hoc Networks
MCDM	Multi-Criteria Decision Making
OSNs	Ordinary Sensor Nodes
PFCH	Packet Forwarder Cluster Head
PSD	Power spectral density
ROVs	Remotely operated vehicles
RSS	Received Signal Strength
RTR	Ready to Receive
SL	Source level
SNR	Signal to Noise ratio
SOAM	Self-Organized Ad hoc Mobile
TDMA	Time Division Multiple Access
TDoA	Time difference of Arrival

TFN	Triangular Fuzzy Numbers
TL	Transmission Loss
TLCS	Transmission Loss cylindrical spreading
TLSS	Transmission Loss spherical spreading
ToA	Time of Arrival
TSK	Takagi–Sugeno–Kang
TWSNs	Terrestrial Wireless Sensor Networks
TxRGW	Transmission range of GW
UUVs	Unmanned Underwater Vehicles
UWSNs	Underwater Wireless Sensor Networks
VBF	Vector Based Forwarding
WBANs	Wireless Body Area Networks

Chapter 1: Introduction

This chapter introduces an introduction to Underwater Acoustic Communication in shallow underwater and the characteristics of underwater acoustic channels. The brief explanation is given about which architectures are used in UWSN, challenges in UWSN, factors which affects the performance of underwater wireless sensor networks.

The motivation and research objectives of this dissertation have been showed. These are followed by our contributions and the organization of the dissertation. The list of publications is also provided at the end of the chapter.

1.1. Research Background

The concept of monitoring the surveillance area and environment is used from long ago. The traditional approaches used to have electronic sensors connected through wired communication were used for the monitoring of the environment. The first approach started with Terrestrial Wireless Sensor Networks (TWSNs). These sensor networks are used to monitor and record physical conditions of the environment such as humidity, wind, pollution, temperature, wind etc. [1]. The wide range of application of these wireless sensor networks enabled more future technologies including Wireless Body Area Network (WBANs), Mobile Ad hoc Networks (MANETs) and Underwater Wireless Sensor Networks (UWSNs).

The TWSNs and UWSNs functions in different way because TWSNs uses electromagnetic waves whereas UWSN uses acoustic waves due to the fact that EM waves are not suitable in water because of high absorption rate. For Underwater Communication acoustic waves were much suitable because of long propagation distance. The propagation speed of sound wave is 1500 m/s in water which causes high propagation delay. On the other hand, TWSN are assumed to have negligible propagation delay. Thus, the challenges are very much different when these two approaches are designed. Next section discusses a brief outline of TWSN to understand its possible issues and objectives.

1.2. Terrestrial Wireless Sensor Networks

TWSNs were deployed for military and commercial purposes about a decade ago. In 1999, DARPA (Defense advanced research projects agency) developed a wireless network of small sensors called motes and the project was known as smart dust. The purpose of this research was to develop small tiny sensors of size like dust particle, sand or grain to monitor physical activities in the environment [2]. TWSNs were used in application such as area monitoring, air quality monitoring, health care monitoring, environmental monitoring, habitant monitoring, forest fire detection, agriculture monitoring, landslide detection, water quality monitoring, natural disaster prevention, industrial monitoring, data logging, wastewater management, structural health monitoring and military surveillance. For a TWSNs networks, there are some of the performance requirements which includes latency, robustness, throughput, scalability, stability, fairness, and energy efficiency. One of the biggest performance requirements was to reduce latency or delay in critical applications like fire accident. The delay or latency to forward a packet from source to destination becomes very important. In cooperative networks, the intermediate node which forward the packet from the source to destination causes the delay to increase thus reducing packet delivery ratio. Retransmission of packet in case of collision, packet length also increases the delay or latency. The robustness is described as network behavior in case of connectivity failure or node failure. Throughput is another performance criteria for TWSNs because it is the most desirable parameters in any network. Scalability is described as ability of a network to perform its tasks even if size of the network increases. Stability is defined as ability of the network to cope with variations in the traffic load. Fairness is defined as effective sharing of resources. Last but not the least, energy efficiency is the main parameters because sensor nodes have limited amount of battery power. Due to this, lower power is the main problem with TWSNs. The low power issues can be minimized at each layer. At physical layer, using low power electronics, using less complex channel coding methods, and using low power transmission signal. At MAC layer, avoiding packets from collisions and packet retransmission can improve the battery life of sensor node. At major level (Network layer) the use of routing techniques for the sensor nodes can significantly improve the battery life.

1.3. Underwater Wireless Sensor Networks

As discussed earlier, EM waves cannot travel in water because of high absorption rate thus the design challenges are different for TWSNs and UWSNs. The issues related with UWSNs are inefficient routing, restricted bandwidth, larger propagation latency, high resource consumption etc. In addition to that, UWSNs suffers from various challenges which includes, energy consumption, void problems, security attacks, node positioning, simulation environment. Limited bandwidth and time synchronization etc. [3]. UWSN comprises of main elements like sensor nodes which are placed on shallow and deep waters. The primary task of the sensor nodes is to gather and transfer the data to elements like ships, buoys, AUVs via acoustic signals. UWSN is now used in real-world technologies like military, pipeline monitoring, object detection, underwater robot localization and navigation. The robot sensing technologies are used to carry out real world tasks, therefore the sensing technology is important for UWSN exploration. The sensing technology has many sensors like positioning sensors, the main types of positioning sensors are short baseline sensors, ultrashort baseline sensors and long baseline sensors. Also, UWSN ranging and imaging sensors like single beam sonar, multibeam sonar and side scan sonar etc. Various robot sensing technologies are developed and used today. [4,5]

1.4. Applications of UWSNs

The major applications of UWSNs are natural habitat monitoring, water quality monitoring, marine life, fish forms and coral reef. Underwater exploration: disaster detection, floods, volcanic eruptions, earthquake, tsunami, oil spills etc. Military: mines, marines, and surveillance. Navigation and Sports.

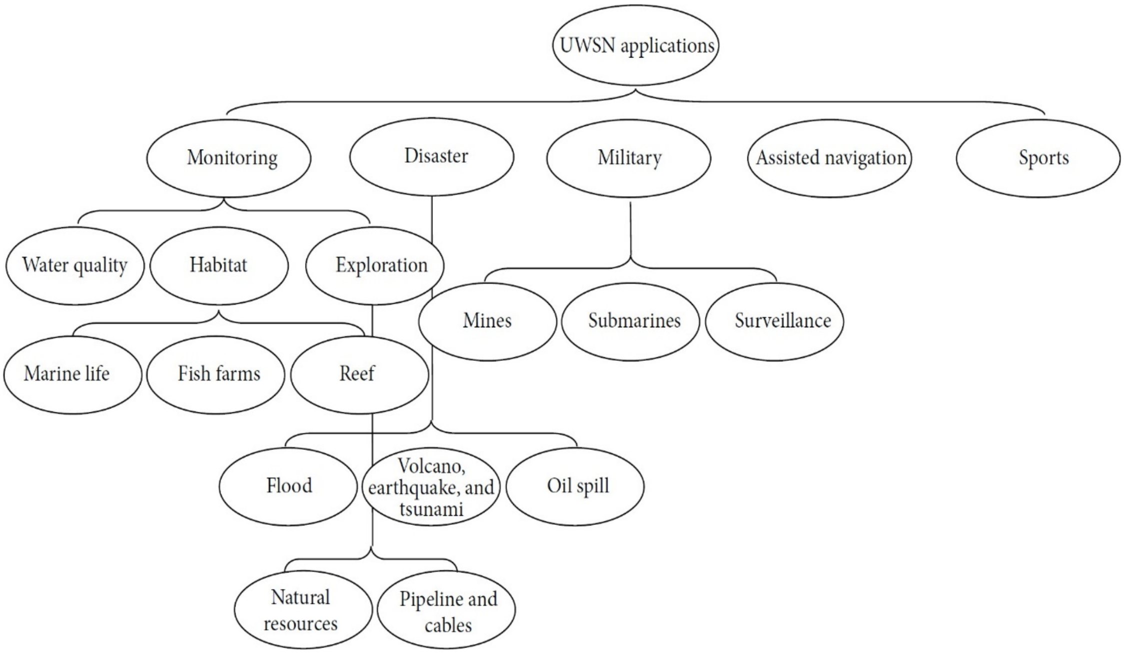


Figure 1.1. Classification of Underwater Sensor Network Applications [6]

1.4.1 Habitat Monitoring

Habitat monitoring is one of the main aspects of underwater sensor networks as they are useful in monitoring underneath life [6]. Habitat monitoring involves monitoring under the water like marine life monitoring, fish farms monitoring and coral reef.

1.4.2 Marine Life Monitoring

The main purpose of this monitoring is to monitor the marine life and detect the possible movements of fish and human in certain area under the water [7].

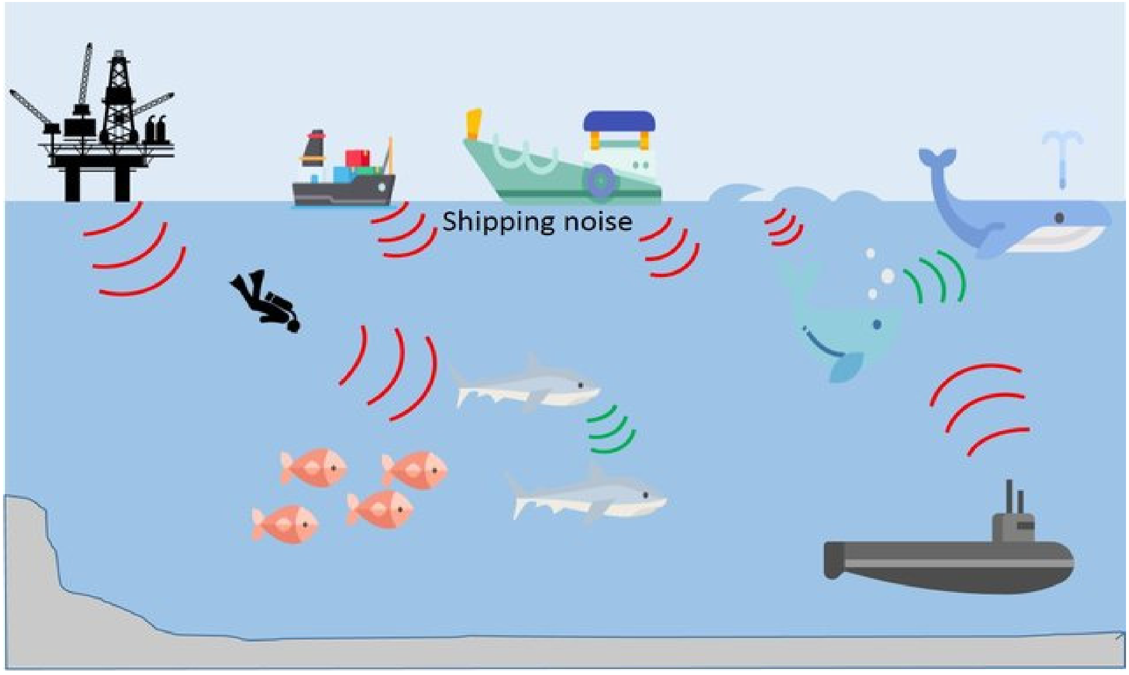


Figure 1.2. Marine life monitoring [8]

1.4.3 Fish Farms Monitoring

Fish farming requires constant monitoring because it is very sensitive and any change in the habitat can affect the life. It is highly delicate. Various techniques are used to measure and keep the underwater environment healthy [9]

1.4.4 Coral Reef Monitoring

Coral reefs are diverse underwater ecosystems and are made by underwater microorganisms. UWSN can monitor coral reef habitat monitoring. [10]

1.4.5 Disaster Detection

One of the main purposes or aim of underwater sensor networks is to timely detect disaster so that actions can be taken to prevent from the loss to occur. These disasters are natural events and causes both financial and human lives loss. It cannot be prevented however actions can be taken to minimize the disasters or losses. UWSN application is one of the main focuses of disaster detection as UWSN system are able to sense the data and send warnings for the people to relocate them and save lives. underwater sensor networks is considered as a humanitarian technology for disaster lessening [11]. The main disaster applications include,

1.4.6 Flood/Earthquake/Tsunami Detection

Flood detection or monitoring is done by placing both surface and underwater sensor nodes and these nodes will collect information such as temperature, humidity, rainfall, water level, force and send it to base station for further analysis. Depending upon the results a warning can be issued to save as much loss as possible by relocating people from the disaster site. Various works have been proposed for Tsunami warnings. 4D underwater architecture for early Tsunami detection is used in [12]. A seismic pressure sensor by which seismic waves are measured and then data is relay to the Gateway node for further actions [13].

1.4.7 Oil Spill leakage Detection

Oil spill harm both human and marine life. UWSN can detect the spill location and can sense the amount of spill along with the harm it has causes to the nearby locations. [14]

1.4.8 Military

Military applications include locating mines and submarines and surveillance. Mines are important to locate in underwater so that drown of the ships can be avoided and submarines are very important to locate for the military purpose. UWSN helps in detecting mines and submarines. Mine are detected using AUV (Autonomous Underwater Vehicles) and UWSN sensors and these sensors are capable of taking high resolution images underwater to detect the mines. [15]. Submarines has been detected using sensors, AUV and UWSN system and it is easy to detect submarines because it is important for military applications [16]. Submarines can also be detected using mobile robots, mobile elementary nodes (ENs), network of cluster-heads (CHs) and Base Station (BS). The presence of submarine is detected by audio signal emitted by submarines [17]

1.4.9 Navigation

UWSN technology can help navigate ships, swimmers, and vessels. However, the navigation equipment used at water surface is not appropriate for underwater communication. UWSN helps swimmers, submarines, in exploring, guiding, and finding paths [18]. UWSNs are use up for aided navigation and control. UWSNs are employed as location reference points by autonomous underwater vehicles (AUVs) [19], remotely operated vehicles (ROVs) [20], and underwater unmanned vehicles (UUVs) [21]. Sensors attached at the ocean's bottom in known locations can provide passing AUVs, ROVs, and UUVs with a location reference and useful water characteristics data. Underwater sensors can also offer important information to ships about where to anchor or enter shallow corridors. One more application of the UWSN is communication with divers [22]

1.4.10 Sports

Sports at the highest level of competition necessarily requires high tech, as each opponent efforts to obtain a competitive advantage through incremental improvement. Data acquisition is critical under this competitive environment because it provides athletes with information. Quantitative insights into each aspect of one's performance are accessible to coaches [23]. UWSN can be used in applications in sports such as kayaking, sailing, and rowing [24]

1.5. Propagation model or behavior of Underwater Acoustic Waves

Underwater acoustic channel suffers from various environmental affects compared to terrestrial communication channel. The acoustic signal propagation is widely affected by these parameters. These parameters include absorption loss, transmission loss, multipath fading, path loss, doppler effect, temperature, salinity, depth, water currents, channel noise etc.

1.5.1 Transmission Loss

The transmission loss is initiated by attenuation and spreading. The transmission loss is caused by distance. Because the absorption loss increases when frequency and distance are increased thus putting a limit of bandwidth available. Therefore, shorter communication links have more bandwidth than a longer one in underwater acoustic systems. Attenuation or path loss occurs in an acoustic channel over a distance l for a signal of frequency f is given by, [25]

$$A(l,f) = A_0 l^k a(f)^l \tag{1.1}$$

where A_0 is a unit-normalizing constant, k is the spreading factor, and α(f) is the absorption coefficient. Acoustic path loss is given in the equation below.

$$10\log\ A(l,f)/A_0 = k \cdot 10\log\ l + l \cdot 10\log\ \alpha(f)\ \text{dB} \tag{1.2}$$

The spreading loss is represented by the first term in the above summation, and the absorption loss is represented by the second term. The k describes spreading factor propagation geometry, and common values considered are (k=2, k=1 and k=1.5) for spherical, cylindrical, and so-called practical spreading respectively. The absorption coefficient can be stated using Thorp's equation, which yields $\alpha(f)$ in dB/km and frequency in KHz. [26]

$$\alpha(f) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100f^2} + 2.75 * 10^{-4} f^2 + 0.0033 \left(\frac{\text{dB}}{\text{km}}\right) \tag{1.3}$$

The equation is an empirical and provides a good approximation at frequencies between 10KHz to 1MHz. A graph is shown below at frequency 100KHz.

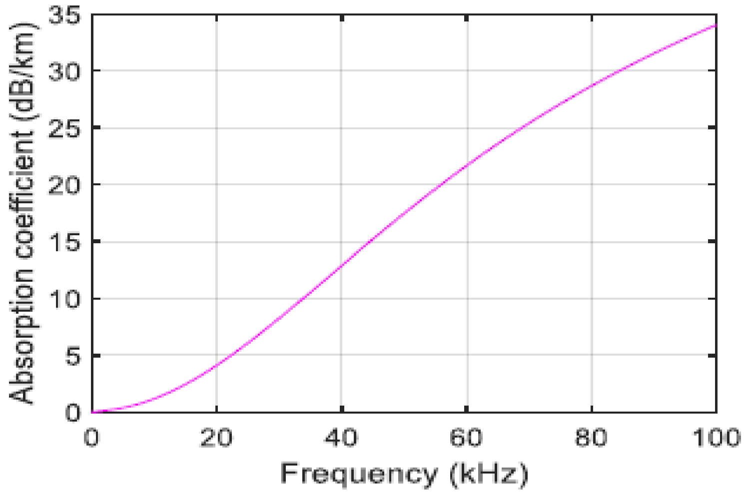


Figure 1.3. Relation between absorption coefficient vs frequency.

The Transmission Loss (TL) is calculated as a function of distance r (m) and absorption coefficient _ (dB/km). It can be expressed in two ways, in cylindrical (TLCS) for shallow waters (depth less than 100 m) and spherical spreading (TLSS) for oceanic waters respectively, as [27]

$$TL_{cs} = 10\log(r) + \alpha(f) * r * 10^{-3}$$
$$TL_{ss} = 20log\,(r) + \alpha(f) * r * 10^{-3} \tag{1.4}$$

where r indicates the hop distance (m) and f is frequency.

1.5.2 Speed of Sound Underwater

The speed of sound in underwater is given by c (m/s), [28]

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.01T)(S - 35) + 0.016d \tag{1.5}$$

where T is temperature in (Celsius), S is salinity in parts per thousand, and d is depth (meters).

1.5.3 Ambient Noise

Noise is an obvious characteristic of communication systems. Noise reduces the signal intensity of any communication system thus degrading the performance of the system. There are two kinds of noises in underwater acoustic communication. These are noises by human beings and ambient noises. Underwater noises are caused by human beings or it is man-made noise which includes heavy machinery, aircraft operation, fishing operation, military operation, shipping operation, sonar operations [29]

Ambient noise is a contribution of at least four factors: turbulence noise (N_t), shipping noise (N_s), wave and other surface noise (N_w), and thermal noise (N_{th}). The frequency dependence of every ambient noise component, is given by [30]

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f) \quad (1.6)$$

$$10 \log N_t(f) = 17 - 30 \log(f) \quad (1.7)$$

$$10logN_s(f) = 40 + 20(s - 0.5) + 26logf - 60 \log(f + 0.03) \quad (1.8)$$

$$10logN_w(f) = 50 + 7.5w^{\frac{1}{2}} + 20logf - 40logf(f + 0.4) \quad (1.9)$$

$$10logN_{th}(f) = -15 + 20logf \quad (1.10)$$

In underwater environment, signal-to-noise ratio (SNR) is based on source level, directivity index, ambient noise, and transmission loss. The SNR at the receiver input, can be calculated, in logarithmic scale as [31]

$$SNR = SL - TL - NL + DL \quad (1.11)$$

where SL stands for the source level expressed in (dB _Pa), which is directly related to the transmitting power; TL is the transmission loss (dB); NL is the ambient noise; and finally, DL is the directivity index (dB) of the transducers.

1.5.4 Multipath Fading

The underwater acoustic waves are reflected both at bottom and the sea surface resulting in multiple copies or multiple paths between transmitter and the receiver. Consequently, the receiver get the multiple copies of the same signal which results in multipath fading [32].

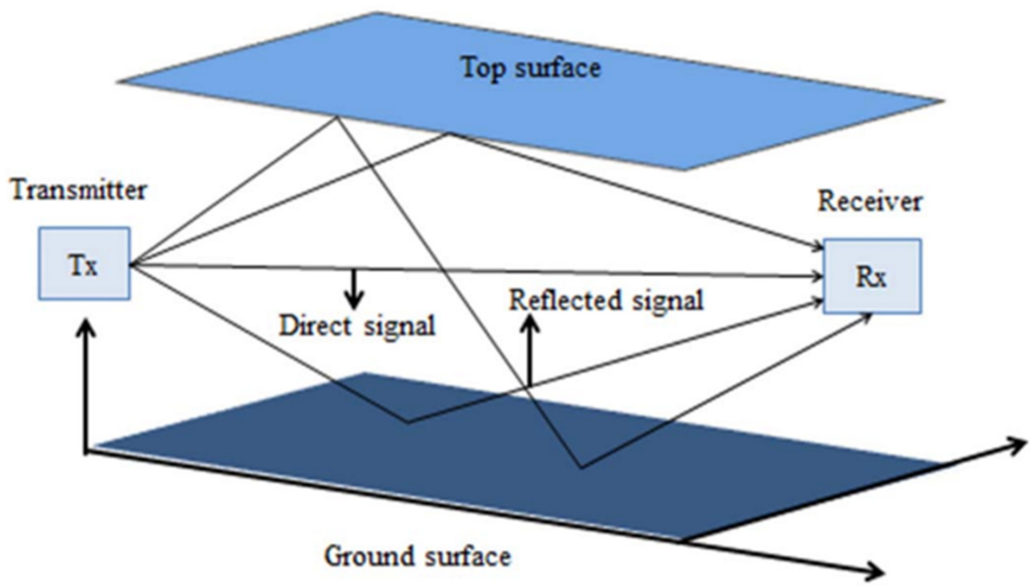


Figure 1.4. Shows multipath fading environment in UASN communication. The signal arrive at the receiver from the direct paths, reflected signals from both sea surface and bottom of the sea [33].

Intersymbol interference (ISI) is caused by delay spread and corrupts the received data. The ISI occurs when the delay spread exceeds the symbol period. Because the delay spread is determined by the environment, it cannot be controlled. To overcome the ISI, the symbol period can be expanded. The sound velocity and channel geometry have a direct influence on the reflection and refraction pattern of the sound waves. The channel impulse response of a water channel, particularly a seawater channel, varies over time due to channel movement. The movement of the channel is caused by currents and tides. The time-varying behavior of the channel is described by coherence time and Doppler spread.

1.5.5 Bandwidth Capacity and Transmission Distance relationship

Using attenuation and noise PSD (Power Spectral Density), SNR (Signal-to-Noise Ratio) can be estimated over a distance l , transmitted signal frequency f and power P. The narrowband SNR can be calculated as,

$$SNR(l,f) = \frac{\frac{P}{A(l,f)}}{N(f)\Delta f} \tag{1.12}$$

Where Δf is the receiver noise bandwidth, $A(l,f).N(f)$ is frequency dependent part of SNR. The factor $1/A(l,f).N(f)$ demonstrates that for every transmission distance l there an optimal frequency for which the maximum narrowband SNR is obtained. The below figure shows the relation between frequency and SNR [34]

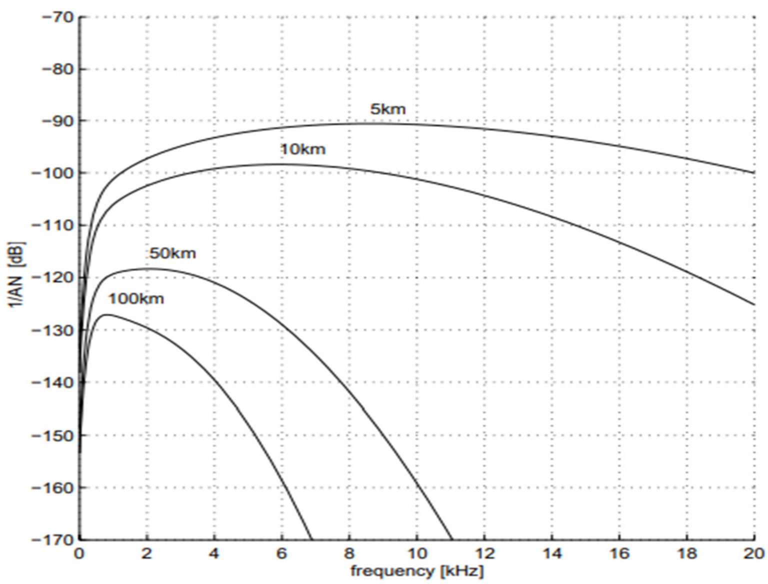


Figure 1.5. Signal-to-noise ratio (SNR) in an acoustic channel depends on the frequency f and distance $\boldsymbol{l}$ [33].

Channel capacity is an important factor in UWSN communication when it comes about SNR. Presuming that the noise is Gaussian, and that the channel is time-invariant. The noise in this narrow sub-band can be approximated as white, with the p.s.d. $N(f_i)$, and the resulting capacity is given by

$$C(l) = \sum_i \Delta f \log_2 \left[1 + \frac{S_l(f_i)A^{-1}(l,f_i)}{N(f_i)}\right] \tag{1.13}$$

The maximum capacity with respect to $S_l(f)$ is subject to a constraint that total transmitted power P_l is finite. The signal p.s.d. should comply with the water-filling principle [35]

$$S_l(f) + A(l,f)N(f) = K_l \tag{1.14}$$

where K_l is a constant and its value can be calculated from the power P_l, and it is understood that $S_l(f) \geq 0$.

1.6. UWSN Architecture

UWSN architecture can be categorized into a) 2D (Two-dimensional UWSN) b) 3D (Three-dimensional UWSN) c) 4D (Four-dimensional UWSN). There are various features of each of the architecture. Architecture defines the real scenario of the placement of sensors nodes, gateway node, buoys etc. Let us briefly discuss each of the UWSN architecture.

1.6.1 Two-dimensional architecture

2D UWSN architecture is defined by Akyildiz [36] where sensor nodes are connected to the bottom of the sea. 2D architecture is useful for shallow sea when the area of interest is only the sea bottom. The nodes are assumed to be at same depth. A possible 2D deployment is shown the figure below. The sensors nodes at the bottom are connected to GW node through acoustic links. The communication from sensor nodes to the GW and GW back to the sensor nodes is referred as 2D communication. For the purpose of communication to and from the GW, both horizontal and vertical transceivers are used. Horizontal transceivers are used for bidirectional communication between sensors nodes and the gateway node. The GW node uses horizontal transceiver to communicate with anchor sensor nodes. Vertical transceivers are used by GW node to forward data to the sink node which is surface ship. A complete scenario of 2D architecture is depicted in Figure 1.6 [37]

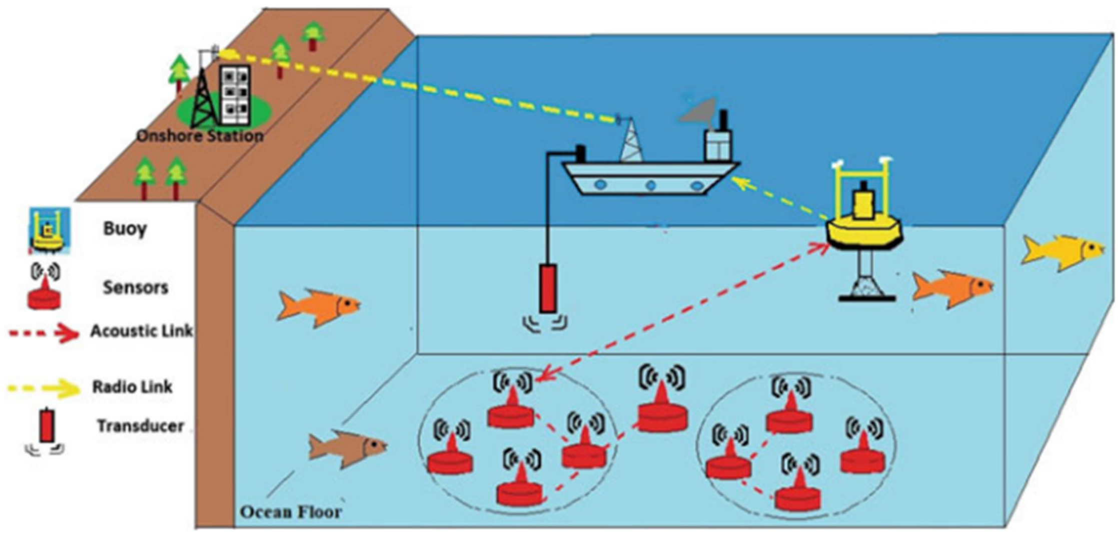


Figure 1.6. Two dimensional UWSN architecture consisting of Buoy, sensors, acoustic links, radio links and transducer.

1.6.2 Three-dimensional architecture

Three dimensional UWSN architecture is different from 2D in a way that in 2D sensors are almost at the same depths whereas in 3D architecture UW sensor node depth of sensor node can be adjusted using wires or rope whose length can be adjusted. [27]. Each sensor is anchored to the ocean floor and has a floating buoy that can be inflated with a pump. The buoy propels the sensor to the ocean's surface.

The depth of the sensor can then be adjusted by adjusting the length of the wire connecting the sensor to the anchor, which is controlled by an electronically controlled engine located on the sensor. The effect of ocean currents on the described mechanism for regulating the depth of the sensors is a challenge that must be addressed in such an architecture.

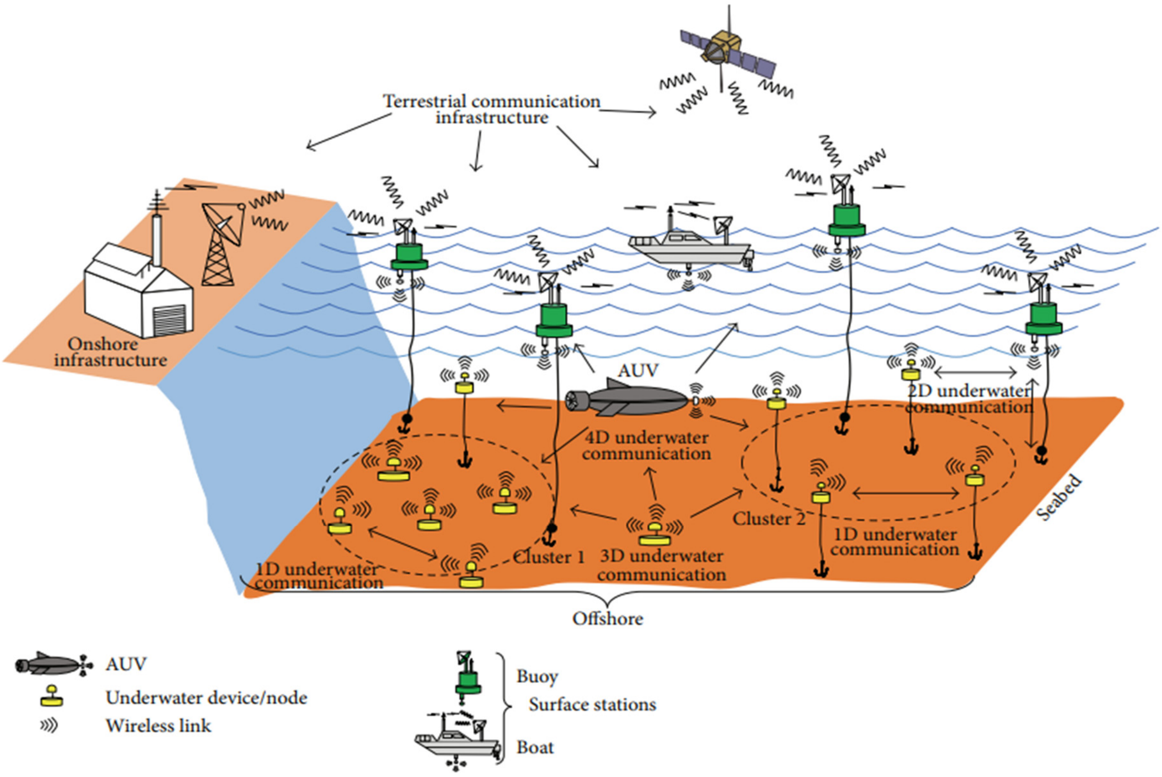


Figure 1.7. 3D UWSN architecture [6].

1.6.3 Four-dimensional architecture

Four-dimensional UWSN architecture consists of both AUV (Autonomous Underwater Vehicle) and ROV (Remotely Operated Vehicles). It is the combination of mobile UWSN and fixed 3D. The purpose of mobile ROVs is to gather the data from anchor node and dispatch it to remote station. In addition to 2D and 3D, data collection in underwater can be done by using AUVs and then AUV relay the gathered data to the sink node. The movement of AUV is done by computer programs at the pre-defined paths. On the other hands, ROVs are remotely navigated using cables and cameras. [38].

[39] is a distributed data collecting algorithm which uses AUV for the collection of data as shown in the figure below. The sensors may use radio links if ROV or AUV is close to the data transmitting node and if the amount of data is too large.

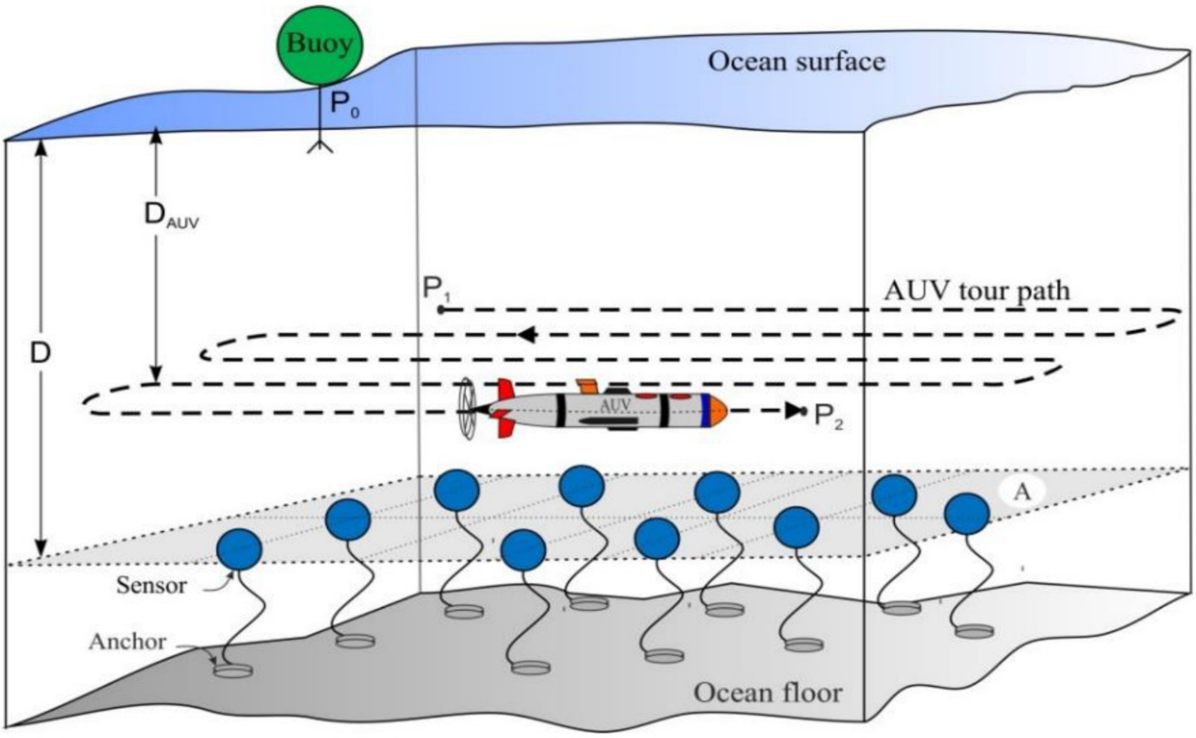


Figure 1.8. AUV based underwater communication [40].

1.7. Dissertation organization

This dissertation consists of 6 chapters.

Chapter:1 comprises of brief explanation about the basic principles of TWSN (Terrestrial WSN) and UWSN. Issues with underwater sensor networks, challenges of acoustic wave propagation, architecture of underwater wireless sensor networks and its limitations.

Chapter:2 covers state of the art used in the existing research methods in UWSN communication. The literature review is extensively done to compare the existing techniques or methods with the proposed scheme. The proposed scheme includes the concept of fuzzy logic and its benefit over existing literature.

Chapter:3 This chapter contains the overview of how energy efficiency is achieved using the concept of fuzzy based decision making compared with the existing literature. The results showed that proposed scheme performs better than the existing routing protocols available in UWSN literature.

Chapter:4 This chapter consists of overview of the Energy-Efficiency achieved through Fuzzy Analytical Hierarchy Process and FAHP is advance version of fuzzy logic which considers goals, criteria and sub-criteria and alternatives as final outcomes. The selection of relay node is done by using goals, criteria and alternatives.

Chapter:5 This chapter Comprises of overview of self-organized ad hoc mobile underwater sensor networks (SOAM). It is reactive, self-configuring, and self-organizing cluster-based routing protocol that uses received signal strength (RSS) for distance estimation. The protocol is designed to establish the routing path among the moving nodes to forward the data to the gateway with minimum end-to-end delay. The network is divided into clusters to minimize the number of hops.

Chapter:6 This chapter consists of conclusion and the future work for the proposed scheme and future technologies which can be useful for further research in UWSN area of research.

1.8. Related publications

Kumar, J.; Luque-Nieto, M.-Á.; Hyder, W.; Otero, P. “Energy-efficient packet forwarding scheme based on fuzzy decision-making in underwater sensor networks”. *Sensors* **2021**, *21*, 4368. https://doi.org/10.3390/s21134368

Kumar, J.; Luque-Nieto, M.-Á.; Hyder, W.; Ariza, A. “Energy-efficient routing protocol for selecting relay nodes in underwater sensor networks based on fuzzy analytical hierarchy process”. *Sensors* **2022**, *22*, 8930. https://doi.org/10.3390/s22228930

Jatoi, G.M.; Das, B.; Karim, S.; **Kumar, J.**; Krichen, M.; Alroobaea, R.; Kumar, M. “Floating nodes assisted cluster-based routing for efficient data collection in underwater acoustic sensor networks”. *Comput. Commun.* **2022**, *195*, 137–147.

W. Hyder, **J. Kumar**, M. -Á. Luque-Nieto, A. A. Laghari and P. Otero, "Self-organized ad hoc mobile (SOAM) underwater sensor networks", in *IEEE Sensors Journal*, doi: 10.1109/JSEN.**2022**.3224993.

Hyder, W.; **Kumar, J.**; Luque-Nieto, M.-Á.; Sheikh, A.A.; Shaikh, M.M. “CLUSMOB protocol based on clusters for mobile underwater networks”. In Proceedings of the 2022 Global Conference on Wireless and Optical Technologies (GCWOT); IEEE, **2022**; pp. 14

Chapter 2: State-of-the-Art

This chapter will go over the existing UWSN routing protocols. This will allow us to better understand the routing issues in UWSN. Routing protocols are divided into two broad categories: proactive routing protocols and reactive routing protocols. The forwarding nodes in proactive protocols already know the next node to which the packet must be forwarded, which reduces packet forwarding time. Proactive protocols are better suited for time-sensitive data. They do, however, have some drawbacks. When the network topology changes or a node fails, they must update the routing tables. Another issue with proactive protocols is scalability. This chapter explains the deep concepts of UWSN used in the research, research gaps and how the proposed protocol is better in terms of other UWSN routing schemes.

2.1. Introduction

Water covers around 70% of the Earth's surface. This proves the importance of exploring the underwater medium. UWSN sensor nodes cover a specific area of the sea to sense some characteristics and communicate with an onshore data center near the water surface [36]. UWSNs faces a number of shortcomings and challenges, involving high interference and noise, high propagation delays, narrow bandwidth, dynamic network topology, and limited sensor node battery. One solution to these problems is the development of routing protocols. A routing protocol in the network can efficiently transfer data from the source node to the destination node [41]. When forwarding data packets from the bottom towards the surface of the water, the sensor nodes communicate with each other in order to choose and use the best paths based on some selection criteria. Routing protocols for UWSNs deal with the selection of such paths to deliver data packets efficiently to the destination [42]. Since the participating nodes are many or in other words among many sensors nodes the need to decide the forwarding node or relay node is of absolute importance because each sensor will have different characteristics like some nodes has limited energy, some nodes are close and far from the gateway nodes, some nodes are single hop away from the GW node while others are far from the gateway node. Considering all the parameters and making the decision of which node has the right to forward the packet can be done by use of effective routing protocols.

The routing protocols can be classified into two main categories i-e reactive routing protocols and proactive routing protocols. In proactive routing scheme the forwarding node already knows the following node where a packet needs to be forwarded which helps in reducing forwarding time. This kind of protocol is suited for delay sensitive applications. The issue or shortcoming with proactive routing protocol is that routing table needs to be updated whenever there is change in the network topology or node failure. Thus scalability is one of the issues with these routing protocols [43]. On the other hand reactive routing protocols, the node finds the next hop to forward the data when it receives a packet to be forwarded or the path between node is established when node decides to send out its packets thus the delay increases which makes reactive routing protocols unsuitable choice for delay sensitive data. However, the regular updates of routing table are not required for that reason in this type of protocol the network is simply scalable. [44]-[45].

The underwater routing protocols are widely classified into many categories based on their applications and functions. The main categories of such routing protocols are available in existing literature. These include, location-based routing protocols, location-free routing protocols, cluster-based routing protocols, energy-efficient routing protocols, received signal strength-based routing protocols, cooperative routing protocols etc. Location-based routing protocols select the next forwarding node based on the node's position in the network. This requires an added sensing device for example a pressure sensor, to determine an underwater node's location. The next node can be selected based on its closeness to the destination or on depth measurements. The extra sensor device consumes more energy, resulting in an unfavorable characteristic for UWSNs. Moreover, since sensor nodes are continually moving so deciding the exact location of a node in 3D UWSNs is challenging task. In the UWSN state of the art we briefly describe each type of UWSN routing protocols from sections (2.2 - 2.7).

2.2. Related Works

The state-of-the-art mentions that Global Positioning System (GPS) is not a suitable choice for UWSN communication or aquatic communication [46]. Still in some studies it is suggested that UWSN nodes can obtain the geographic axis using localization services but it is challenging task [47]. Vector Based Forwarding (VBF) is a location-based protocol [48]. It popularized the concept of virtual pipes. A virtual pipe is a collection of nodes from the source to the sink that can potentially forward packets. To avoid packet losses and node failures, data packets are forwarded by multiple nodes within the virtual pipe. Nevertheless, voids may occur in networks with low node density, lowering the delivery ratio. Because of three-way handshaking, power consumption is high. Hop-by-Hop is a method for dealing with voids in VBF. Instead of going from source to destination, VBF (HH-VBF) [49] proposes a virtual pipe from one node to another. Each forwarding node creates a new virtual pipe. The mentioned protocols are greedy and location-based in which those forwarding nodes are chosen within virtual pipe which are facing in the direction of the destination.

Author in [50] proposes multi-hop transmission protocol wherein the packets are delivered from one hop to another hop and ultimately to the sink. The packets from source node to sink are chosen via cluster head using fuzzy logic. This methodology uses three input parameters, current energy, trust factor, and distance from base station are calculated to the selected cluster. If the cluster head has a greater number of cluster heads between sink and itself, it employs the fuzzy logic to choose the preferred cluster head to reach the data. The neighbor node, nearer to sink can be elected by the best forwarding node. The best forwarding node is selected based on high trust factor and distance to sink node. The protocol results in increased lifetime and reduces overhead in the network. RECRP [51] propose a location-free single copy protocol where no extra hardware is required to determine the location, parameters like received signal strength indicator (RSSI) and doppler scale shift measurement (relative speed) are used for estimation of distance. Transmission power and channel frequency parameters are dynamically controlled by optimal min-max technique. It uses two-hop forwarding facilities to achieve energy efficiency. Additional advantage of the protocol is that it can prevent communication voids. The protocol results in decreased energy per node per message and end-to-end delay compared to other techniques, while keeping an increased packet delivery ratio.

The energy efficiency issue has been addressed in SOSRP [52], where a decentralized self-organized scalable routing protocol is suggested, where a node failure does not impact the communication in the network. It is a hop-by-hop-based communication protocol where messages are forwarded to the gateway by the relay or intermediate nodes. This scheme considers nodes deployed randomly at different depths. Initialization of the network is done by means of HELLO packets; the gateway broadcasts this packet amongst nodes within its transmission range. After the packet is received, a node increments a counter, stores the hop count and re-broadcasts the packet. A temporary failure is introduced to further test the system and identify fault tolerance. This scheme is based on 3D distance between source and destination and hop count. The routing protocol EECOR (Energy Efficient Cooperative Opportunistic Routing) [53] is proposed to forward the packets to the sink node. The source node determines the forwarding relay set based on local information of the forwarding node. To select the best relay, fuzzy logic is used considering two input parameters, i.e., energy consumption ratio and packet delivery probability. The output value is described by a figure of merit called Chance; a high value of Chance in the proposed scheme indicates that the neighbor node in the forwarding relay has the opportunity to be selected as best relay. Besides, to avoid packet collision, the concept of holding time is established for each forwarder to schedule packet transmission towards the sink. The protocol results in better end-to-end delay due to avoidance of packet collision and achieves lower energy consumption. Though, the weakness is that parameters such as distance, transmission range, and hop count are not considered while designing the protocol.

In [54] fuzzy logic is used for parent node selection as well as for scheduling and tree formation. The selection of the forwarding node is made based on the minimum number of dynamic neighbors. Fuzzy based enhanced cluster head selection FBECS [55] is cluster based where sensor nodes send or forward the data to their respective cluster heads. In this scheme, an eligibility index is determined for every node for choosing the suitable cluster head. The parameters considered for eligibility are remaining energy, distance from the sink, and node density. This protocol achieves load balancing by selecting the best candidate to be the cluster head based on the parameters considered. A problem that usually appears in these cases is that a node is isolated, that is, it does not belong to any cluster. In [56] authors propose a solution for forwarding node selection that frequently causes energy imbalance in the network and creates the void hole, which is the situation when a node has no next hop forwarding node in its transmission range, and due to this void node, the data forwarding ceases. To overcome the issue of void holes, the preferred forwarding nodes are selected inside small cubes to reduce interference and making routing decisions more efficient, which results in enhanced lifetime of the network and also packet delivery ratio. Likewise, a three-dimensional division of the network is done which makes the network scalable, and linear programming is used to reduce end-to-end delay and energy consumption and to increase packet delivery ratio in the network. Another approach to choose the forwarding node is the location-based protocol. The Relative Distance-Based Forwarding (RDBF) routing protocol [57]

A fitness factor is proposed in this scheme to select the appropriate node, which reserves the right to forward packets to nodes whose fitness factor is better than a threshold value; simply those nodes will participate in the forwarding process. Thus, the benefited relay nodes are selected based on shortest distance from the gateway and minimum hop count to forward the packets. Therefore, only a small number of nodes are part of the forwarding process, which reduces energy consumption and also reduce the end-to-end delay. It also selects the optimal path from source nodes to the gateway, in terms of residual energy and distance. This RDBF protocol also has the advantage of controlling transmission time for multiple forwarding nodes, which helps in reducing the duplication of packets. Perhaps the simplest technique to choose the forwarding node is to consider the number of hops. RPSOR (Reliable Path Selection and Opportunistic Routing) [58] protocol introduces a priority function for UWSNs to select the forwarding packet and prefer the nodes that need the lesser number of hops to reach the gateway. This is done through the Shortest Path Index (SPI) parameter for every node that forwards data. In addition, the parameters considered for calculating the SPI are hop count, weighting depth difference sum between two hops, and node depth of the next hop.

In GCORP (Geographic and Cooperative Opportunistic Routing Protocol) [59], the concept of the multi-sink is introduced. Intermediate relay nodes are placed between source nodes and sink for packet routing. Source nodes determine the relay forwarding set from neighbor relay node based on a depth fitness factor. Weighted scheme is applied on normalized energy, packet delivery probability, and normalize distance. The relay node with highest weight value is selected as best relay node. The protocol results in improved packet delivery ratio, low end-to-end delay, and enhanced network lifetime. However, the protocol suffers from void occurrence and multipath problem. The use of fuzzy decisions in routing protocols has received growing interest in recent years. One of the classic applications is to select the cluster head (CH) node in a cluster-based network topology, using multiple criteria in the assignment of that role mainly to increase the network lifetime. In this area, we have decision schemes such as the fuzzy technique for order of preference by similarity to ideal solution (Fuzzy-TOPSIS) [60]; LEACH fuzzy clustering (LEACH-FC) [61]; data gathering protocol in unequal clustered WSNs utilizing fuzzy decisions (DGUCF) [62]; multiple-attribute decision making (MADM) [63] using criteria such as residual energy, distance from the base station, and number of neighbors; energy-efficient distributed clustering algorithm based on fuzzy scheme (EEDCF) [64] to overcome uneven load on the network and select CH using the fuzzy Takagi–Sugeno– Kang (TSK) model; adaptive network based on fuzzy inference system (ANFIS) [65] which employs a fuzzy neural network; or using the density of nodes [66] jointly with the Mamdani method of fuzzy inference for selecting the CH.

Another typical application for fuzzy decisions is the selection of an efficient routing path using multihop links (node-by-node hops), such as in the relay node selection scheme based on fuzzy inference algorithms (RNSFIA) [67]. In RNSFIA, a fuzzy inference algorithm is used to select the relay node, where the criteria used for the decision are distance between nodes, priority on residual energy, and degree of communication. Compared to MOD-LEACH [68], RNSFIA has a higher throughput and network lifetime. Another example for efficient routing with fuzzy decisions is multi-criteria decision making (MCDM) [69], where weights and criteria such as hop count, packet transmission frequency, and residual energy are used.

A second block of strategies (hierarchy processes) is based on multiple comparisons under different criteria. Examples include the analytical hierarchy process (AHP) [70], which selects the relay node in body area networks (WBANs) using weights among several candidate nodes; AHP MCDM [71], which uses a two-phase clustering scheme that includes finding the location of the nodes by using sink position and criteria such as the number of neighbors, centrality, and residual energy; or the analytical network process (ANP) [72] based on MCDM which selects the best CH node using criteria such as initial and residual energy, energy consumption rate, average energy of the network, and distance of a node from CH. Others (e.g., [73]) consider both ANP and AHP using a fuzzy scheme for solving the CH selection in a cluster network. In the UWSN area, various methods are considered to achieve energy efficiency. We have used input parameters such as hop count, distance to the sink, and number of neighbors using the FAHP MCDM strategy and obtained better results compared to some of the existing research techniques. FAHP is almost identical to AHP except for the conversion of verbal appreciation into the numeric scale. AHP indicates the relative importance of criteria in MCDM, being preferable in qualitative judgments, and cannot accept fuzzy numbers as input. Thus, fuzzy AHP (FAHP) was introduced because AHP lacks the benefits of managing vagueness in judgment. For example, a decision maker cannot make exact judgment between number 4 and 6 instead of using exactly the number 5. However, fuzzy numbers are the way to integrate such imprecision, giving benefits for FAHP compared to AHP schemes. The last family of routing techniques considered here is out of the scope of the two cited before. Usually, a specific solution is proposed for the path's creation through the network. For example, in the distributed energy-efficient zonal relay node-based secure routing protocol (DEZMSR) [74], a relay node is selected based on zone radius by means of a division in two kinds of nodes, namely zonal and district relay nodes; other examples include using load balance [75], using comparison rules such as the Cauchy inequation [76] between energy used and routing distance, employing a specific hierarchy in the cluster deployment and using a weighted product model (WPM) [77], among many others.

The Energy-Efficient and Obstacle-Avoiding Routing (EOAR) [78] protocol selects the forwarding node employing fuzzy logic. The result is dependent on the propagation delay, angle between the two nodes, and residual energy. To avoid collisions, packets are routed based on their priority. The received packet's timestamp which indicates when it was received is used to determine the propagation delay. Owing to various propagation delays and some degree of mobility, this technique involves time synchronization between the nodes which is a challenging task for UWSNs. DBR-MAC [79] is a cross-layer routing protocol based on node depth, angle information and number of hops. Time synchronization is essential for the protocol to estimate the propagation delay among the nodes. The transmission and propagation times, and the fixed packet size are used by the nodes to count their neighbors' transmission and the reception schedule. This facilitates the nodes to schedule their own transmissions to avoid collisions. The Time of Arrival (ToA) technique is used to estimate the distance between the gateway and the nodes. The angle information is achieved with help of depth and the distance information between the gateway and the nodes. The performance of DBR-MAC highly depends on the accuracy of time estimation. One of the cluster-based routing protocols considered, is the Distributed Underwater Clustering Scheme (DUCS) [80], which is also a self-organizing protocol. The nodes form the clusters by one of the nodes assume the role of cluster head (CH). These CHs aggregate data received from single-hop cluster nodes and send it to the sink using multihop routing via other CHs. It is assumed that within a cluster the nodes are close to each other and may send the correlated data to the CH. Therefore, a CH filters out the redundant data from the cluster nodes and sends only non-redundant data to the sink. The filtering of redundant data helps to save the energy of the CH. A node is assigned as CH on the basis of the maximum battery capacity and the current battery level. The nodes inside a cluster bind to the nearest CH which requires them to measure their distance with all the CHs. This distance is calculated by the Time of Arrival (ToA). Another function of the CH is to control the communication among the cluster nodes and with the other CHs. The cluster head assign the time slot to each cluster node based on Time Division Multiple Access (TDMA) where the time slots are assigned using Code Division Multiple Access (CDMA). CDMA is also the modulation used by the clusters to send data to the sink. Nodes in a cluster keep rotating the role of cluster head among themselves to conserve energy.

Opportunistic Power Controlled Routing (OPCR) [81] is an opportunistic protocol for Internet of Things (IoTs). It is based on link quality, nodes density, distance, packet advancement and energy consumption. Opportunistic routing and variable transmission power control mechanism work together to reduce the energy waste. The concept of OPCR is very simple. The forwarding node reduces the transmission power where the node has high neighborhood density, if the link quality between the neighbor nodes and the forwarding nodes is good enough to deliver the data reliably. Hence, a transmitter node must have the information of the neighboring nodes. A beacon packet is used to discover the neighbor nodes. To determine which neighbor nodes can forward the packet towards the gateways, the location of the nodes needs to be known. OPCR does not define any localization method itself and recommends using any localization protocol proposed for UWSNs.

The protocol HAMA [82] is an AUV based protocol which uses multiple AUVs to provide high availability of data collection. The nodes away from the AUV trajectory send data to the nodes close to the trajectory, which eventually forward the packet to AUVs when they pass by them. The nodes closer to the AUV path consume their energy faster than the other nodes, since they not only have to send their data, but also have to retransmit the data of the other nodes. It is also possible that the AUV goes down because of some malfunction. HAMA avoids this problem using multiple AUVs, changing trajectories and spreading the AUV failure intimation throughout the network. The nodes determine their location to use it with AUV's trajectory path to determine whether they have sufficient time to send packets to the moving AUV. However, it is not described that how the nodes will determine their location. The nodes can predict the location of the AUVs because of their predefined path. Other protocol, in this case thought for radial topology, is SOFRP [83] a location free, self-organizing, cross-layered protocol. It is a proactive protocol to minimize the routing delay. Before data transmission begins, the routing path for all the nodes to send data to the gateway is established. The routing paths formation is initiated by the gateway. The nodes find their neighbors and the network topology by using the messages only. The messages are sent at randomly selected timeslots to avoid collision. The routes are formed in such a way that the only the nodes in a straight line (called string) forward the packets. To make the protocol robust the routing path can be changed if a node goes down. The nodes forward the data packets use string identification (ID) in the header of each packet. Since the forwarding node does not need to match the source ID or change the destination ID, the packet forwarding quite fast in SOFRP. As an example of a high data throughput and conserving energy protocol, Self-Organized Proactive Routing Protocol (SPRINT) [84] is a self-organized, proactive, cross-layered protocol. SPRINT selects the next forwarding nodes based on the distance between source and the relays, number of relays used to traverse the packet from the source node to the gateway and the number of neighbors of each relay. The distance is measured by received signal strength (RSS) to make the protocol location free. We have used input parameters such as hop count, distance to the sink, and number of neighbors using the FAHP MCDM strategy and obtained better results compared to some of the existing research techniques.

FAHP is almost identical to AHP except for the conversion of verbal appreciation into the numeric scale. AHP indicates the relative importance of criteria in MCDM, being preferable in qualitative judgments, and cannot accept fuzzy numbers as input. Thus, fuzzy AHP (FAHP) was introduced because AHP lacks the benefits of managing vagueness in judgment. For example, a decision maker cannot make exact judgment between number 4 and 6 instead of using exactly the number 5. However, fuzzy numbers are the way to integrate such imprecision, giving benefits for FAHP compared to AHP schemes. The last family of routing techniques considered here is out of the scope of the two cited before. Usually, a specific solution is proposed for the path's creation through the network. In conclusion, the effectiveness of fuzzy algorithms for selecting the CH node in clusters has been proved.

However, routing in an ad hoc topology requires first creating the paths between every node and the sink node (on the surface) with an unknown location of the nodes. On the other hand, complex multi-criteria decision problems can be managed efficiently by a standard formulation using hierarchy processes such as AHP. To our knowledge, there is no routing protocol using FAHP in the underwater environment for a random network topology that does not use clusters as hierarchy. In this work, we show that is possible to apply AHP including fuzzy decisions (FAHP) to the problem of the initial path creation after deployment of a random-topology UWSN. From our point of view, this is a new alternative for performing node forwarding selection in UWSNs. UWSN can be connected to the machine learning concepts in future as described in [85], the concept of machine learning is used. The reinforcement learning (Q-learning is used) which reduces the energy consumption and latency. Data forwarding is done based on rewards; the rewards are calculated using Q-learning updated tables. The node with high Q value is chosen for data forwarding. The authors in [86] uses machine learning as supplementary method to optimization model to predict networks parameters and energy consumption of the UWSN nodes. Neural network and regression are used to analyze the performance of these models. The highest energy depleted by sensor nodes in minimized in each transmission round using optimization method which is used to balance energy; thus the technique reduces the energy consumption.

2.3. Conclusion

To substantiate the research work done in this thesis, major shortcomings of the existing protocols need to be highlighted. The summary of the issues is as given below. I) Some protocols are based on full duplex communication. However, full duplex communication is very difficult to implement in underwater acoustic communication systems because narrow acoustic bandwidth. II) Most of the routing protocols for UWSN assume that the geographical location of the nodes is known to form the routing paths. However, there are two subtle problems in location-based routing in UWSN. First issue is that the sensor nodes determine their position with respect to the GW, which in turn determines its position via GNSS. Due to varying speed of acoustic waves and the mobility of the nodes, the probability of error in 35 position determination is quite high. Second issue is that the position determination by the depth sensors increases the power consumption and cost of the sensor nodes. III) Some routing protocols like EOAR use timestamp to estimate the propagation delay and some others like PICS and PRCS use timestamp to estimate time of arrival to determine the node position. That requires synchronized time clock between the nodes. Time synchronization in wireless sensor networks is usually achieved by time information exchange between the nodes. However, time synchronization is a challenging task in underwater networks because of variable-propagation delay and node mobility. IV) Requirement of additional devices like depth sensor and array of transducers (for Angle of Arrival method) increase the power consumption of the sensor node. Energy conservation is more important in UWSN compared to WSN because the nodes are very expensive, and their underwater deployment is very costly and difficult. V). In centralized routing path formation, the sink node forms the routing path for the nodes or cluster heads based on the collected information from the nodes. This approach may produce optimum routes as the sink node has all the information to establish the best routing path. However, changing the routing path in case of a node failure or addition of a node will not be easy. In addition to that, to change the routing path in case of any change in the network requires the nodes to send the information to the central node periodically which decreases the data throughput and increases the energy consumption. VI). As mentioned in section 2.1, the reactive protocols have their own disadvantages. Reactive protocols add packet forwarding delay because of the time required to select the next forwarding node. This delay becomes substantial for time-critical applications in large networks. VII). Cluster based protocols have relatively low throughput. The cluster heads become the bottle neck for the data traffic. Each node sends data to its cluster head which decreases required the transmission power. However, cluster head becomes the point of traffic congestion, particularly for sensor networks that produce high data rate. VIII). Cluster based networks and centrally controlled networks pose the threat of single point of failure. When the cluster head is down, then all the cluster nodes get disconnected from the rest of the network until they choose another network node as a cluster head. IX). Opportunistic routing protocols broadcast the data packet and multiple copies of the data packet to the destination node, which increases the probability of data packet delivery. The purpose of sending the multiple copies is to increase the packet delivery reliability. However, this increases the number of transmissions for each forwarding node which may significantly increase the power consumption. Increase in power consumption decreases the nodes operational life as replacement of the nodes batteries is very difficult.

Chapter 3: Energy efficient underwater routing protocols based on Fuzzy decision making-An enhancement of SPRINT protocol (SPRINT-FUZZY)

In this chapter we have presented the details of Energy efficient underwater routing protocols based on Fuzzy decision making. A technical view is presented to understand the methods used. The experimental results are compared with one of the techniques available. The results show that by employing the fuzzy logic scheme the performance of the nodes in terms of energy-efficiency increases.

3.1. Introduction

The scenario considered is a 3D UWSN where nodes are positioned at different depths in an underwater three-dimensional area. A channel model for underwater medium is also implemented considering the environment factors of USWNs that include transmission loss, absorption loss, signal to noise ratio, various noises, and energy consumption during a packet transmission and reception. It is also important to consider the energy consumption parameter while designing protocols for UWSN due to the inadequate energy available at the nodes.

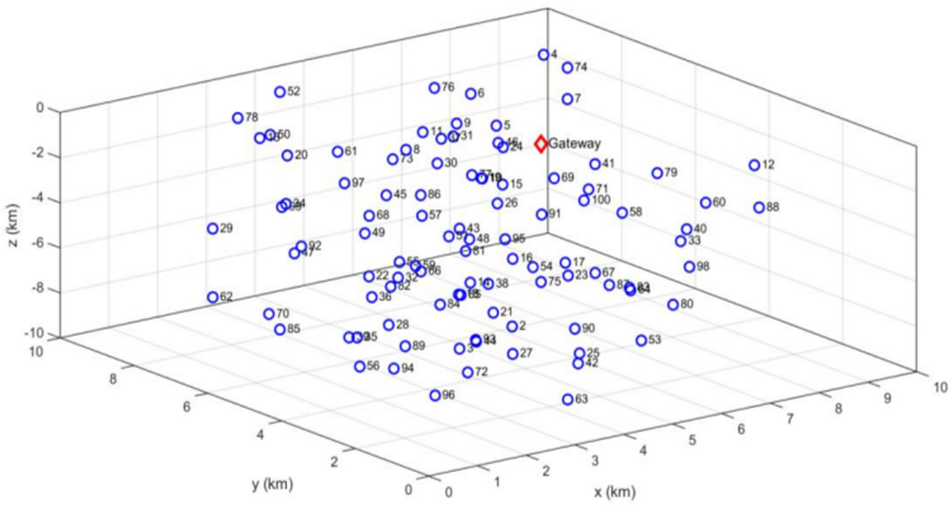


Figure 3.1. Random deployment of nodes in 3D UWSN architecture.

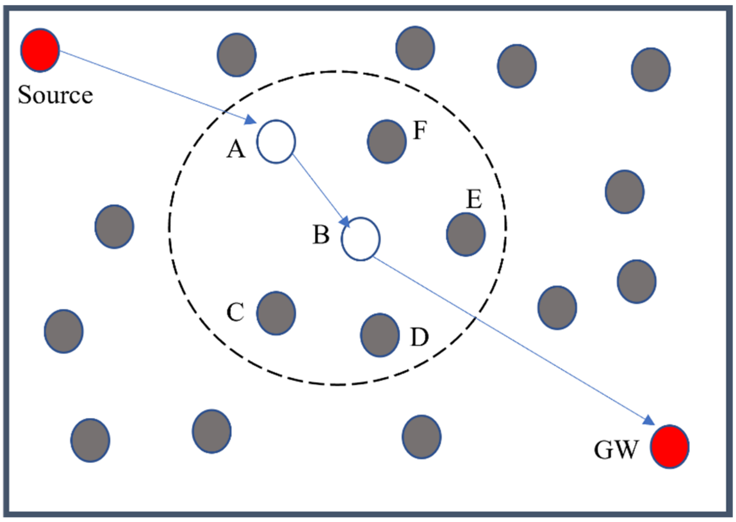


Figure 3.2. Selection of relay node scenario.

It can be seen from the above figure that in a cooperative network, the nodes send the data towards the GW node via intermediate nodes known as relay nodes. For example, nodes A,B,C,D,E and F are shown in the network and only B,E and D nodes are one hop(single hop) away from the GW node while other nodes are multihop to reach to the GW node. To choose a relay it is important to know position of its candidate nodes. In this case, only the nodes which are closer to the GW can act as relay node and can forward the data towards the gateway node. Thus, it is evident that not only number of hops is the criteria to select a relay node, but the selection depends upon other parameters like number of hops, number of neighbors and the distance from the gateway. However, finding the position or location of sensor node in underwater sensor network is a complicated task. One solution to determine the position of the node is using Global Navigation Satellite System (GNSS) but to achieve this task in UWSN is challenging because of absence of GNSS signal in underwater. One more factor which affects the position of sensor node in underwater is due to the continuous moment of sensor node in 3D UWSN. Various methods have been used in the literature to find the position of nodes. Time of arrival (ToA) [87], TDoA (Time difference of arrival) [88], Angle of arrival (AoA) [89] and RSS (Received Signal Strength) [90]. Time of arrival is used to calculate the time travel from source node to destination node. Time stamp is used by the sender when sending the packets and receiver calculates the time travel by difference of its local time and estimates the distance. The problem with this is it requires time synchronization method. Attaining the time synchronization is tough task in 3D UWSN due to mobility of the sensors nodes which occurs due to water currents. Time difference of arrival (TDoA) method performed by simple determine the distance between two nodes by evaluating the time difference of the anchor and beacon nodes. Angle of arrival (AoA) is distributed localization technique which supposes sensor node can identify incident signal angles from adjacent nodes [91]. RSS is another method to estimate the position or location of the sensor nodes. In this technique sensor nodes employ the received signal power to determine the distance between transmitter and receiver. Consequently, synchronization is not needed in this technique. Hence, RSSI is an alternative to measure distance. [92], [93].

In order to deal with such issues. Efficient routing protocol is proposed in this thesis which is the modification of SPRINT protocol. Keeping in view the position or location problems in 3D UWSN we have used distance as metric of selection in our protocol and the distance is estimated by RSS (Received Signal Strength).

3.2. Fuzzy logic-based energy efficient ad hoc routing protocol

Our proposed protocol uses RSS metric to find which node is the closest neighbor of the transmitting node. Accompanied by distance two more metric of selection are used which are number of hops between the sender and the sink node and number of neighbors of the candidate nodes. RSS estimation suffers from many channel impairments including fading, path loss, absorption loss and mobility which are discussed in chapter 1.

Considering underwater constraints including the propagation model, harsh environment, water current, and depth in 3D UWSNs, a packet forwarding protocol based on alternate path to conserve the energy is proposed. The proposed protocol is based on SPRINT protocol which is designed to achieve trade-off between energy consumption and throughput. A packet forwarding node selects one of its neighbors as a relay node. The main criterion to select a relay node is the minimum distance to conserve the energy. The distance is estimated by the received signal strength (RSS). However, minimum distance is not the only criterion. The use of number of hops or relay nodes from source to final destination affects the throughput. Each hop adds to the delay in packet forwarding and, as a result, reduces throughput. Therefore, along with the distance parameter, the number of hops between the relay and the sink and the number of neighbors of the relay node are also taken into consideration. The minimum number of hops is used to maximize the throughput while minimum number of neighbors is used to minimize the traffic congestion and energy consumption of the relay. It is possible that the selected relay node is not the optimal selection due to error in RSS estimation. However, the optimal node may be selected later as the relay selection process is recursive. The routing path formation will be initiated by the sink and data packets will be sent once the routing path formation process is over. To avoid the network overhead and enhance packet delivery ratio, the routing path will be updated recursively at some suitable interval depending on the data packets arrival rate. The distance, energy consumption and number of neighbors are not static parameters of the network. The distance between the two nodes may change due to the limited mobility of the nodes. Furthermore, the energy consumption of some nodes may be higher than the others and number of neighbors may also change because of the nodes limited mobility and failures. As the selection parameters are not static and the optimal routing path is sought, a fuzzy logic scheme to select the relay node has been envisaged. The selection is based on three input parameters: (i) number of hops in the path, (ii) number of neighbors of a node, and (iii) distance from a transmitting node to the forwarding node. In SPRINT protocol, three weight factors are used with those three parameters. In this proposal, a fuzzy inference method is applied to select the forwarding node, and it will be shown that it is possible to reduce both the packet delay and the overall energy used by the network.

The structure of a fuzzy logic system can be seen in Figure 3.3 . The system has three elements or stages: the input mapping or fuzzification stage, the decision core (also called "fuzzy rules" or "fuzzy logic engine" in technical literature), and the output mapping or defuzzification stage. In the first stage, the so-called membership functions map the possible values of the input variables to the real range [0,1]. Simple analytic canonic functions like triangular, rectangular, or gaussian functions are used as membership functions, although other shapes are also possible, such as sigmoid and bell functions. In this work, triangular functions have been used due to their simplicity. The second stage, the so-called core decision, is implemented by a set of rules (Boolean, IF-THEN). All rules are evaluated in parallel using fuzzy reasoning. Eventually, the outputs of the core decision stage enter the defuzzification stage, where they are combined to provide a normalized numerical value called Chance, which is the response of the fuzzy logic system. The defuzzification stage also uses a membership function.

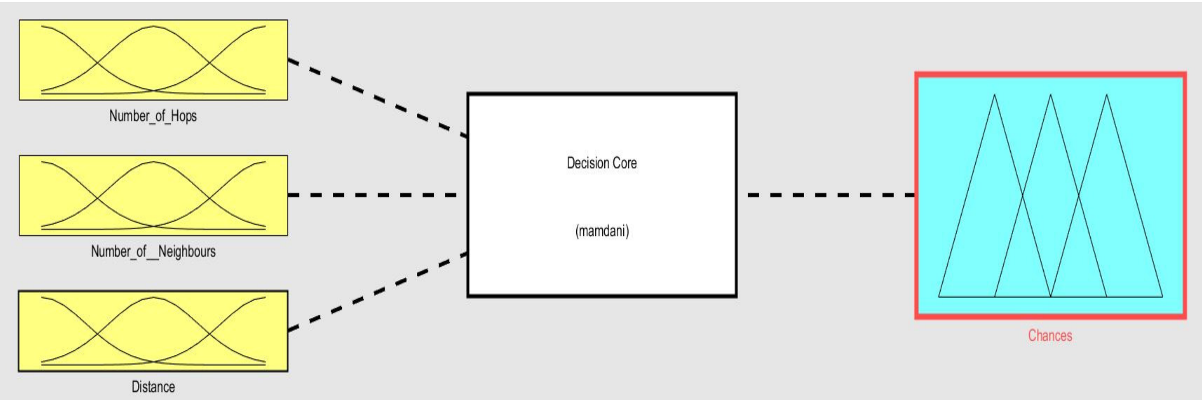


Figure 3.3. Fuzzy Inference System.

3.3. Fuzzy Logic

Fuzzy logic is a type of multi-valued logic that deals with reasoning to provide an approximate rather than exact result. Fuzzy logic is also used for estimating and making a decision among multiple variables. Figure 3.4 shows a block diagram that illustrates the block diagram of a fuzzy logic system. Fuzzy inference is the name of the process of mapping a given input to an output using fuzzy logic.

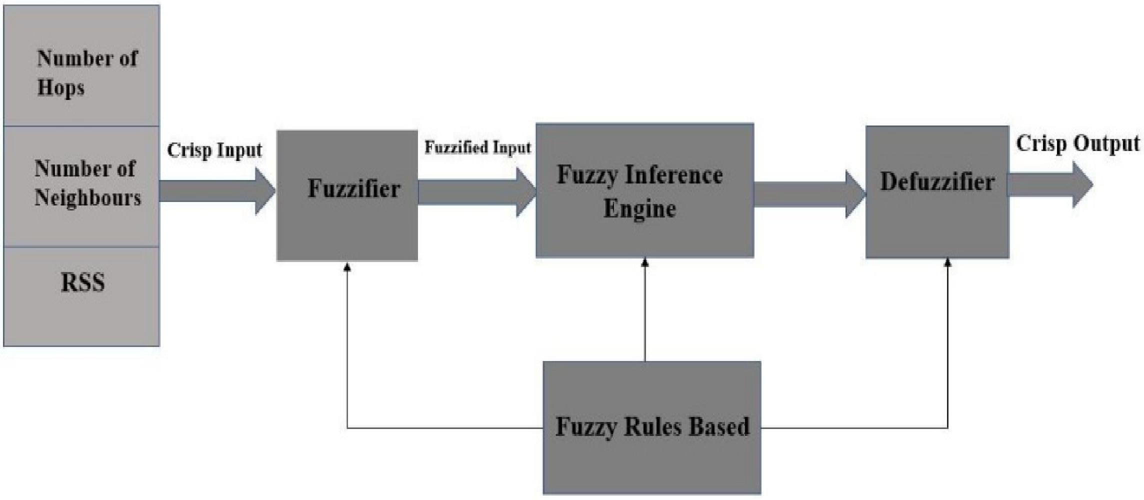


Figure 3.4. Fuzzy logic scheme for the proposed protocol based on three metrics of selection.

In the first and third stages, linguistic terms are used to map the stage input variables to the real interval [0,1]. The mapping is performed by the so-called membership functions. The linguistic terms are shown in the tables below. The fuzzy inference provides a basis from which decisions can be made or patterns distinguished [20]. The system output is a real number in the interval [0,1]. The term Chance is used to refer to either the linguistic term or the numerical values. It has been found that Chance or possibility is used to represent the score of a node to be chosen as forwarding node. The three stages of the system are described below.

Table 3.1. Linguistic terms used for fuzzification.

Input	**Membership**		
Number of hops	Minimum	Average	Maximum
Number of neighbors	Minimum	Average	Maximum
Distance	Near	Close	Far

Table 3.2. Linguistic terms used for defuzzification.

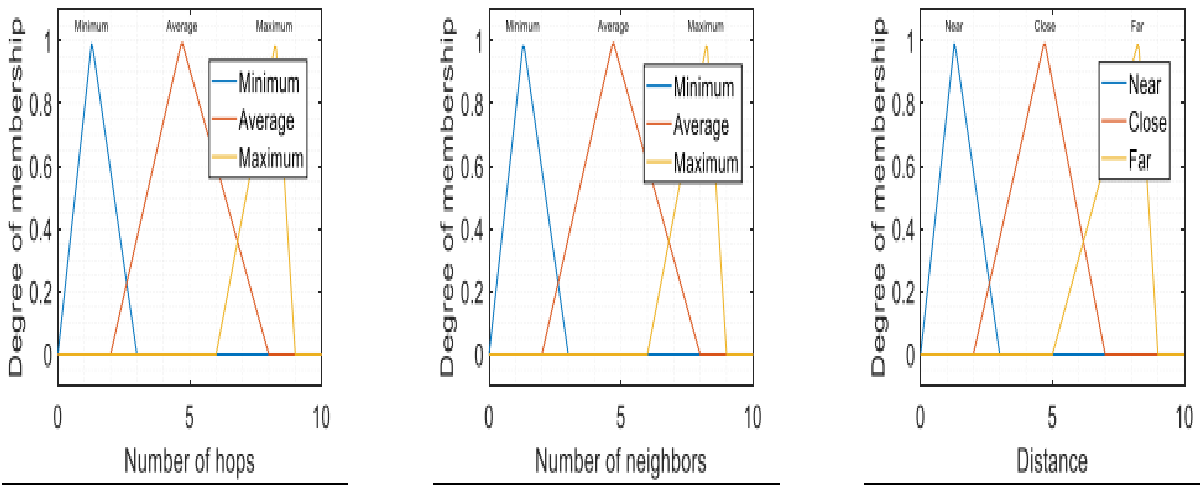
	Linguistic Variables
Chance	Very Best, Best, Far Better, Better, Good, Fair, Bad, Worse, Worst

3.3.1 Fuzzification

There is a membership function associated to every linguistic term in Table 3.1. The first stage is to evaluate the membership functions for each input (number of hops, number of neighbors and distance). The triangular membership function is calculated as [94]

$$\mu(x) = \begin{cases} 0, & x \leq a \\ \dfrac{x-a}{b-a}, & a \leq x \leq b \\ \dfrac{c-x}{c-b}, & b \leq x \leq c \\ 0. & c \leq x \end{cases} \tag{3.1}$$

The membership function μ(x) provides the degree of membership. In Figures below, the three used membership functions are shown jointly with the associated linguistics terms.



Membership Functions	Values Considered
Minimum	0-3
Average	2-8
Maximum	6-onwards

Membership Functions	Values Considered
Minimum	0-3
Average	2-8
Maximum	6-onwards

Membership Functions	Values Considered
Near	0-3
Close	3-7
Far	5-onwards

Figure 3.5. A joint fuzzy triangular membership function for number of hops, number of neighbors and distance respectively [95].

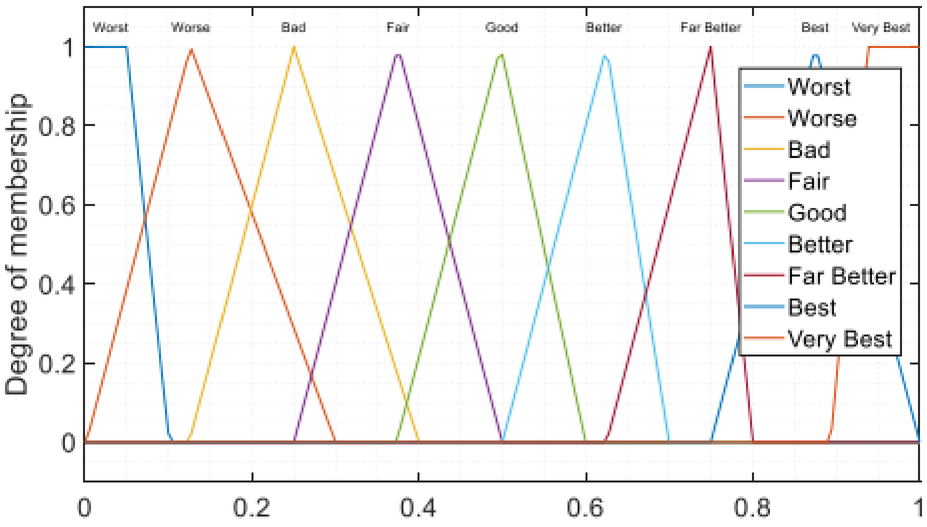


Figure 3.6. Defuzzified values (Chances of a node as Relay node).

3.3.2 Fuzzy Rules

Fuzzy rules are based on IF-THEN consequences by applying Boolean AND/OR operations to the input. To do that, Mamdani method has been used [96]. As an example, the fuzzy rules for the limit values of Chance are explained (limit values of Chance are Best and Worst; they are used because they are more illustrative than others). Instance 1: IF number of hops are Minimum, AND number of neighbors are Minimum AND RSSI distance is Near, THEN Chance of packet forwarding is Very Best. Instance 2: IF number of hops are Maximum, AND number of neighbors are Maximum AND RSSI distance is Far, THEN Chance of packet forwarding is Worst.

Table 3.3. Fuzzy rules proposed for the proposed scheme.

No. Rule	No. Hops	No. Neighbors	Distance	Chance	No. Rule	No. Hops	No. Neighbors	Distance	Chance
1	Min.	Min.	Near	**Very Best**	**15**	Max.	Avg.	Near	**Good**
2	Min.	Min.	Close	**Best**	**16**	Min.	Avg.	Near	**Good**
3	Max.	Min.	Close	**Best**	**17**	Avg.	Min.	Near	**Good**
4	Min.	Avg.	Close	**Best**	**18**	Min.	Avg.	Far	**Good**
5	Max.	Min.	Close	**Best**	**19**	Min.	Min.	Far	**Good**
6	Max.	Max.	Close	**Far Better**	**20**	Max.	Min.	Near	**Good**
7	Max.	Avg.	Close	**Far Better**	**21**	Avg.	Avg.	Far	**Fair**
8	Min.	Min.	Far	**Far Better**	**22**	Avg.	Max.	Near	**Fair**
9	Min.	Max.	Close	**Better**	**23**	Avg.	Max.	Far	**Bad**
10	Avg.	Max.	Close	**Better**	**24**	Max.	Max.	Far	**Bad**
11	Avg.	Avg.	Close	**Better**	**25**	Max.	Max.	Near	**Bad**
12	Avg.	Min.	Near	**Better**	**26**	Avg.	Max.	Far	**Worse**
13	Avg.	Avg.	Near	**Better**	**27**	Max.	Max.	Far	**Worst**
14	Avg.	Min.	Far	**Better**					

Note: Min. = minimum, Med.=medium, Max.=maximum, Avg.=average

3.3.3 De-Fuzzification

The defuzzification stage involves two steps. In the first step, the membership function is evaluated at the values obtained in the second stage. In the second step, a single number is obtained. In this work, the Center of Mass (CoM) method has been used, and the single number is calculated as,

$$z = \frac{\sum_{i=1}^{q} x_i \, \mu(x_i)}{\sum_{i=1}^{q} \mu(x_i)} \tag{3.2}$$

where μ(x) are the triangles and z are Chance. The node with a larger value z is the node with better Chance to be the forwarding node or relay node. The implementation of fuzzy scheme is assigning weights to the nodes and the node with the highest weight will have the chance to act as relay node.

Table 3.4. Result of fuzzy operation.

Case No.	No. Hops	No. Neighbors	Distance	Chance
1	7	6	8	0.375
2	6	6	6	0.474
3	5	8	6	0.312
4	3	4	5	0.625
5	7	3	2	0.564
6	2	3	4	0.875
7	1	2	7	0.637
8	5	8	7	0.196
9	1	1	1	0.929
10	1	1	2	0.917

It is well recognized that using the fuzzy logic to choose the forwarding node becomes very easy compared to SPRINT technique, which uses the weights method using normalized values to select the forwarding node and RECRP which uses RSSI and Doppler scale shift measurement to estimate distance using optimal min-max method, and next hop selection is based on the information in a routing table that is updated from the beginning to the ending node. In RECRP, due to regular updates of the routing table, the energy consumption will be increased. Similarly, among the neighbors, the forwarding node is chosen based on the largest value. The process is continued until the sink is reached.

3.4. Network performance

The indicators used to evaluate the proposed scheme have been already introduced: number of hops, number of neighbors, and RSSI. Additionally, different transmission ranges have been considered to assess the performance of the system in terms of energy consumption and average number of hops. The energy consumption in UWSNs is usually due to network operations such as processing, gathering, forwarding, and receiving data. Therefore, the total energy consumption is the energy dissipated due to these actions in the nodes.

Number of hops: Number of hops refers to intermediate nodes that a packet must visit to reach the destination which is the gateway. This parameter has a direct relationship with the distance, which is the third indicator, obtained from the RSSI.

Distance (RSS): Distance is related to energy consumption. Due to the law of transmission power proportional to the square of the distance, multi-hop communication is preferred. Nevertheless, the energy used in a node for receiving and processing a message, and not for transmission, might modify this criterion. However, the larger the number of hops, the larger the end-to-end delay.

Number of Neighbors: Number of neighbors is the second indicator the select the forwarding node. This indicator is a measure of the priority of selecting the forwarding node. The lower number of neighbors implies a greater chance of a node to be selected as forwarding node

3.5. Simulation Results

The energy performance of the protocol is analyzed in terms of two magnitudes: average and total energy consumption by nodes. The algorithms and protocols described have been developed in MATLAB®. For the simulations, a variable number of nodes, up to 600, have been quasi-randomly located in the scenario, which is a cubic region of side 10 km. Here, quasi means that there is the restriction of a minimum distance between nodes; they that cannot be within 1 km of each other to avoid undesired overlaps. The speed of sound could be calculated with Equation (4). In the simulations, the used value is 1500 m/s. Several transmission ranges have been considered, from 1 km to 8 km. Ten (10) cases were simulated for each value of the transmission range. The summary of parameters used in this scheme is given in the following table.

Table 3.5. Simulation parameters used in proposed scheme.

Simulation Parameters	Value	Unit
Speed of sound	1500	m/s
Data rate	5000	bit/s
Frequency	48	kHz
Packet length	256	bit
Header length	30	bit
Transmission power	18	W
Number of nodes	100 to 600	--
Simulation length	10	--
Minimum distance	1	km
Transmission range	2 to 8	km

MATLAB® was chosen to implement the protocol. Average number of hops vs. transmission range were calculated: average energy consumed per node and per packet (energy/node/packet), average number of hops, and average total energy.

First, the impact of the transmission range on the average number of hops has been analyzed. The results are shown in Figures 3.7–3.11. It can be observed that the average number of hops decreases with increasing transmission range.

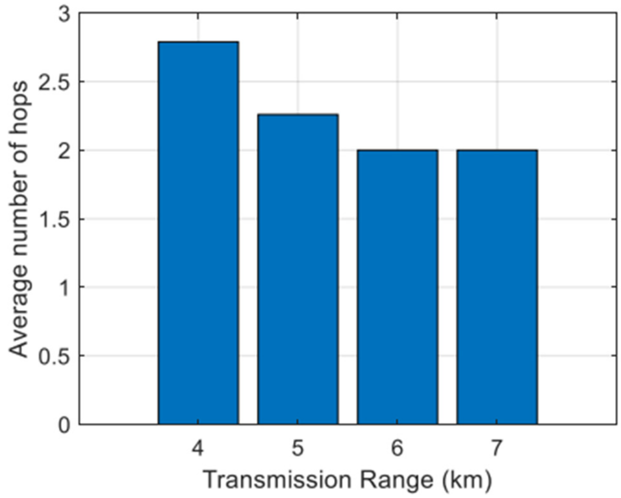


Figure 3.7. Average number of hops for 100 nodes.

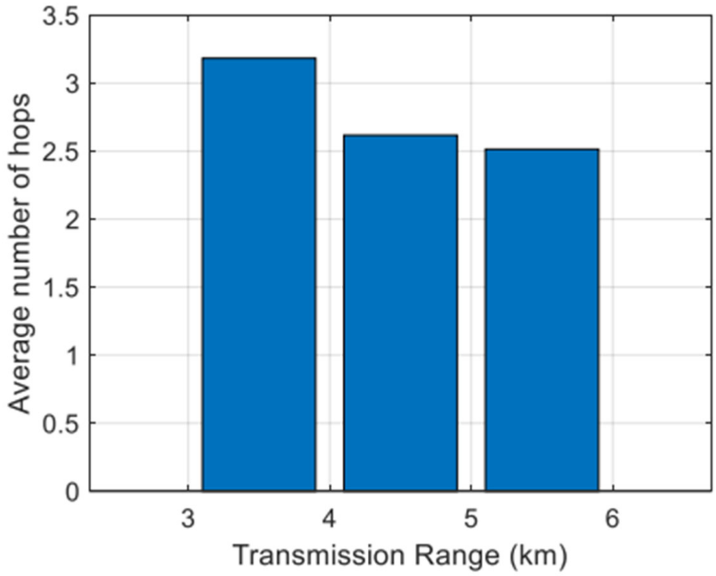


Figure 3.8. Average number of hops for 175 nodes.

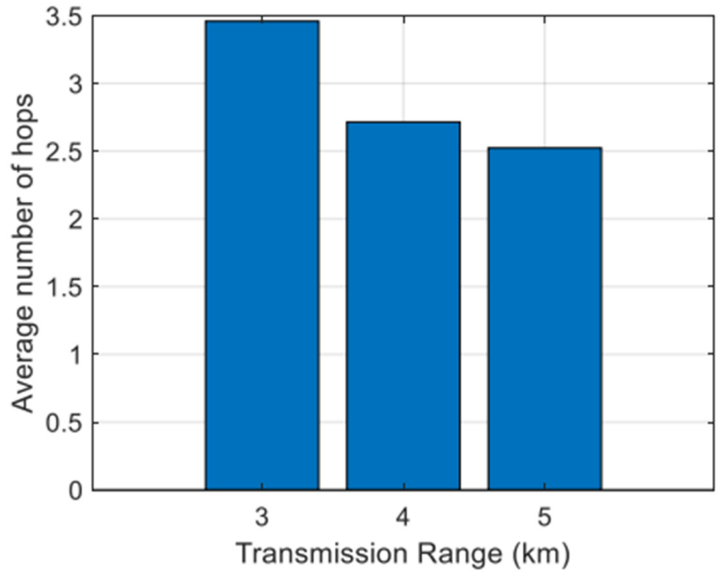


Figure 3.9. Average number of hops for 250 nodes.

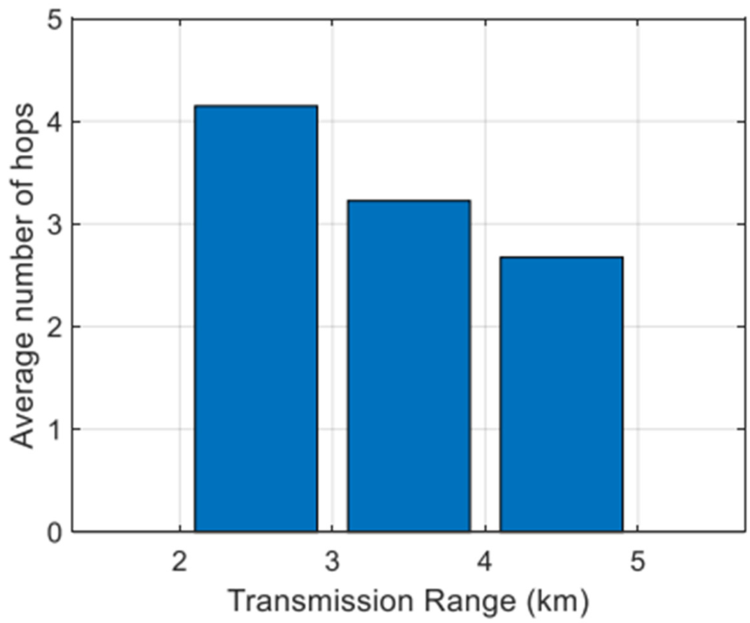


Figure 3.10. Average number of hops for 325 nodes.

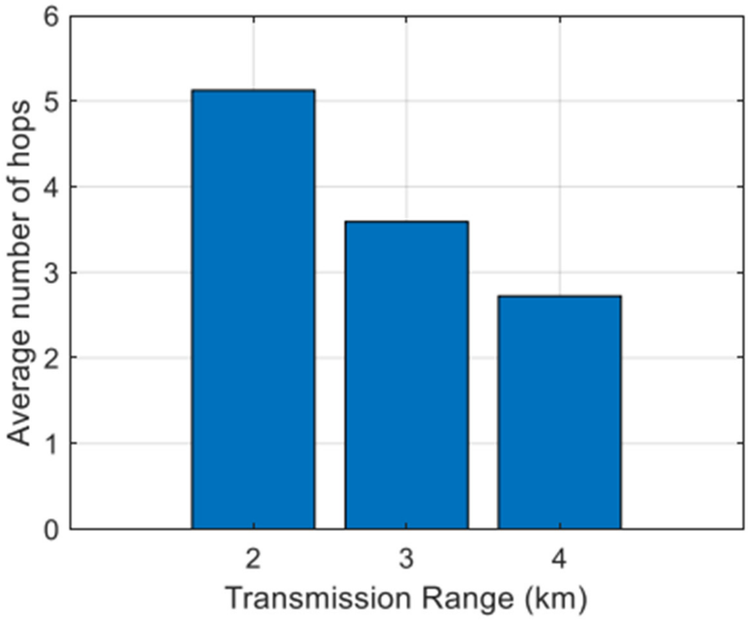


Figure 3.11. Average number of hops for 400 nodes.

As mentioned at the end of the previous section concerning the law of transmission power proportional to the square of the distance, the multi-hop scheme could be more efficient. In addition, and not least, the end-to-end delay increases with the number of hops. For these two reasons, a path with fewer jumps is preferred. Simulations were also carried out to analyze the influence of the transmission range on the energy/node/packet and the average number of hops. When there are fewer nodes in the scenario, the transmission range must be longer, and the opposite. The transmission ranges considered for the different number of nodes are shown in Table 3.4. The simulation results of the average number of hops vs. transmission range are shown in Figures (3.7 – 3.11).

Table 3.6. Transmission ranges and number of nodes.

Number of nodes	Transmission range (km)
100	4, 5, 6, 7
175	3.5, 4.5, 5.5
250	3, 4, 5
325	2.5, 3.5, 4.5
400	2, 3, 4

Figures 3.12–13.15 show that the energy/node/packet increases with the transmission range, as described above. It can also be observed that the energy decreases with the node density. For instance, with a transmission range of 4 km, the energy/node/packet is 1.9 J with 100 nodes and goes down to 0.71 J with 400 nodes.

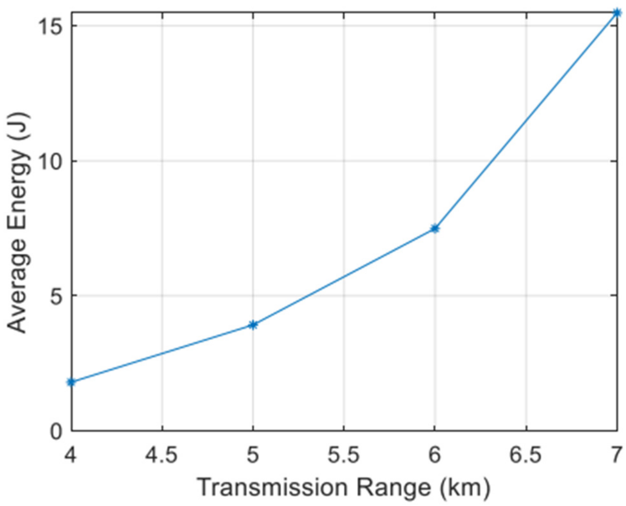


Figure 3.12. Energy/node/packet for 100 nodes.

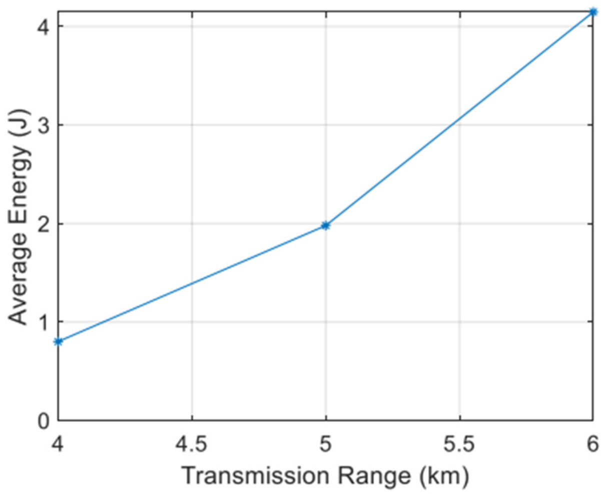


Figure 3.13. Energy/node/packet for 200 nodes.

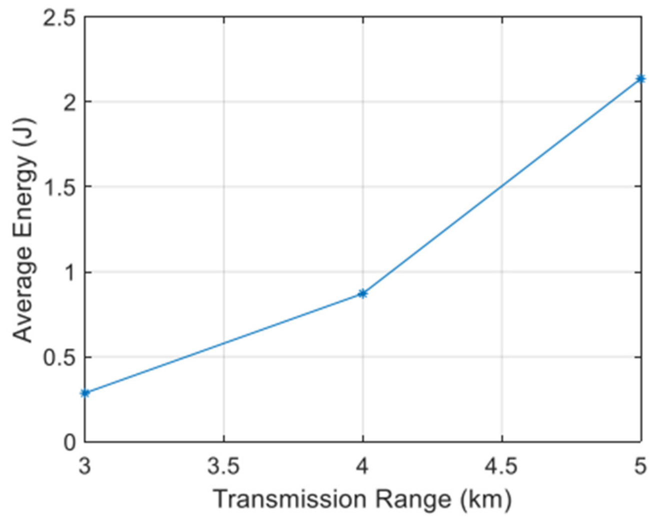


Figure 3.14. Energy/node/packet for 300 nodes.

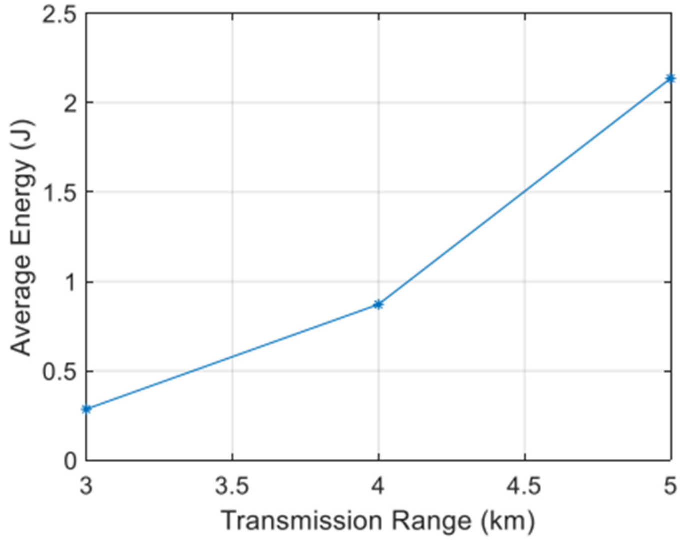


Figure 3.15. Energy/node/packet for 400 nodes.

As shown in Figure 3.16. the larger number of nodes the lower energy/node/packet. When there are 100 nodes, the energy used is approximately 10.9 J and for 600 nodes it is around 0.2 J. It can be seen that a higher node density results in lower energy/node/packet.

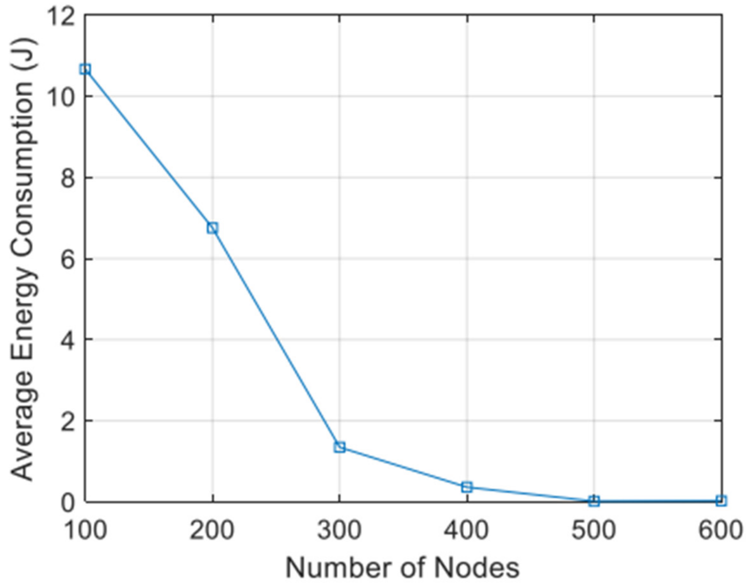


Figure 3.16. Energy/node/packet vs. number of nodes.

Figure 3.17 shows the energy/node/packet used *vs*. the number of nodes, with transmission range as parameter. There is not a clear trend of average consumption vs. number of nodes, but it clearly increases with the transmission range. A good conclusion of Figure 3.17 is that, in terms of energy consumption, the network is scalable and stable, that is, the energy used does not show abrupt increments with the network size.

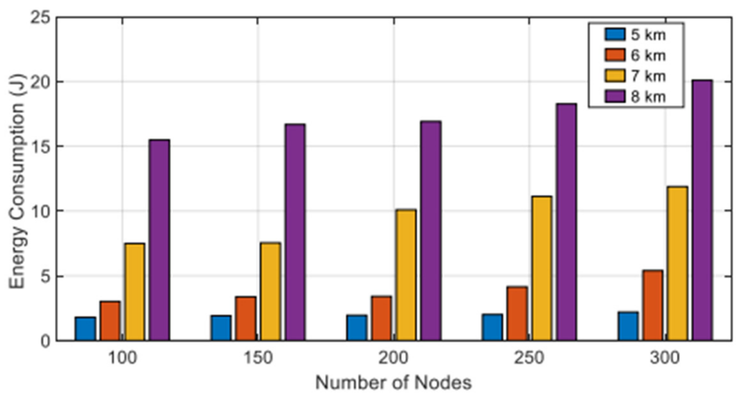


Figure 3.17. Energy/node/packet used vs. number of nodes for different transmission ranges.

The effect of network size (actually, the network density) on the average number of hops is shown in Figure 3.18, jointly with the average number of hops of SPRINT protocol. In comparison of two graphs, it is well evident that average number of hops of the proposed fuzzy scheme is lower than the same figure obtained with SPRINT protocol.

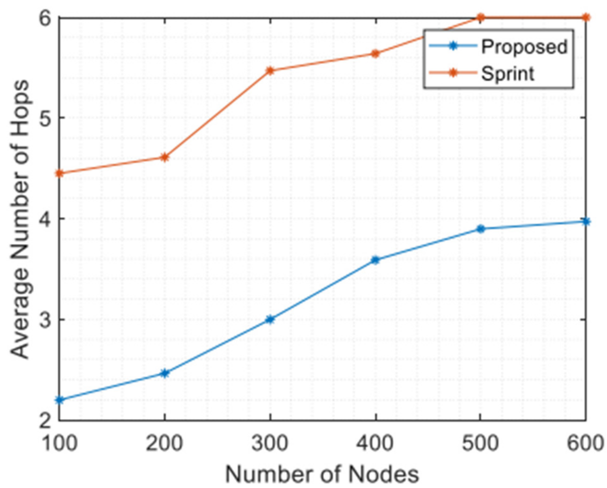


Figure 3.18. Average number of hops vs. number of nodes.

Figures 3.19 shows a comparison of the results of the proposed protocol and the same results of the SPRINT protocol. The fuzzy inference scheme finds paths with fewer hops and lower energy consumption. Table 3.5 shows a comparison in terms of energy consumption between our protocol and both protocols SPRINT and RECRP.

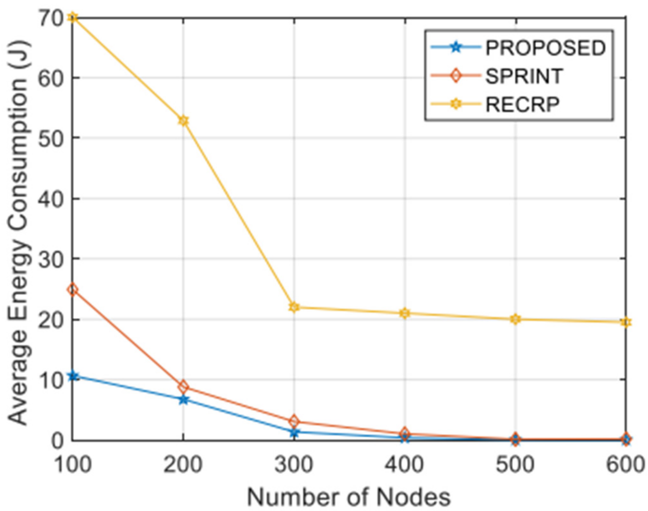


Figure 3.19. Energy/node/packet vs number of nodes.

Table 3.7. Comparison Table of Proposed vs Existing techniques.

	Energy (J)		
Number of nodes	**Proposed**	**SPRINT**	**RECRP**
100	10.5	25.56	70
200	6.55	8.451	52.9
300	3.10	3.433	22
400	0.99	1.249	21
500	0.25	0.528	20
600	0.15	0.637	19.5

3.6. Conclusion

The performance of UWSNs can be improved by taking advantage of data reception at neighboring relay nodes and their cooperation in forwarding the data to the next hop. Since the sensor nodes have limited energy, it is impossible for the nodes to forward the packets by utilizing only one-hop routing; therefore, multihop routing is preferred. The problem is when source nodes send the data to all their neighbor nodes overhearing the packets within the transmission range, owing to the propagation nature of wireless communication. Thus, selecting an efficient forwarding relay is the main task [7,8]. Besides many other challenges in UWSNs, the packet forwarding or relaying through a node with energy efficiency and low end-to-end (E2E) delay will be crucial, while the second-best relay node will be selected among all the remaining candidate nodes [9]. A way to establish a relay forwarding scheme is by setting the priority among the nodes: a node with the highest priority will be selected for packet forwarding to the next hop. Several investigations have been conducted on the selection of forwarding nodes, which include the weight methods as described in the SPRINT protocol [10]. Information residing in the routing tables allows assigning the forwarding node based on those with lower distance and lower hop counts from the sink, as in [11]. One problem with some of these techniques is that some useful input parameters, such as the received signal strength indicator (RSSI) as a distance measure, or the number of hops, number of neighbors, and residual energy of a node, are not considered while designing the protocol. To address these issues, in this work, we introduce a forwarding relay mechanism based on two tasks: (i) selecting the best forwarding node using fuzzy decision jointly with a weight method and (ii) using the time-division multiple access (TDMA) scheme among nodes to avoid collisions, reducing delay. In order to implement the novel fuzzy decision presented in this work, the SPRINT protocol [10] is used, but the decision process is changed to select the forwarding node to include FAHP. FAHP is based on pairwise comparisons between nodes to assign a score value (named relative importance) of a node over the other under a specific criterion. So, three novel strategies are introduced (details in Section 4.2) for determining the relative importance of the comparisons, one for every criterion considered in this work: distance to the gateway, number of hops, and number of neighbors. After that, the relative importance values are arranged in three matrices (one for each criterion) before FAHP can be applied. Lastly, a final score is calculated for every candidate node, and the highest score node is selected as the best option to be the next node in the path.

In this paper, we presented a routing protocol for randomly deployed underwater network. The sensor nodes are deployed randomly to monitor the environment or to warn of natural disasters, like tsunamis. The protocol is designed to optimize the data throughput and energy consumption of the sensor nodes. This protocol does not require additional sensing devices to ascertain the location. Hence, the proposed routing protocol is based neither on the location of the nodes nor on the topology of the network. SPRINT is a proactive protocol to minimize the routing delay. Each node that wants to send a packet knows the forwarding node in advance. At regular intervals, when a node receives the data packet, it computes RSS, hops, and neighbors to optimize the routing path and overcome the issue of a dead node. This regular update of the routing path makes the protocol resilient and more efficient. However, computing routing path parameters upon receiving each data packet will increase the energy consumption significantly; therefore, the routing path update will be carried out after certain number of data packets, depending on the arrival rate. Energy consumption is low due to the adaptive transmission power, which is adjusted with the help of RSS estimation. Throughput can also be increased by reducing the relay nodes between the data source node and the gateway. Data traffic among the relay nodes is distributed evenly by considering the number of neighbors at the time of forwarding node selection.

Chapter 4: Energy Efficient UWSN routing protocol using Fuzzy Analytical Hierarchy Process

This chapter produces the concepts of Fuzzy Analytical Hierarchy Process and explains how FAHP can be used to select the best forwarding node by considering the input parameters. This technique is an advanced version of fuzzy logic. Results show that FAHP performs better than existing techniques like SPRINT, SPRINT-FUZZY and so on.

4.1. Introduction

UWSN consists of many nodes and the decision is taken by one of the nodes to forward or relay the packet towards the gateway node (GW). Thus, it is very important for a sensor node to make a decision and the decision is made considering several parameters. In the previous scheme we have made the decision to choose a relay node based on fuzzy logic. However, UWSN communication needs to take Multicriteria decision making (MCDM) [97] to efficiently select the relay node. One of the MCDM technique which we have utilized in our proposed scheme is FAHP (Fuzzy Analytical Hierarchy Process) [98], [99]. Multicriteria decision making works in a different way as compared to fuzzy logic because MCDM is based on goal (what is goal or objective)- the objective is to select the relay node. The next is criteria (what is the criteria of selection of relay node)- in our case we have considered three main parameters as discussed in chapter 3. Then, sub-criteria (what are the sub-criteria which affect the criteria). E.g.- criteria is throughput then sub-criteria can be number of hops and number of neighbors because ultimately these two parameters affect the throughput. In the last, considering all the said steps an alternative is chosen based on weight scheme. The alternative are sensor nodes and the node which has the highest weight will forward the packet towards the GW node and the process continues until the sink is reached. It is obvious that selection of a forwarding node cannot be done in single criteria because a number of input parameters are considered while selecting the relay node.

4.2. FAHP based efficient routing protocol.

The UWSN routing protocols generally consist of four phases: network deployment, neighbor discovery, relay node selection, and communication phase. The scope of this work is limited to relay node selection by using decision making. Nodes are located randomly at various locations and depths, except for the gateway (GW) node that resides on the surface (random location too). After the deployment task, we can consider for analysis purposes that nodes will remain static (anchored to the seafloor or fixed to a buoy) and be placed far enough to prevent sending the same packet from multiple nodes to the sink or avoid undesired overlaps (minimum distance between two adjacent nodes or neighbor nodes.

In the creation of a path from a node to the gateway, the next forward node selection has been performed by considering input parameters such as distance between nodes, number of hops to reach the GW, number of neighbor nodes, and the transmission range by applying a fuzzy process (based on FAHP technique) explained in the next section. As a result, the last node of the path chooses as next relay node the node having the highest score (weights in FAHP) among the rest of candidate nodes.

The proposed protocol uses a fuzzy analytical hierarchy process (FAHP) to select the best relay node among several alternatives. These alternatives are selected based on three input parameters: number of hops, number of neighbors, and distance to the gateway.

4.2.1 Fuzzy Analytical Hierarchy Process

Fuzzy AHP is a technique used to solve many complex problems, and it is efficient in decision-making problems, which usually are complicated to manage. In AHP, the decision is made based on priorities, and the best decision is selected among the alternatives. AHP consists of three levels: the main goal, the evaluation criteria, and the alternatives. During a decision-making process, the alternatives are compared with each other, which helps in the selection of the best choice. Pairwise AHP is helpful in reducing complicated decisions and becomes helpful for decision makers, allowing them to reduce decision biases. In AHP, every criterion has a weight assigned that indicates its importance. The proposed criteria are then applied to the alternatives, assigning a priority to each of them to select the best candidate . The objective of AHP is to select the alternative (node) that best describes the set of criteria, calculating the weights of each criterion [100].

Fuzzy pairwise comparison is applied to criteria and alternatives through linguistic variables which are represented by real numbers named triangular fuzzy numbers (TFNs). A membership function is the linear representation of the TFNs. We will use a triangular shape function which is defined in equation (3.1). Many operations can be performed on TFNs, and in our case, we will employ three of them: addition, multiplication, and reciprocal. These operations can be introduced by the following equations.

$$(l_1, m_1, u_1) \oplus (l_2, m_2, u_2) = (l_1 +, l_2, m_1 + m_2, u_1 + u_2) \tag{4.1}$$

$$(l_1, m_1, u_1) \otimes (l_2, m_2, u_2) = (l_1 * l_2, m_1 * m_2, u_1 * u_2) \tag{4.2}$$

$$(l_1, m_1, u_1)^{-1} = \left(\frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1}\right) \tag{4.3}$$

It can be noted in (4.3) that in the reciprocal TFN, an increasing order of the components is needed to fulfill the definition of a membership triangular function. In this work, we will use both the Chang [101] and Buckley [102] methods to calculate the final weights for selecting the best alternative. The steps of applying FAHP are given in the next subsections.

4.2.2 Criteria Selection

The problem of selecting the relay node can be represented by a three-level diagram as shown in Figure 4.1. We will consider here three criteria: distance to the gateway, number of hops, and number of neighbors. Additionally, we choose to limit the alternatives to four (or fewer, depending on the number of candidate nodes).

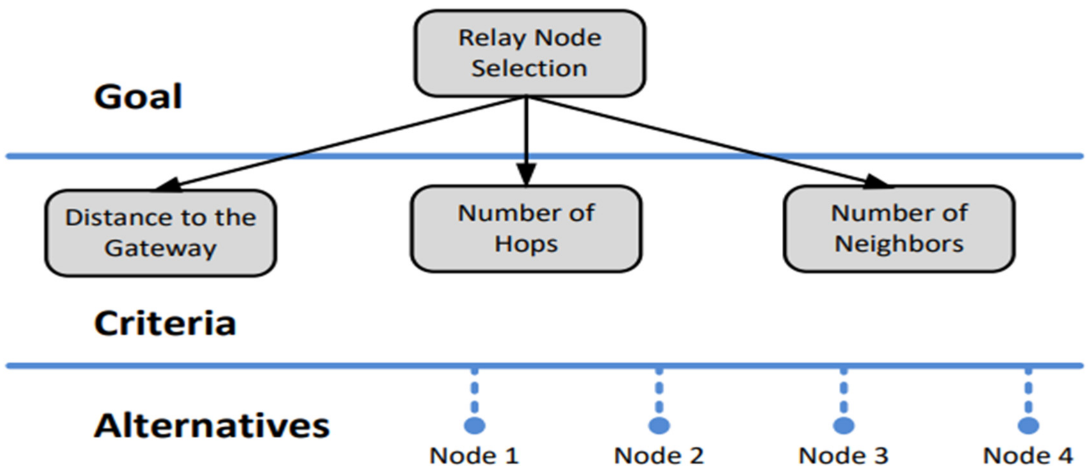


Figure 4.1. FAHP scheme applied to select best relay node of four alternatives (node or candidates).

In a four-level scheme, FAHP can contain sub-criteria under the criteria level. But in the case of interest, due to the ad hoc network is random, we have not more criteria relevant than those mentioned, because the topology is unknown until the paths are created.

4.2.3 Pairwise Comparison Matrix

The next step is to create a comparison matrix between every pair of criteria. That means to set how important is a criterium versus another one. For example, if a candidate node (i.e., within the transmission range of the node running FAHP) is far from Gateway (is bad for routing: high delay), but has many neighbors (high reliability to reach the Gateway), which criteria will be more important? The answer is a pairwise matrix which establishes the level of importance between two criteria. This is the starting point of FAHP, similar to establishing priorities between the set of criteria.

Firstly, we should consider a range of values to measure the importance. Usually, this importance value follows the Saaty scale [103] (refer Table 4.1), starting from Equal significance (value 1) to Extreme significance (value 9).

Table 4.1. Saaty Scale.

Importance	Definition	TFN	Reciprocal Scale TFN
1	Equal Significance	(1,1,1)	(1,1,1)
3	Moderate Significance	(2,3,4)	(1/4, 1/3, 1/2)
5	Strong Significance	(4,5,6)	(1/6, 1/5, 1/4)
7	Very Strong Significance	(6,7,8)	(1/8, 1/7, 1/6)
9	Extreme Significance	(9,9,9)	(1/9, 1/9, 1/9)
2	(Intermediate values)	(1,2,3)	(1/3, 1/2, 1)
4		(3,4,5)	(1/5, 1/4, 1/3)
6		(5,6,7)	(1/7, 1/6, 1/5)
8		(7,8,9)	(1/9, 1/8, 1/7)

Average Pairwise Comparison Matrix In the case of K multiple decisions (K ≥ 1), it is necessary to average all of them, using.

$$\tilde{m}_{ij} = \frac{1}{K}\sum_{k=1}^{K} m_{ij}^{k} \tag{4.4}$$

yielding an average comparison matrix $\tilde{T}$, expressed as

$$\tilde{T} = \begin{bmatrix} \tilde{m}_{11} & \cdots & \tilde{m}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{m}_{n1} & \cdots & \tilde{m}_{nn} \end{bmatrix} \tag{4.5}$$

4.2.4 Geometric Means: By using the geometric means method of Buckley, the TFN values of every criterion in the fuzzy pairwise comparison can be obtained by the following equation

$$\tilde{g}_i = \left(\prod_{j=1}^{n} \tilde{m}_{ij}\right)^{\frac{1}{n}}, i = 1,2,\dots,n \tag{4.6}$$

Where $\tilde{g}_i$ is the geometric mean TFN value for the i-criterion.

4.2.5 Fuzzy Weights of Criteria

The calculation of the weights for each i-criterion can be summarized in the following operation

$$\tilde{w}_i = \tilde{g}_i \otimes (\tilde{g}_1 \oplus \tilde{g}_2 \oplus \cdots \oplus \tilde{g}_n)^{-1} \tag{4.7}$$

where addition (⊕), multiplication (⊗), and reciprocal (( )−1) operations over TFNs have been previously defined in (4.1)–(4.2). Note that the fuzzy weight for the i-criterion $\widetilde{w}_i$ resultant is a TFN as well, so it can be expressed in its components of the membership function as

$$\widetilde{w}_i = (lw_i, mw_i, uw_i) \tag{4.8}$$

4.26 Real Normalized Weights

At this point, we have a TFN weight for every i-criterion ($\widetilde{w}_i$). In order to obtain a single value for every TFN ($\widetilde{w}_i$), is necessary to perform the defuzzification process. In our case, we employ the well-known center of area method [104],

$$q_i = \frac{l_{w_i}+m_{w_i}+u_{w_i}}{3} \tag{4.9}$$

where q_i stands for the final real weight for the i-criterion.

In order to use a relative quantity among all the criteria set, is necessary to normalize every weight by using the following relation,

$$l_i = \frac{q_i}{\sum_{k=1}^{n} q_k} \tag{4.10}$$

where l_i is the normalized weight of the i-criterion.

Before applying the FAHP technique presented, we need to establish how to compare two nodes under the three criteria considered and give a value (the relative importance) as a result on the Saaty scale.

4.3. Metric of Selection

4.3.1 Criterion 1: Distance to the Sink

With the objective of obtaining the relative importance between two nodes on the Saaty scale, an initial estimation value for the longest possible direct route is marked in Figure 4.2, which would be that between a node located in the bottom corner opposite to the upper corner in diagonal, where the GW would be located (on the surface). This maximum distance of the direct longest route (no hops, only theoretical) is given by

$$d_{Max} = \sqrt{(a-0)^2 + (0-b)^2 + (0-c)^2} = \sqrt{a^2 + b^2 + c^2} \tag{4.11}$$

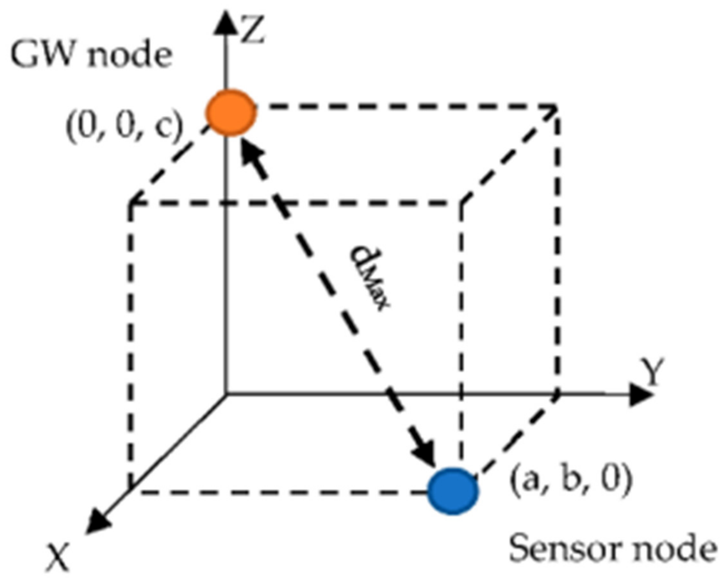


Figure 4.2. Maximum distance in a 3D box.

Of course, there could be longer routes once they are created due to the multiple hops to reach the GW, but this value can be updated as long its known by the network (i.e. the route has reached the final node, the GW).

The final objective of the comparison now, is to set the relative importance between two nodes for constructing the pairwise matrix that is necessary to apply for FAHP among the alternatives (not between the criteria, that has been set by T^k in (4.5)).

In Figure 4.3, we introduce a situation to introduce the problem of comparing the relative importance of distance to the gateway node. We have two nodes A and B with different distances dA and dB, respectively. Additionally, we can assume two restrictions in the deployment zone: a minimum (dmin) and maximum (dmax) distance (to the gateway) that a node can have. The problem is determining how to grade the importance on the Saaty scale proposed (a value in the range [1,9]) when a node is closer to or further from the gateway than another one.

Figure 4.3. (left) distances (right) constraints for applying decision criteria.

In order to compare how good is the distance of node A related to node B to the Gateway, the difference between its distances can be firstly considered, and then use a linear normalization to give a value in the Saaty scale (within [1,9]). For doing that, we can take into account the limit situations i.e. the best case and the worst case. Assuming that $d_B > d_A$ (A is closer than B), both cases are defined by the difference of distances:

$$\text{(Best case:)} \qquad \Delta_b = d_B - d_A \quad / \ \{d_B = d_{max}, d_A = d_{min}\} = d_{max} - d_{min} \tag{4.12}$$

$$\text{(Worst case:)} \quad \Delta_w = d_B - d_A \quad / \ \{d_B = d_A + \ \delta\ \} = \delta \tag{4.13}$$

where Δ_b and Δ_w stand for the best and worst possible distance differences respectively. The parameter δ is a threshold to define what is considered as the same distance in a practical way. In order to have nine equally space intervals in the domain of difference of distances (δ, Δ_b), a new interval $\Delta_{S,d}$ (S subindex comes from Saaty) is defined:

$$\Delta_{S,d} \ = \frac{d_{max} - d_{min}}{9} \tag{4.14}$$

Finally, in order to get a single natural value of importance of d_A vs. d_B only remains to employ the following expression, where $\lceil\cdot\rceil$ is the ceil function (round toward positive infinitive):

$$I_{AB} = \begin{cases} \left\lceil \frac{d_B - d_A}{\Delta_{S,d}} \right\rceil & , if\ d_B > d_A \\ 1 & , if\ |d_B - d_A| \le \delta \end{cases} \tag{4.15}$$

where I_{AB} is the importance level for distance criterion on the Saaty scale of node A vs. node B. Note that $I_{AB} \in [1, 9]$. In case of dA > dB, the comparison is similar but in the opposite way: it would be the comparison of the B node with the A node. In that case, the reciprocal TFN value should be used in the pairwise comparison matrix for node A vs. node B. As an example, Figure 4.4, shows the importance level I_{AB} calculated by (20) for various locations of two nodes A and B. While one is approaching the gateway (node B) from the maximum distance, another one is going away (node A) from the minimum distance to the gateway.

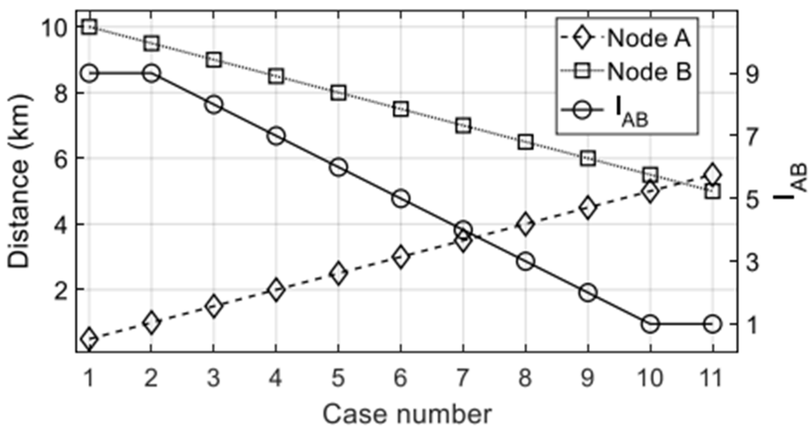


Figure 4.4. Importance value IAB (circles) when nodes A, B are compared under the distance criterion. Data: dmax = 10 km, dmin = 0.5 km, $\boldsymbol{\delta}$=1.

4.3.2 Criterion 2: Number of Hops

Following similar steps regarding the distance criterion, the number of hops is another important measure to compare candidate nodes to be selected for a routing path. The objective is clear: inside a set of several nodes (candidates), a pairwise comparison matrix must be constructed, where every value of importance for a pair of nodes (I_{AB}) in the matrix should be on the Saaty scale (within the interval [1, 9]).

In order to set the scale of the problem, a starting point is to estimate the limits. In this sense, we can use the latter two parameters: the minimum (d_{min}) and maximum (d_{max}) distance to the Gateway that a node can have. Assuming two nodes A and B with d_A and d_B distances to the Gateway ($d_B > d_A$ i.e. A is closer than B to the Gateway), we can consider two scenarios for the best and worst cases for estimating the N_h (number of hops) as:

$$\text{(Best case:)} \quad \{\, d_A = d_{min}\,,\ d_B = d_{max}\} \Rightarrow N_{h,A} = 1\,,\ N_{h,B} = \left\lceil \frac{d_{max}}{d_{min}} \right\rceil \tag{4.16}$$

$$\text{(Worst case:)} \quad \{\, d_B - d_A = d < \delta\,\} \Rightarrow N_{h,A} = N_{h,B} \in \left[1, \left\lceil \frac{d}{d_{min}} \right\rceil\right] \tag{4.17}$$

where the parameter δ has the same meaning as in distance criterion: a threshold to define what is considered as the same distance in a practical way, and $N_{h,A}\,, N_{h,B}$ are the number of hops from every node to reach the Gateway. In order to have nine equally intervals in the domain of number of hops (1, $\left\lceil \frac{d_{max}}{d_{min}} \right\rceil$), a new interval $\Delta_{S,h}$ is defined:

$$\Delta_{S,h} = \frac{{}^{d_{max}}/_{d_{min}} - 1}{9} \tag{4.18}$$

Evaluating the comparison between A and B nodes, the importance in the best case, would have a value of 9 in the Saaty scale, meaning that is very convenient to choose A node instead of B node under this criterion of number of hops. In the opposite case (worst) the importance I_{AB} would having a value of 1 indicating that any node has the same number of hops, and both has the same opportunity to be selected. In a general case the final expression for the relative importance between for two nodes A , B, can be given by,

$$I_{AB} = \begin{cases} \left\lceil \dfrac{{}^{d_B}/_{d_A}}{\Delta_{S,h}} \right\rceil & , if\ d_B > d_A \\ 1 & , if\ |d_B - d_A| \le \delta \end{cases} \tag{4.19}$$

where $[\cdot]$ stands for the nearest integer function. It can be observed again that $I_{AB} \in [1,9]$. Another waypoint is to compare directly the number of hops between the two nodes A , B ($N_{h,A}\,, N_{h,B}$) from the limits value ($N_{h,max} = \left\lceil \frac{d_{max}}{d_{min}} \right\rceil$, $N_{h,min} = 1$)

$$I_{AB} = \begin{cases} \left\lceil \dfrac{N_{h,B} - N_{h,A}}{\Delta_{S,NH}} \right\rceil & , if\ N_{h,B} > N_{h,A} \\ 1 & , if\ \left|N_{h,B} - N_{h,A}\right| \le \delta \end{cases}, \qquad \Delta_{S,NH} = \frac{N_{h,max} - 1}{9} \tag{4.20}$$

As usual, in case of $N_{h,A} > N_{h,B}$, the value of I_{BA} would be the inverse of the equivalent I_{AB} . A similar example as in distance criterion is shown in Figure 4.5, to prove a good behavior of above equation.

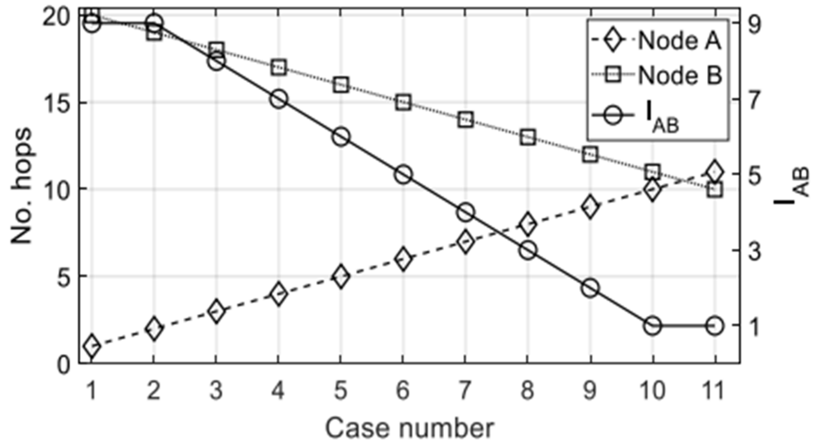


Figure 4.5. Importance value IAB (circles) when nodes A, B are compared under the number of hops criterion. Data: dmax = 10 km, dmin = 0.5 km, $\boldsymbol{\delta}$=1.

4.3.3 Criterion 3: Number of Neighbors

As done with the two previous criteria, distance and number of hops, the numbers of neighbors between two candidate nodes are compared, and a final value should be obtained within the Saaty scale [1, 9] to build the corresponding pairwise matrix. In a random network, is impossible to know a priori what the maximum number of neighbors of a node is. However, we can approximate the problem to be in an intermediate situation bounded by the best and the worst topologies. The best topology we can imagine is a dense and regular mesh of nodes, where all of them are at the distance d_{min}, imposed by the deployment conditions for the network. When more nodes are included, a node in the center of a sphere of radius d_{Tx} (transmission range) will have a greater number of neighbors. Due to the problem being 3D, it is necessary to think of filling this sphere (radius d_{Tx}) with a regular structure of nodes. The solution is to use regular polyhedrons, which can be inscribed in a sphere and keep the regularity. That is, the nodes (vertices) will keep the distance dmin between adjacent vertices. Among the five regular polyhedrons known (tetrahedron, cube, octahedron, dodecahedron, and icosahedron), the polyhedron with the greatest number of vertices is the dodecahedron with 20 vertices and 12 faces, shown in Figure 4.6.

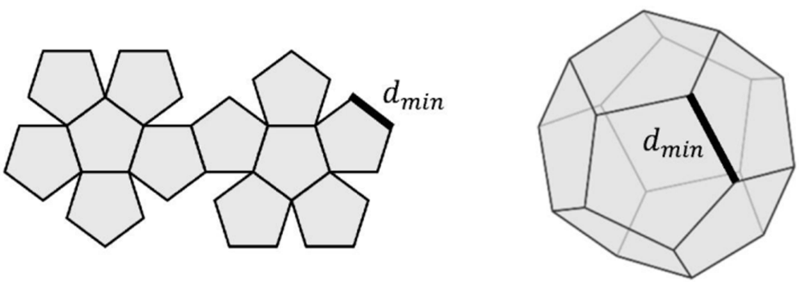


Figure 4.6. Dodecahedron: sided (left) and polyhedral (right) shape.

The best topology for having maximum number of neighbors is to fill the big sphere of radius d_{Tx} with equal dodecahedrons of side length d_{min} . This way, between two adjacent nodes (vertices), a distance d_{min} is conserved and the mesh is a 3D structure. In spite of exist holes in the space when we fill a sphere with dodecahedra (the rhombic dodecahedron is the structure that tessellates the space without holes), we follow with this reasoning (simpler), and by using the volumes of sphere and dodecahedron, the expression to get the total number of neighbors (nodes) $N_{n,max}$ can be approximate as

$$V_{sphere} = 4\,\pi\,d_{Tx}^3 \tag{4.21}$$

$$V_{dodecahedron} = \frac{1}{4}\left(15 + 7\sqrt{5}\right)d_{min}^3 \tag{4.22}$$

$$N_{n,max} \sim \frac{V_{sphere}}{V_{dodecahedron}} \times 20 - N_{common} \tag{4.23}$$

being N_{common} the number of common vertices when a set of dodecahedra are joined together. This number is easy to get from a practical way and a possible empirical solution is presented in the Table below (is not the only one, depends on the position selected for the new dodecahedron with respect to others). It is assumed that every added dodecahedron is set to share the greatest number of faces as possible, for its nodes are nearest of the rest of vertices already present. So, we can approximate that the new one added always is sharing 3 common faces.

Table 4.2. Common vertices in structures composed of dodecahedra.

No. dodecahedra (n)	$\boldsymbol{N_{common}}$
2	5
3	5 + 2 x 5 = 15
4	15 + 3 x 5 = 30
5	30 + 3 x 5 = 45
More than 6	(n-2) x 15

In the opposite direction, the worst case for a node *A* having a minimum number of neighbors is that in which exists only another node *B* inside the region included in a sphere of radius d_{Tx} with center the location for node *A*. Any other situation can be assumed to be bounded into these two situations (best and worst). For this reason, to compare the number of neighbors of two nodes *A* and *B* with number of neighbors N_A and N_B respectively, and have the information value that $I_{AB} \in [1,9]$ (Saaty scale), a suitable expression could be the following:

$$I_{AB} = \begin{cases} \left\lceil \dfrac{N_{n,B} - N_{n,A}}{\Delta_{S,NH}} \right\rceil & , \; if\; N_{n,B} > N_{n,A} \\ 1 & , \; if\; \left|N_{n,B} - N_{n,A}\right| \le \delta \end{cases} \quad , \qquad \Delta_{S,NH} = \frac{N_{n,max} - 1}{9} \tag{4.24}$$

where $\lceil\cdot\rceil$ is the ceil function (round toward positive infinitive). In the Figure 4.7, the comparative value of the importance I_{AB} is measured in a set of cases where two nodes *A*, *B* are considering getting closer in number of neighbors. In the first case of the graph, $N_{n,A} = N_{n,max}$ and $N_{n,B} = 1$, which is the best possible case. In this situation, $I_{AB} = 9$ i.e., the node *A* has the maximum chance to be selected against node *B*, considering the number of neighbors criterium. On the other side, it can be seen as I_{AB} reach value 1 when both nodes have similar number of neighbors. The values shown in the Figure 4.7 are given in the Table 4.3 for clarity.

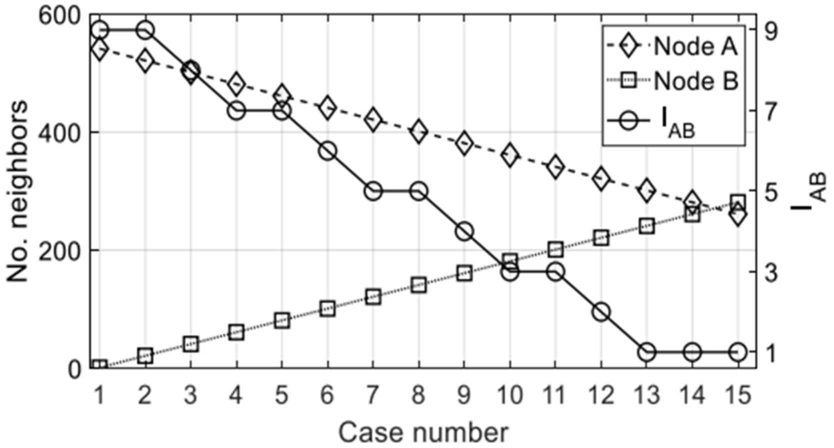


Figure 4.7. Importance value $\boldsymbol{I_{AB}}$ when nodes A, B are compared under the number of neighbors criterion. Data: dmin = 0.5 km, dTx = 2 km, $\boldsymbol{N_{n,max} = 550}$, $\Delta_{S,n} = \boldsymbol{61}$, $\boldsymbol{\delta}$ = 5.

Table 4.3. Information values from Figure 4.7 (number of neighbors criterion).

No.case	$N_{n,A}, N_{n,B}$	I_{AB}	No.case	$N_{n,A}, N_{n,B}$	I_{AB}	No.case	$N_{n,A}, N_{n,B}$	I_{AB}
1	541 , 1	9	6	441 , 101	6	11	341 , 201	3
2	521 , 21	9	7	421 , 121	5	12	321 , 221	2
3	501 , 41	9	8	401 , 141	5	13	301 , 241	1
4	481 , 61	7	9	381 , 161	4	14	281 , 261	1
5	461 , 81	7	10	361 , 181	3	15	261 , 281	1

4.4. Application of FAHP to Criteria

At this point, the FAHP will be used specifically to our problem of selecting the best relay node among the best four alternatives (nodes). Firstly, the different criteria considered are evaluated in the Saaty scale, as show the Table 4.1. These values including the reciprocal numbers calculated as its inverse value (e.g., if Distance vs. No. Hops value is 6, then No. Hops / Distance will be its reciprocal with value 1/6). The reason to use an importance value of 6 if for stability, in the middle of the Saaty scale, although other values are possible, and the method works fine.

Table 4.4. Pairwise comparison matrix of criteria.

Pairwise comparison	Distance	No. Hops	No. Neighbors
Distance	1	6 *	6 *
No. Hops	1/6	1	6 *
No. Neighbors	1/6	1/6	1

* 6: between 5 (Strong significance) and 7 (Very strong significance)

The next step is to calculate fuzzy criteria of importance, introducing TFN in Table 4.4, yielding to values presented in Table 4.5.

Table 4.5. Pairwise comparison matrix of criteria as TFN.

Pairwise comparison	**Distance**	**No. Hops**	**No. Neighbors**
Distance	(1,1,1)	(5,6,7)	(5,6,7)
No. Hops	(1/7,1/6,1/5)	(1,1,1)	(5,6,7)
No. Neighbors	(1/7,1/6,1/5)	(1/7,1/6,1/5)	(1,1,1)

According to (4.6), we can calculate the geometric mean $\tilde{g}$ from every criterion from Table 4.5, yielding to values in Table 4.6. As an example, for the distance criterion, its TFN $\tilde{g}$ extended over every criterion of the 3 considered, will be calculated as follows,

$$\tilde{g} = (l, m, u) = \left((1 \cdot 5 \cdot 5)^{\frac{1}{3}}, (1 \cdot 6 \cdot 6)^{\frac{1}{3}}, (1 \cdot 7 \cdot 7)^{\frac{1}{3}}\right) = (2.924, 3.3019, 3.6593)$$

Table 4.6. Geometric mean of criteria.

Criteria	$\tilde{g}$
Distance	(2.924, 3.3019, 3.6593)
No. Hops	(0.8939, 1, 1.1187)
No. Neighbors	(0.2733, 0.3029, 0.3420)
Total Mean ($\sum_{i=1}^{3} \tilde{g}_i$)	(4.0912, 4.6048, 5.12)
Reciprocal of Total Mean	(0.1953, 0.2171, 0.2444)

Once the mean of every criterion has been obtained, is time to calculate the fuzzy weights from (4.7). This can be calculated by multiplying each $\tilde{g}_i$ value with the reciprocal value of the total mean, yielding to values in Table 4.7. For example, for the distance criterion, its TFN weight $\widetilde{w}$ would be calculated as follows,

$$\widetilde{w} = (l, m, u) = \left(\frac{2.924}{5.12}, \frac{3.3019}{4.6048}, \frac{3.6593}{4.0912}\right) = (\, 0.5711, 0.7171, 0.8944)$$

Table 4.7. Weighted matrix of criteria $\widetilde{w}$.

Criteria	$\widetilde{w}$
Distance	(0.5711, 0.7171, 0.8944)
No. Hops	(0.1746, 0.2172, 0.2734)
No. Neighbors	(0.2733, 0.3029, 0.3420)

From Table 4.7 it is possible obtain the non-fuzzy weights q_i from (4.9), and their corresponding normalized values l_i from (4.1), whose values are presented in Table 4.8. As example, in case of the distance criterion, its weight q_i is calculated as: (0.5711 + 0.7171 + 0.8944) /3 = 0.7275, and its corresponding normalized value: 0.7275 / (0.7275 + 0.2217 + 0.0676) = 0.7155. Note that the summation of the normalized weights l_i is equal to 1.

Table 4.8. Non-Fuzzy (q_i) and normalized (l_i) weights.

Pairwise comparison	$\boldsymbol{q}$	$\boldsymbol{l}$
Distance	0.7275	0.7155
No. Hops	0.2217	0.2180
No. Neighbors	0.0676	0.0665

At this point, we have the normalized weights (l_i) corresponding to every criterion, that will be applied to every candidate node to select the best one. In order to make the final decision it is necessary to carry out a similar comparison process by means of a matrix between every pair of candidate nodes (alternatives) under every criterion considered. The final result of this process is to obtain a new set of normalized weights l_i^k for every alternative i under the criteria k. The whole process in a case of example, is given in Appendix A (4.14-4.23)

A valid definition for the final score of every alternative is given by the rank:

$$Rank_{\mathrm{i}} = \sum_{k=1}^{3} l_k \cdot l_i^k \tag{4.25}$$

where l_k is the local weight of criteria k (from Table 4.8) and l_i^k is the weight of the criteria k calculated for the alternative (node) i. The selected alternative (node) will be the higher ranked of the four alternatives considered.

4.5. Computer Simulation Results

To test the performance of FAHP, the protocol SPRINT has been employed in its first version, changing the decision process of selecting the forwarding node by the multi criteria FAHP scheme presented in this work. Moreover, to compare the results obtained with another Fuzzy technique, a recent SPRINT Fuzzy-based version has been run under the same conditions presented in Table 4.9. The software used was MATLAB.

Table 4.9. Simulation Parameters.

Parameters	Value	Unit
Speed of sound	1500	m/s
Data rate	1500	bit / s
Frequency	48	kHz
Packet length	256	bits
Header length	30	bits
Transmission power	18	W
Number of nodes	100, 400	
Simulation length	10	
Minimum distance	1	km
Transmission range	2-7	km

For every transmission range considered, a number of 10 simulations have been done where everyone has a different random topology, and the results have been averaged. The area (volume) of deployment has been considered as 10 x 10 x 10 km. Although could seems that is a very high deep, is convenient to have a dispersive location of the nodes in 3D, being more difficult to create routes to the Gateway. Besides that, other authors also use the same volume for giving simulation results [51].

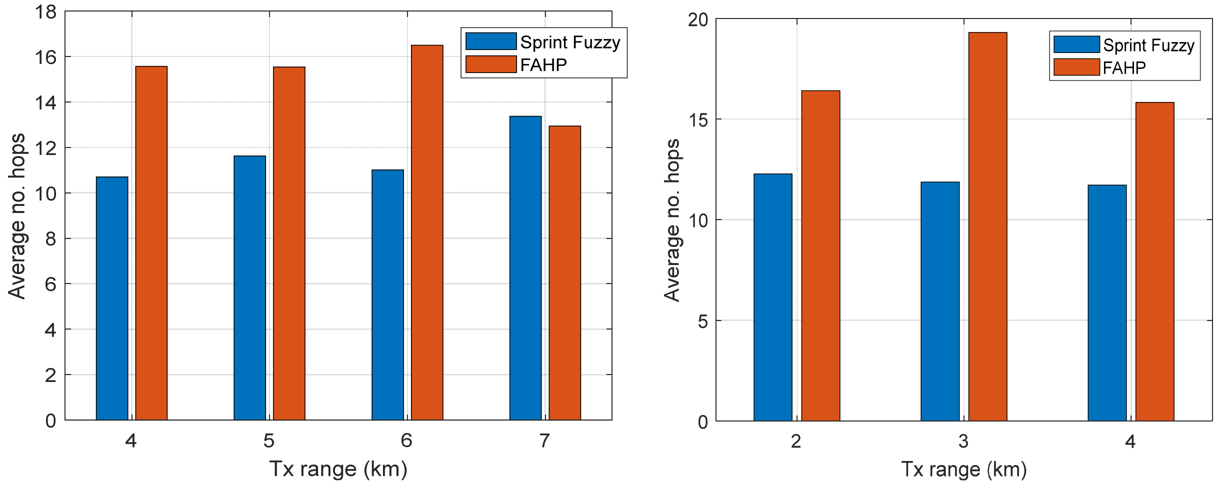


Figure 4.8. Average number of hops (left bar: SPRINT with Fuzzy Logic, right bar: FAHP method). Number of nodes: (a)100, (b) 400.

Table 4.10. Statistical comparison for average no. hops.

No. nodes	Tx range (km)	Av. No. hops Sprint	FAHP (%)	
100	4	10.7	15.57	(+46%)
100	5	11.62	15.54	(+33.7%)
100	6	11.01	16.49	(+49%)
100	7	13.37	12.94	(-3.2%)
400	2	12.28	16.41	(+33.6%)
400	3	11.87	19.3	(+62.6%)
400	4	11.73	15.83	(+35%)

Path length

One of the important parameters in the establishment of the paths for the initial random topology is the mean path long, i.e., average the number of hops of every path over all of them. Every path will end in the Gateway node on surface. The results obtained in FAHP and in SPRINT-Fuzzy are shown in Figure 4.9, sweeping in number of nodes (100 and 400) and different transmission ranges (4-7 km for 100 nodes, 2-4 km for 400 nodes).

Although the conclusion is that FAHP has a worse behavior than SPRINT-Fuzzy in creating the paths, they are close (see 100 nodes, transmission range 7 km). Moreover, FAHP can admit more criteria to be taken into account for enhance the selection. So, these results are not definitive, and they can be enhanced when including new metrics in FAHP, as density nodes in a region, residual energy for extending lifetime, etc.

Number of collisions

A metric related with the efficiency of energy consumption, is the number of collisions occurred during the phase of routes creation. In this sense, a lower number of collisions means a lower energy consumption and a suitable transmission range adopted. This problem is inherent to non-guided channel as underwater is. In the SPRINT protocol used here, there is a mechanism TDMA-based for avoid collisions, but due to the random position of the nodes in the network, in the initial creation path phase is impossible to avoid it completely.

The results obtained for both methods, FAHP and SPRINT-Fuzzy are presented in the Figure 4.9. It can be seen that FAHP is as good as SPRINT-Fuzzy, or even better in case of high number of nodes (e.g. 400 nodes), which is a more complex network and have more free degrees to make routes.

End-to-end delay

The end-to-end (E2E) delay can be defined as the elapsed time which an outgoing packet from a node takes to get the destination following a multihop path. In this case, a packet from an underwater sensor node to reach the Gateway node on surface. The longer the routes are, the higher the E2E delay is.

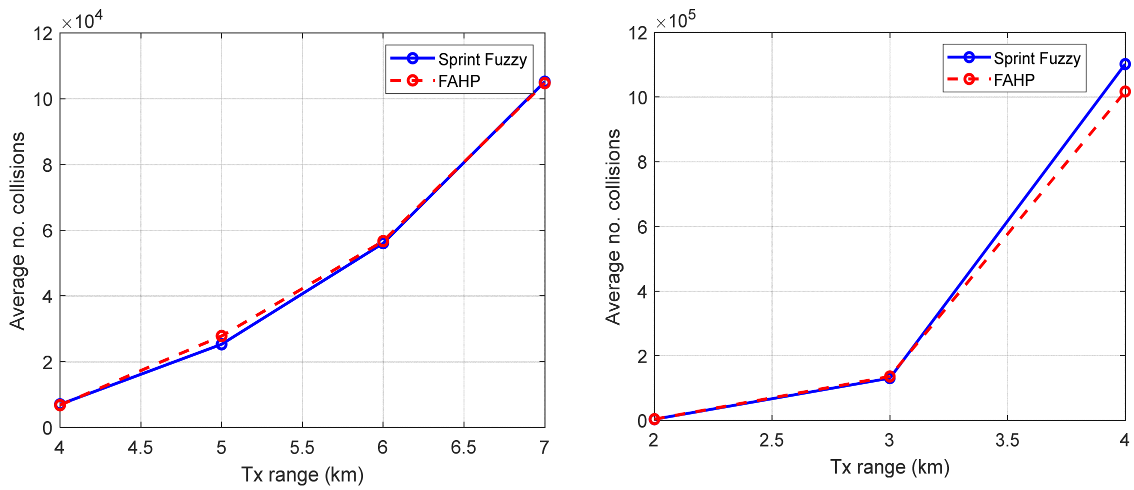


Figure 4.9. Average number of collisions. Number of nodes: (a) 100, (b) 400.

Table 4.11. Statistical comparison for average no. collisions.

No. nodes	Tx range (km)	No. collisions	
		Sprint	FAHP (%)
100	4	7041.9	6786.7 (-3.6%)
100	5	25296.5	27830.4 (+10%)
100	6	56056.3	56676.1 (+1.1%)
100	7	105135	104748 (-0.4%)
400	2	3680.7	3806.33 (+3.4%)
400	3	130852	135981 (+3.9%)
400	4	1101770	1016980 (-7.7%)

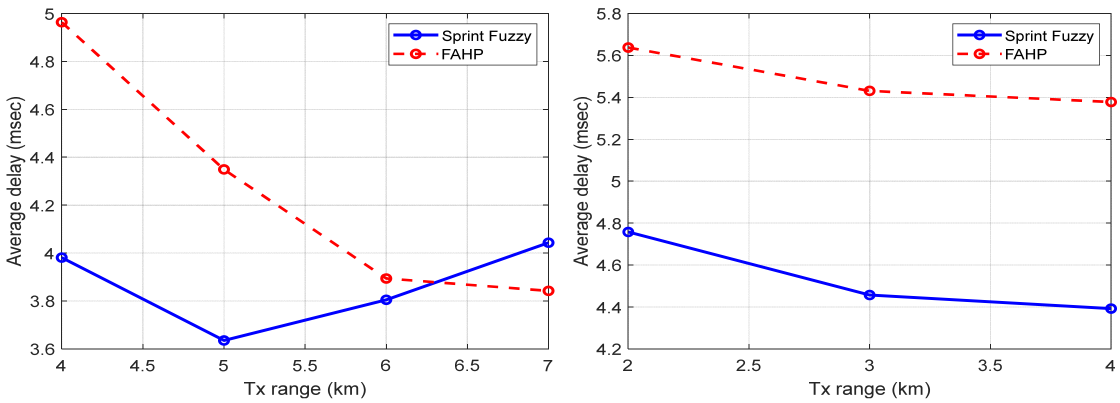


Figure 4.10. Average delay to reach the Gateway node. Number of nodes: (a) 100, (b) 400.

Table 4.12. Statistical comparison for E2E packet delay.

No. nodes	Tx range (km)	E2E delay (msec.)		
		Sprint	FAHP (%)	
100	4	3.98	4.96	(+24.6%)
100	5	3.64	4.35	(+19.5%)
100	6	3.8	3.89	(+2.4%)
100	7	4.04	3.84	(-5%)
400	2	4.76	5.64	(+18.5%)
400	3	4.46	5.43	(+21.7%)
400	4	4.39	5.38	(+22.6%)

The results obtained by simulations for both FAHP and SPRINT-Fuzzy are presented in Figure 4.10. It can be noted as FAHP has an acceptable delay when compared to SPRINT-Fuzzy but is a little worse in dense networks (400 nodes). The best behavior is observed when the transmission range is high, evident in Figure 4.10 for a transmission range of 7 km, obtaining a better delay than SPRINT-Fuzzy. This is logical due to a lower value of hops average for that specific case, shown in Figure 4.8.

A second analysis can be done from these results: FAHP is stable. Despite of increasing the network size in a factor of 4 (from 100 to 400 nodes), the average E2E delay is kept in a 4-6 msec interval, although the transmission range is changed between 2-7 km.

Energy consumption

In relation to the energy consumption, the computation takes into account the sum of both the average energy used in transmission and in reception for all nodes when all the paths have been created, i.e. the instant when all the nodes belong to a route that ends in the Gateway node.

Figure 4.11 contain the average energy consumption in the network. The value is a little worse for FAHP than for SPRINT-Fuzzy in this chapter, but it is justified by longer routes in FAHP, that takes more energy for packets to reach the Gateway.

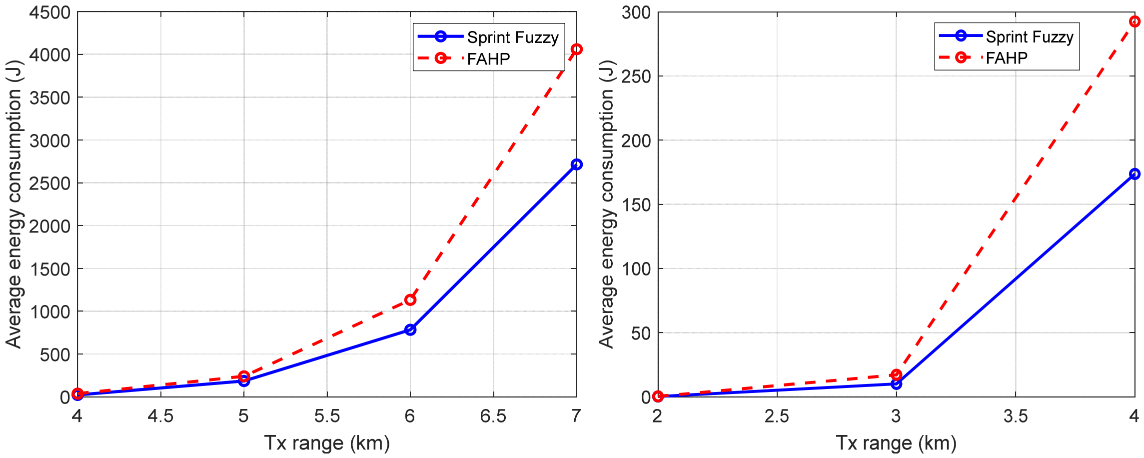


Figure 4.11. Average energy consumption. Number of nodes: (a) 100, (b) 400.

Table 4.13. Statistical comparison for E2E packet delay.

No. nodes	Tx range (km)	Av. Energy consumption (J)		
		Sprint	FAHP (%)	
100	4	21.8	36.6	(+67.9%)
100	5	183.6	238.8	(+30.1%)
100	6	782.3	1132.14	(+44.7%)
100	7	2714.2	4060.4	(+49.6%)
400	2	0.19	0.31	(+63.2%)
400	3	10	17.1	(+71%)
400	4	173.6	292.5	(+68.5%)

Appendix

In this appendix, the weights for every alternative under the three criteria considered is calculated step by step. For using numbers more than variables, we can assume a specific case of 4 alternative (nodes), where the alternative 2 is the most important and alternative 3 the least.

The starting point for applying the FAHP method is to obtain the pairwise comparison matrix, presented in Tables 4.14-4.16 for every criterion. The tables have been obtained by comparing every pair of nodes of the alternative set.

Table 4.14. Pairwise comparison matrix for distance criterion.

	Node 1	Node 2	Node 3	Node 4
Node 1	1	1/6	2	8
Node 2	6	1	3	7
Node 3	1/2	1/3	1	1/4
Node 4	1/8	1/7	4	1

Table 4.15. Pairwise comparison matrix for no. hops criterion.

	Node 1	Node 2	Node 3	Node 4
Node 1	1	1/5	2	6
Node 2	5	1	3	5
Node 3	1/2	1/3	1	1/3
Node 4	1/6	1/5	3	1

Table 4.16. Pairwise comparison matrix for no. neighbors criterion.

	Node 1	Node 2	Node 3	Node 4
Node 1	1	1/3	2	4
Node 2	3	1	4	3
Node 3	1/2	1/4	1	1/5
Node 4	1/4	1/3	5	1

The next step is to fuzzy the relative importance of the criteria, introducing TFN in Tables 4.14-4.16, yielding to values presented in Tables 4.17-4.19.

Table 4.17. Pairwise comparison matrix for distance criterion as TFN.

	Node 1	Node 2	Node 3	Node 4
Node 1	(1,1,1)	(1/7,1/6,1/5)	(1,2,3)	(7,8,9)
Node 2	(5,6,7)	(1,1,1)	(2,3,4)	(6,7,8)
Node 3	(1/3,1/2,1)	(1/4,1/3,1/2)	(1,1,1)	(1/5,1/4,1/3)
Node 4	(1/9,1/8,1/7)	(1/8,1/7,1/6)	(3,4,5)	(1,1,1)

Table 4.18. Pairwise comparison matrix for no. hops criterion as TFN.

	Node 1	Node 2	Node 3	Node 4
Node 1	(1,1,1)	(1/6,1/5,1/4)	(1,2,3)	(5,6,7)
Node 2	(4,5,6)	(1,1,1)	(2,3,4)	(4,5,6)
Node 3	(1/3,1/2,1)	(1/4,1/3,1/2)	(1,1,1)	(1/4,1/3,1/2)
Node 4	(1/7,1/6,1/5)	(1/6,1/5,1/4)	(2,3,4)	(1,1,1)

Table 4.19. Pairwise comparison matrix for no. neighbors criterion as TFN.

	Node 1	Node 2	Node 3	Node 4
Node 1	(1,1,1)	(1/4,1/3,1/2)	(1,2,3)	(3,4,5)
Node 2	(2,3,4)	(1,1,1)	(3,4,5)	(2,3,4)
Node 3	(1/3,1/2,1)	(1/5,1/4,1/3)	(1,1,1)	(1/6,1/5,1/4)
Node 4	(1/5,1/4,1/3)	(1/4,1/3,1/2)	(4,5,6)	(1,1,1)

Applying (4.6)-(4.10) to the values in the Tables 4.17-4.19, it is possible to calculate for every node and criterion: the geometric mean $\tilde{g}$, the fuzzy weights $\tilde{w}$, the non-fuzzy weights q_i , and normalized weights l_i . The obtained results are presented in Tables 4.20-4.22

Table 4.20. Geometric mean ($\tilde{g}$) and weights ($\tilde{w}$, q, l) for distance criterion.

	$\tilde{g}$	$\tilde{w}$	q	l
Node 1	(1, 1.2779, 1.5244)	(0.1511, 0.2283, 0.3318)	0.2371	0.2269
Node 2	(2.7832, 3.3504, 3.8687)	(0.4205, 0.5986, 0.8421)	0.6204	0.5936
Node 3	(0.3593, 0.4518, 0.6389)	(0.0543, 0.0807, 0.1391)	0.0914	0.0875
Node 4	(0.4518, 0.5170, 0.5874)	(0.0683, 0.0924, 0.1279)	0.0962	0.0920

Table 4.21. Geometric mean ($\tilde{g}$) and weights ($\tilde{w}$, q, l) for no. hops criterion.

	$\tilde{g}$	$\tilde{w}$	q	l
Node 1	(0.9554, 1.2447, 1.5137)	(0.1504, 0.2377, 0.3621)	0.2501	0.2361
Node 2	(2.3784, 2.9428, 3.4641)	(0.3743, 0.5621, 0.8286)	0.5883	0.5554
Node 3	(0.3799, 0.4855, 0.7071)	(0.0598, 0.0927, 0.1691)	0.1072	0.1012
Node 4	(0.4671, 0.5623, 0.6687)	(0.0735, 0.1074, 0.1600)	0.1136	0.1073

Table 4.22. Geometric mean ($\tilde{g}$) and weights ($\tilde{w}$, q, l) for no. neighbors criterion.

	$\tilde{g}$	$\tilde{w}$	q	l
Node 1	(0.9306, 1.2779, 1.6549)	(0.1505, 0.2593, 0.4372)	0.2823	0.2609
Node 2	(1.8612, 2.4495, 2.9907)	(0.3010, 0.4970, 0.7901)	0.5294	0.4893
Node 3	(0.3247, 0.3976, 0.5373)	(0.0525, 0.0807, 0.1419)	0.0917	0.0848
Node 4	(0.6687, 0.8034, 1)	(0.1082, 0.1630, 0.2642)	0.1785	0.1650

The last parameter in Tables 4.20-4.22 (normalized weights l_i) is employed for calculating the final score of every alternative: the rank (4.25). Using the previous calculated normalized weights for criteria in Table 8, finally the rank is calculated in Table 4.23. From this Table 4.23, can be seen as the winner is the alternative 2 (node 2) which will be selected as the next forward node in the path. Note that the summation of the node ranks is unity, as it was expected.

Table 4.23. Rank calculation for every node.

	Distance $(l_{dist} \cdot l_{node}^{dist})$	**No. Hops** $(l_{hops} \cdot l_{node}^{hops})$	**No. Neighbors** $(l_{neigh} \cdot l_{node}^{neigh})$	**Rank** $(\sum)$
Node 1	0.7155 × 0.2269	0.2180 × 0.2361	0.0665 × 0.2609	0.2312
Node 2	0.7155 × 0.5936	0.2180 × 0.5554	0.0665 × 0.4893	**0.5783**
Node 3	0.7155 × 0.0875	0.2180 × 0.1012	0.0665 × 0.0848	0.0903
Node 4	0.7155 × 0.0920	0.2180 × 0.1073	0.0665 × 0.1650	0.1002

4.6. Conclusion

To address these issues, in this work, we introduce a forwarding relay mechanism based on two tasks: (i) selecting the best forwarding node using fuzzy decision jointly with a weight method and (ii) using the time-division multiple access (TDMA) scheme among nodes to avoid collisions, reducing delay. In order to implement the novel fuzzy decision presented in this work, the SPRINT protocol [10] is used, but the decision process is changed to select the forwarding node to include FAHP. FAHP is based on pairwise comparisons between nodes to assign a score value (named relative importance) of a node over the other under a specific criterion. So, three novel strategies are introduced (details in Section 4.2) for determining the relative importance of the comparisons, one for every criterion considered in this work: distance to the gateway, number of hops, and number of neighbors. After that, the relative importance values are arranged in three matrices (one for each criterion) before FAHP can be applied. Lastly, a final score is calculated for every candidate node, and the highest score node is selected as the best option to be the next node in the path.

Number of Collisions A metric related to the efficiency of energy consumption is the number of collisions occurring during the phase of route creation. In this sense, a lower number of collisions means a lower energy consumption and a suitable transmission range adopted. This problem is inherent to non-guided channels such as underwater channels. In the SPRINT protocol used here, there is a TDMA-based mechanism for avoiding collisions, but due to the random position of the nodes in the network, is impossible to avoid them completely in the initial creation path phase.

In this work, it has been proved as with only those three parameters (distance, hops, and neighbors), the problem is solved in a random topology with efficiency similar to that of other techniques (SPRINT-Fuzzy) in time (E2E delay packet) and energy consumption. Moreover, stability can be demonstrated by the results provided when considering 400 nodes, which is a large size for this type of network. These reasons are coupled with the existence of a random topology in the initial deployment phase and the consideration that FAHP can handle more criteria than those presented here in future work, which makes the presented technique a suitable option for the routing problem in UWSNs.

Chapter 5: Self-Organized Ad Hoc Mobile Underwater Sensor Networks (SOAM)

In this chapter we have presented the details of Self-Organized Ad Hoc Mobile Underwater Sensor Networks (SOAM). SOAM is a location free protocol. The clusters are formed with the help of received signal strength. The AUVs form the clusters to save energy using received signal strength to select the nearest cluster head. The selection of CH is briefly explained in this chapter.

5.1. Introduction

There are many routing protocols for UWSN where the nodes are either fixed or anchored to the bottom of the sea. These UWSNs are used to sense data in a predefined area like environmental monitoring of plume or surveillance of marine structures. However, UWSN are also needed for applications where the sensor nodes are mobiles. Ad hoc mobile underwater wireless sensor networks (AMUWSN) have applications like mobile marine surveillance and marine explorations. The mobile nodes may be the divers, Autonomous Unmanned Vehicles (AUV) or Remote Unmanned Vehicles (ROV). The randomly moving mobile nodes need to communicate with each other, either to forward each other's data or exchange information, such as the divers need to communicate with each other. The mobile nodes may also need to send the data to some station on the sea surface or on shore data gathering station. The continuous movement of the nodes makes the communication and routing of the data packets very challenging. Any of the existing UWSN routing protocols may not work for AMUWSN because they are designed for fixed topology networks. The routing protocols may be proactive and reactive. However, due to the continuous random movement of the nodes, the routing protocol must be reactive. The UWSN consists of a few to hundreds or even thousands, with each node connected to other sensors. Clustering is a critical method for extending the network lifetime in underwater wireless sensor networks (UWSNs). It entails clustering sensor nodes and electing cluster heads (CHs) for all clusters. CHs collect data from specific cluster nodes and forward the aggregated data to the base station. A major challenge is to select appropriate cluster heads (CH).

5.1.1 Main contribution: The main contribution of this work in this thesis is that we have proposed a self-organized cluster-based routing protocol for AMUWSN and compared its performance with P-AUV [2] in terms of end-to-end delay and packet delivery ratio. The comparison shows that PDR of SOAM is better than P-AUV [2]. SOAM is a location free protocol. The clusters are formed with the help of received signal strength. The AUVs form the clusters to save energy using received signal strength to select the nearest cluster head. If the RSS values are the same between the contending cluster heads, then cluster head having the minimum number of hops will be chosen. Even if the number of hops is the same then the cluster head having maximum remaining energy will be chosen. The cluster nodes forward the data packets to their respective cluster heads which forward the packets to the gateway.

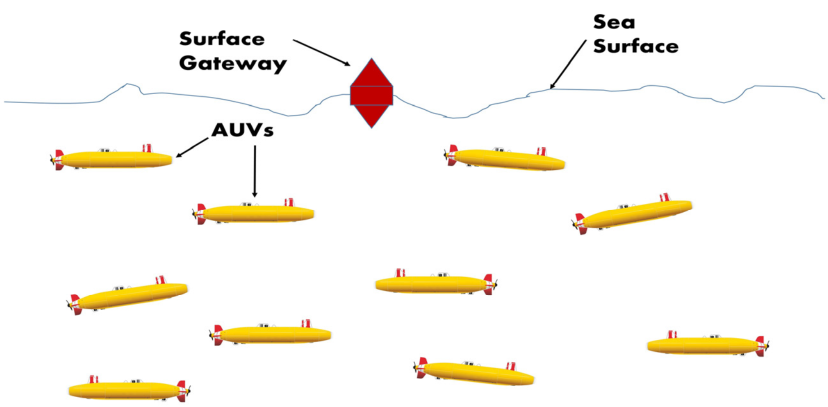


Figure 5.1. Typical architecture of AMUWSN for quasi-randomly moving Autonomous Underwater Vehicles (AUV).

5.2. Overview of SOAM protocol

Let's describe the major steps of SOAM, in brief, to understand how the protocol works. For convenience, the steps have been described in the form of a flow chart as well. The movement of the AUVs has been explained in Figure 5.1. The routing protocol presented in this work, Self-Organized ad hoc Mobile (SOAM) protocol, is intended for ad hoc mobile underwater sensor networks (AMUWSN). SOAM is a cluster-based protocol where the Gateway (GW) is stationary while the CHs and OSNs are randomly moving AUVs. Figure 5.2 shows the clusters in AMUWSN topology. The triangle shows GW, the pentagon shows the Cluster Heads (CHs), the circles show Ordinary Sensor Nodes (OSNs) and the dashed line circles show the clusters.

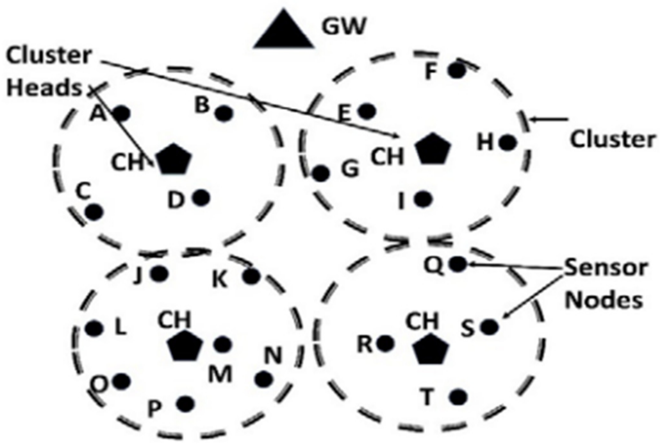


Figure 5.2. Clustering of randomly moving OSNs with CHs.

A CH node is assumed to have a longer transmission range and have more energy available than the OSNs. The CH will also move randomly to collect data like the OSNs and will forward the data of other OSNs within its cluster range as well. The GW will initiate the path formation by broadcasting beacon (BCN) packets periodically to find the CHs around it. The CHs that will receive the BCN packet will form a path with the GW and will be responsible to forward the data packets of their own cluster nodes and the other clusters to the GW. Therefore, they are called packet forwarder cluster heads (PFCHs). The PFCHs will announce their role of packet forwarder (PF) to their one hop away CHs by broadcasting the BCN packet. The CHs which will receive the BCN packet from the PFCH will rebroadcast the BCN. This will continue until all the CHs in the network have received the BCN packet. A CH will select the next forwarding CH when the data is to be forwarded. The selection will be based on the number of hops and residual energy. An OSN will select the nearest CH comparing the distances to the different CHs. The PFCH will broadcast the BCN packet whenever it will receive from the GW node. The process of CH selection by OSNs will also occur every time the BCN packet is broadcast by the CHs. The rate of repeated broadcast of BCN packet from the gateway, PFCH and CHs, will depend on the speed of the moving nodes. Figure 5.3 shows the flow chart of routing path formation started by the GW and traverses through the CHs.

5.2.1 SOAM WORKING FLOWCHART

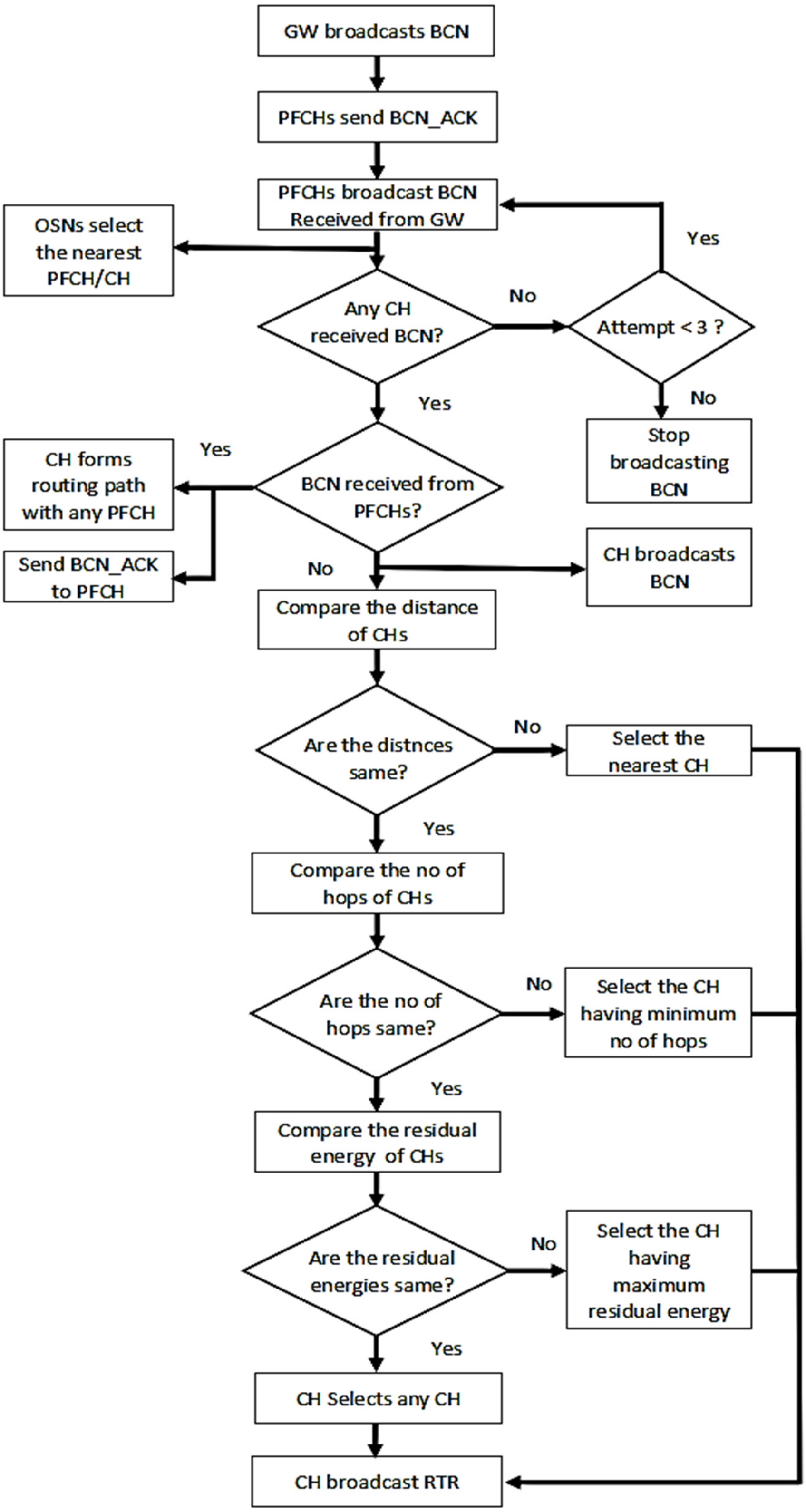


Figure 5.3. SOAM working flowchart.

A typical network model of the randomly moving AUVs is shown in Figure 5.4. The triangle shows the sink, circles show the moving OSNs, and asterisks show the moving CHs.

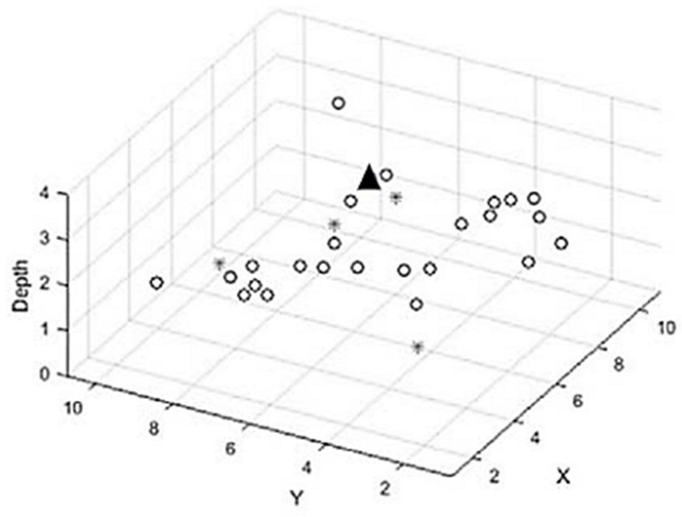


Figure 5.4. 3D moving AUVs in different directions.

The trajectories of four randomly moving OSNs are shown in Figure 5.5. to Figure 5.7 . The four OSNs are sown by '+', '*', 'o', and 6 '◊' markers. Figure 5.5. shows the top view (z-axis), Figure 5.6. shows side view from North (x-axis) and Figure 5.7. shows side view from East (y-axis).

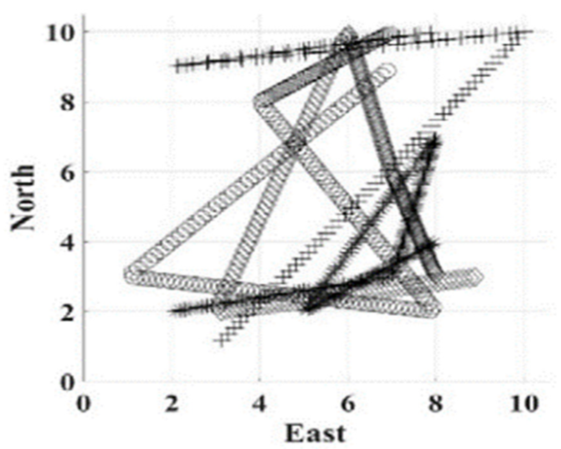


Figure 5.5. Top view of moving OSNs and CHs. The lines show their moving path.

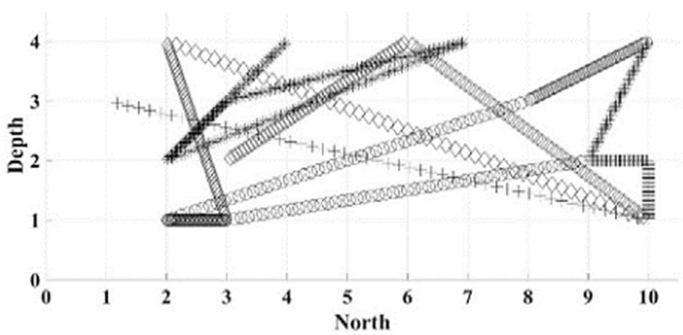


Figure 5.6. North-side view of the moving OSNs and CHs.

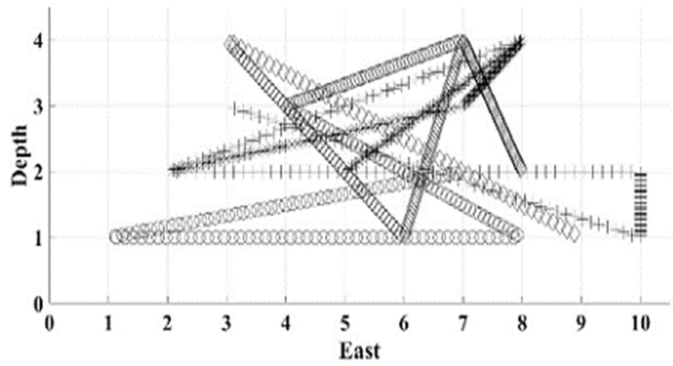


Figure 5.7. East-side view of the moving OSNs and CHs.

5.3. SOAM Working

Now let's describe the sequence of exchange of control packets among the gateway, cluster heads and, cluster nodes to form the routing path from the sensor nodes to the gateway. The clusters' formation process and packet forwarding mechanism are also explained with help of packet header details. The BCN will be broadcast by the GW at predefined intervals. The BCN packet will contain the gateway ID (GW_ID), packet type, number of hops, and residual energy. The BCN packet will be received by CHs and OSNs but only the CHs will send the acknowledgment (BCN_ACK) to the GW. The randomly moving CHs which received the BCN packet from the GW will be called PFCHs and they will rebroadcast the BCN packets at randomly selected time slots. The total number of time slots will be twice the number of CHs possibly present in the maximum transmission range of GW. The length of a time slot is the sum of the maximum propagation delay and the transmission delay. The PFCHs will set the value of the number of hops field to "1" before they rebroadcast the BCN packet. This will indicate to the other CHs that the source CH is one hop away from the gateway and it can forward their packet to the GW. The CHs which will receive the BCN from the PFCHs will select them as the next forwarding CH without carrying out any selection process because they are the only possible choice for them. If a CH will receive the BCN packet from more than one PFCH then it may select any one of them. Once the selection is done, the CHs will send BCN_ACK to the PFCHs. The PFCH will broadcast the BCN packet again if it failed to receive the BCN_ACK. A PFCH will try a maximum of three times to get BCN_ACK. If a PFCH does not receive BCN_ACK after three attempts, then it will assume that there are no more clusters present in the network. To traverse the BCN packet throughout the network, the CHs will keep broadcasting the BCN packets. This process of broadcasting the BCN packets by the GW and the CHs will never stop and will be carried out at a predefined interval. The broadcasting of the BCN packet will depend on the movement of the nodes. If the nodes are moving too fast and the network topology is changing rapidly then the interval will be short. The maximum speed of the AUV will determine the frequency of BCN broadcasting. For the purposes of this work, we simulated an AUV travelling at a maximum speed of 4 m/s. If there are numerous candidates for the next forwarding CH, the CH with the highest RSS will be chosen. If the distance is equal, the CH with the fewest hops will be chosen. If there are the same number of hops, the CH with the highest leftover energy will be chosen. In addition to finding the next forwarding CH, the formation of a cluster is another essential process. The formation of a cluster is also a continuous process due to the continuous random movement of the AUV nodes. Since both processes of finding the forwarding CH and cluster formation are continuous and simultaneous, we need the CHs to be able to communicate with the OSNs and the other CHs simultaneously. This requires the CHs to be equipped with two modems communicating at different frequencies. The BCN packets will be received by the randomly moving OSNs as well and they will estimate their distance from a CH by computing RSS of the BCN packets. The CH which will have a larger value of the RSS will be selected as the CH by an OSN. The CHs will also indicate to OSNs whether they have established a forwarding path. The OSNs will send their data packets only when they will receive Ready to Receive (RTR) packet from the CH. This will save the energy of the OSNs by refraining them from transmitting the data packets, which will be discarded by the CHs if the forwarding path has not been established. In case of collision the packet will be lost. Therefore, the OSNs will send the data to the CHs at randomly selected timeslots to avoid collision at the CHs. However, collision may occur if two nodes the same timeslot and they are at the equal distance from the CH. There is another possible scenario of data collision where two nodes are at different distances from the CH but send their packets such that the packets arrive at the same time at CH.

Packet header format shown in Figure 5.8. has seven header fields.

Bits	0	10	20	52	55	60	68	76
Field Name	S_ID	D_ID	PKT_ID	PKT_TYPE	HOPS	TX_POWER	ENERGY	DATA
Field Size	10	10	32	3	5	8	8	

Figure 5.8. Packet Header Format used in proposed scheme.

Header fields S_ID and D_ID are the device IDs of sender and receiver of the packet respectively. PKT_ID is a unique packet ID constructed by combining S_ID and a random number. S_ID is added in the PKT_ID to make sure that any two nodes do not generate the same PKT_ID. Every time a CH forwards the packet to another CH it increments the HOPS field by one. The sender node adds the power of transmission and residual energy in TX_POWER and ENERGY respectively. Below algorithm shows how a BCN propagates through the CHs and form the clusters. TxRGW is the transmission range of GW.

Algorithm for Routing Path Formation.

GW sends *BCN*
if *CH* is within TxR_{GW}
    then *CH* sends *BCN_ACK*
end if
PFCH sets *HOPS* = 1
repeat =1
while repeat ≤ 3 **do**
    PFCHs send *BCN*
    CHs send *BCN_ACK*
    if *PFCH* failed to receive *BCN_ACK*
        then repeat = repeat + 1
        else break while loop
    end if
end while
OSN estimates *RSS*
OSN selects *CH* = max [*RSS*]
CH sends *RTR*

5.4. SIMULATION AND RESULTS

We evaluated the performance of the SOAM using simulation on a MATLAB simulator. The simulated network is based on autonomous randomly moving sensor nodes and CHs, and a stationary GW node on the surface of the sea. The parameters for the simulation are given in Table 5.1.

Table 5.1. Simulation Settings.

S. No.	Parameter	Value
1	Speed of Sound	1500 m/s
2	Data Rate	35000 bps
3	OSN transmission range	1000 m
4	CH transmission range	2000 m
5	Network Size	10 km ×10 km
6	Depth	4 km
7	Packet header size	76 bits
8	Data size	1024 bits
9	Data packet size	1100 bits

The random movement of the AUVs is created by way point trajectory function of MATLAB simulator. We simulated the packets with the number of OSNs ranging from 10 to 45 and CHs from 5 to 7. The OSNs and the CHs move in random directions. We have analyzed the performance of SOAM using three parameters namely end-to-end packet delay (in seconds), throughput (in bits per second), and packet delivery ratio (PDR). The CHs forward the packets using the First In First Out (FIFO) packet forwarding mechanism. Figures 5.9 to 5.11 show the average end-to-end delay for the various number of nodes and cluster heads. Figure 5.9. shows that the average delay increases almost linearly as the number of nodes increases. It also shows that as the number of cluster heads increases there is a slight increase in the average delay as well. Figure 5.10. shows the average delay for the number of CHs from 5 to 7 for each number of OSNs. It also shows that the average delay increases slightly as the number of CHs increases while the number of OSNs remains the same. However, Figure 5.11. shows that increasing the number of OSNs has a significant effect on the average delay.

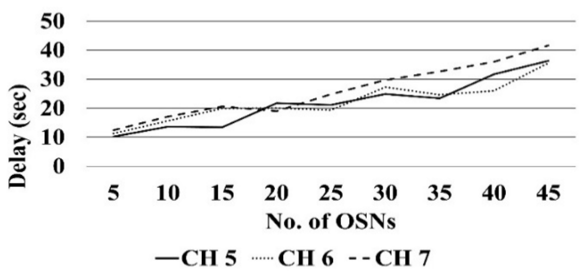


Figure 5.9. Average delay of OSNs packets vs. number of CHs.

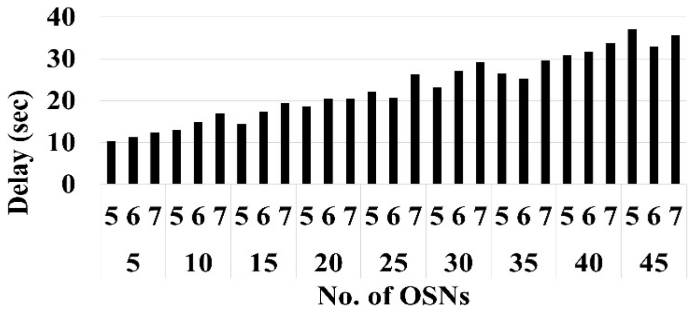


Figure 5.10. Average delay vs. number of OSNs.

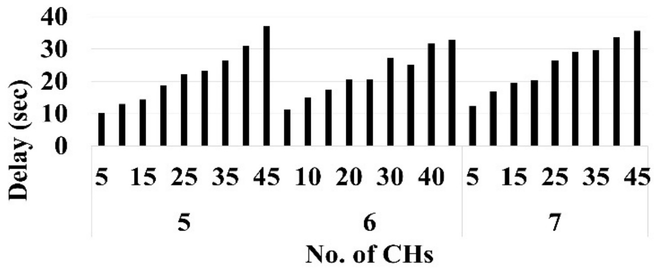


Figure 5.11. Average delay vs. number of CHs.

Figure 5.12. to 5.14. show the average throughput for the various number of nodes. There is no clear behavior to predict the throughput with the change in the number of OSNs or CHs. However, if we compare the throughput for the number of OSNs 5 and the number of OSNs 45 in Figure 5.13, we see the throughput is slightly better for 5 OSNs. This makes sense because the queue delay at cluster heads is low due to a fewer number of packets.

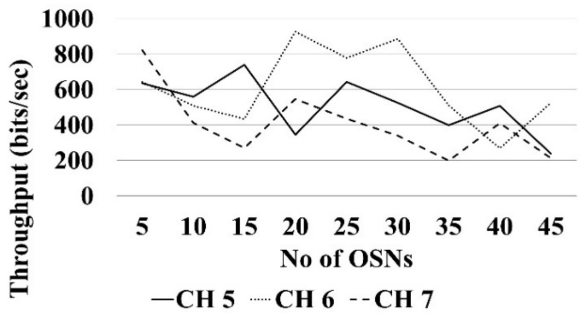


Figure 5.12. Average throughput of OSN packets vs. number of CHs.

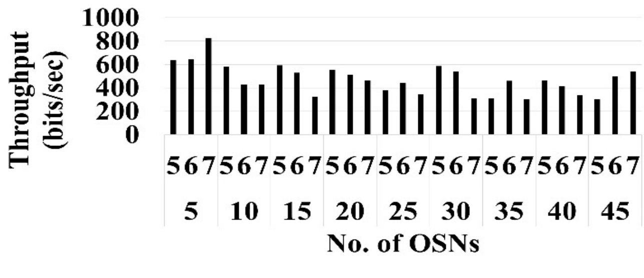


Figure 5.13. Average throughput vs. number of OSNs.

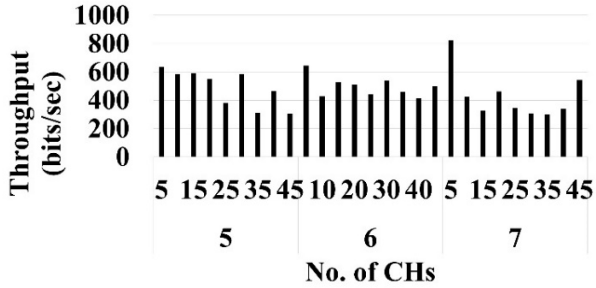


Figure 5.14. Average throughput vs. number of CHs.

Figures 5.15.-5.17 show that average PDR also has got no clear relationship with the increase in number of OSNs. In a static network, we expect to have better PDR with increase in number of nodes. However, in the case of a fully ad hoc network, this is not the case because of the random movement of the CHs.

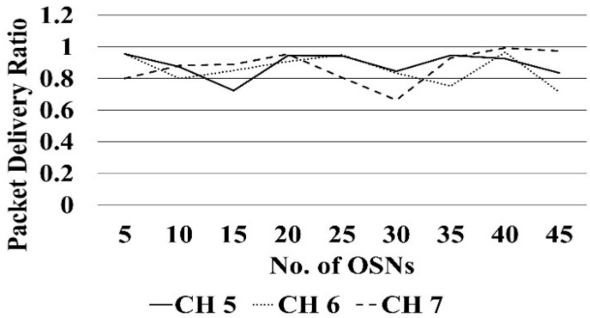


Figure 5.15. Average PDR of OSN packets vs. number of CHs.

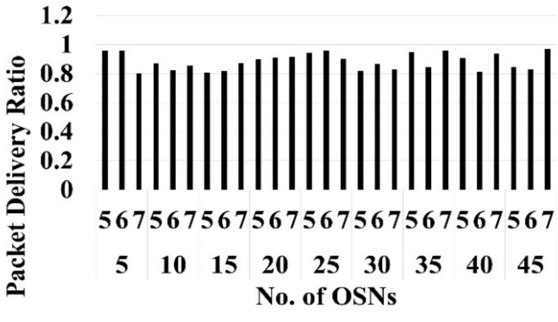


Figure 5.16. Average PDR vs. number of OSNs.

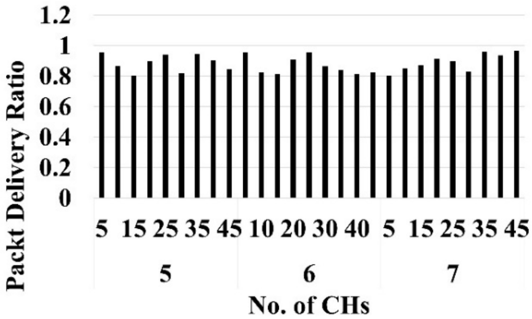


Figure 5.17. Average PDR vs. number of CHs.

5.4.1 SOAM vs P-AUV: We have compared our simulated results with P-AUV because its architecture is similar to our proposed architecture. We have compared P-AUV and SOAM in terms of end-to-end delay and packet delivery ratio. Figure 5.18. shows the end-to-end delay of P-AUV for the various number of nodes. The comparison of Figure 5.18. and Figure 5.19. shows that end-to-end delay of P-AUV varies from 3.5 to 5 seconds (approximately) whereas end-to-end delay of SOAM varies from 10 to 40 seconds (approximately).

The reason for the large delay of SOAM is that it is a cluster-based protocol and to avoid the collision the nodes select time slots randomly to send the packet.

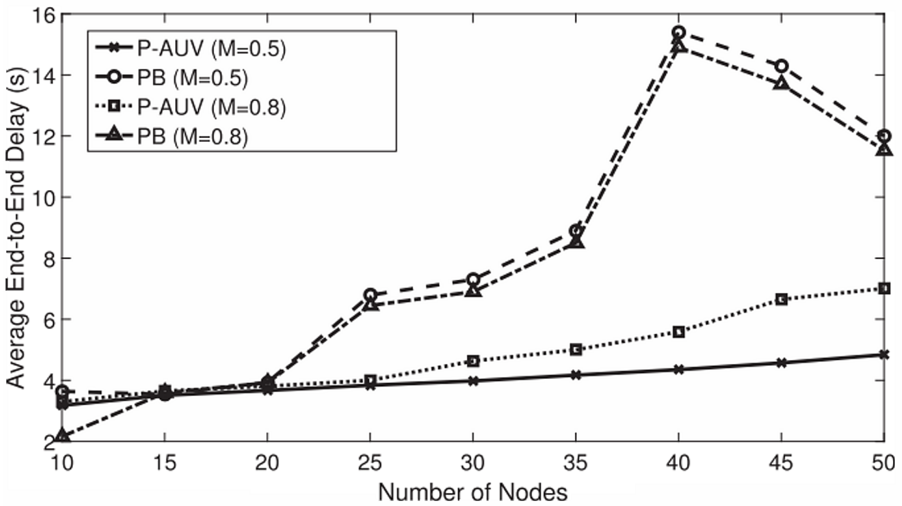


Figure 5.18. Variation of end-to-end delay performance vs. number of nodes and ratio of mobile nodes [105].

Figure 5.19. shows PDR of P-AUV for various number of nodes. The Comparison of Figure 5.19. and Fig. 5.15. shows that PDR of P-AUV ranges from 0.85 to 0.9 (approximately) whereas PDR of SOAM ranges from 0.7 to 0.0.98 (approximately).

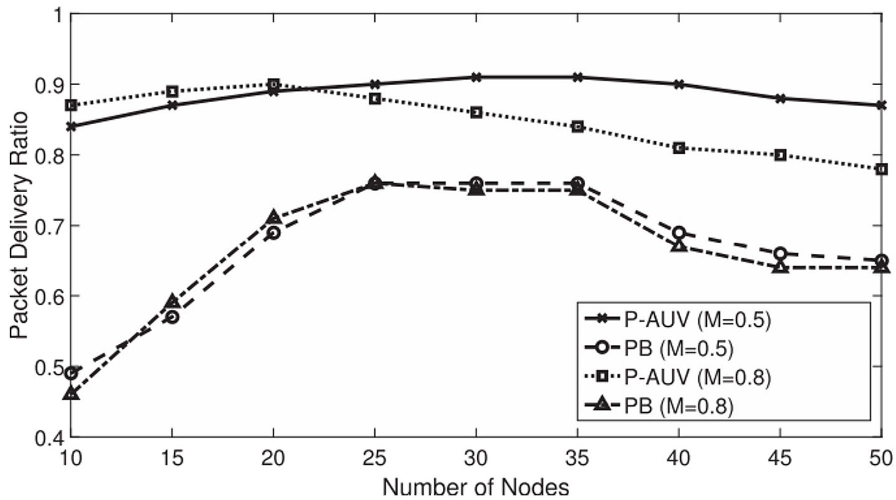


Figure 5.19. Variation of PDR performance vs. number of nodes and ratio of mobile nodes [105].

The results of the comparison between SOAM and P-AUV show no clear advantage of SOAM over P-AUV. However, comparison of the routing methods shows that SOAM has some advantages over P-AUV in two ways. First is that, unlike P-AUV, there is no requirement for location assertion in SOAM.

We have already mentioned in Related Work that P-AUV nodes must be aware of their location at the time of deployment and during the operation as well. In order to update its position, a node uses IMU with DVL which causes error in position estimation. [2] mentions that the expected error is 8 m/hour which is about 0.11% of traveled distance. In addition to that, due to continuous movement of the AUVs, accurate DVL transmits acoustic signals in different directions which causes unnecessary energy consumption. However, SOAM is a location free routing protocol and requires no additional sensors.

Chapter 6: Conclusions and Future Work

This chapter summarizes the work presented in this dissertation and indicates some interesting directions in which this work can be extended.

6.1. Conclusions

UWSNs suffer from limited energy available to operate. The routing scheme is of paramount importance in that scenario. Smart path selection can also improve other performance indicators of the network, as the end-to-end-delay. In this thesis, forwarding node selection algorithm has been proposed, based on fuzzy inference, for the SPRINT protocol. The objective of the work was to improve the energy efficiency of an UWSN routing protocol, which also helped to reduce the number of hops and, consequently, the end-to-end delay. The contributions of the work are (i) the use of fuzzy inference to select the forwarding node to form the path, (ii) the set of rules that form the logic of the fuzzy inference, and (iii) the effect of the transmission range on the number of hops to reach the gateway and on the average energy consumption. The fuzzy inference has been implemented in MATLAB®. The input variables to the fuzzy logic algorithm are distance (through RSSI value), number of neighbors, and number of hops. Simulations were carried out to obtain the energy/node/packet and number of hops vs. transmission range and number of nodes. In fact, number of nodes means node density, because the considered scenario has a fixed volume. If the transmission circuit is the main energy consumer, it seems that less hops need more power, due to the transmission power law proportional to the squared distance. However, the simulations show that it is possible to find a path with fewer hops, but still less energy consumption. Moreover, fewer hops mean shorter end-to-end delays. The algorithm improves the efficiency of the USWN in terms of used energy and number of hops, which also reduces the end-to-end delay. Simulations results of the proposed scheme show a more energy efficient performance when compared to other UWSN routing protocols such as SPRINT and RECRP.

After the deployment of sensors in an ad hoc UWSN, the submerged nodes have to create paths using multihop technique (from node to node) to route the packets to the gateway node on the surface. In this starting phase, parameters such as delay, and throughput are unknown until all the nodes are connected by at least a route that ends in the gateway. In that scenario, among the parameters that can be estimated are distance to the gateway (e.g., using received signal strength indicator (RSSI) in the packet), the number of hops that a node needs to reach the gateway in the partial route created, and the number of neighbors that are in the range of a node. These three parameters have been considered in FAHP to select the next node that belongs to a partial route coming from the gateway to the sea bottom. The FAHP scheme has been used in complex decision problems in which multiple criteria are applied to make the best selection among candidates. The problem of selecting which nodes belong to a route to have a low packet delay or energy wasted in the nodes is an interesting problem that relies on the field of FAHP. In this work, it has been proved as with only those three parameters (distance, hops, and neighbors), the problem is solved in a random topology with efficiency similar to that of other techniques (SPRINT-Fuzzy) in time (E2E delay packet) and energy consumption. Moreover, stability can be demonstrated by the results provided when considering 400 nodes, which is a large size for this type of network. These reasons are coupled with the existence of a random topology in the initial deployment phase and the consideration that FAHP can handle more criteria than those presented here in future work, which makes the presented technique a suitable option for the routing problem in UWSNs.

In this paper, we have presented a reactive routing protocol for mobile underwater sensors. The movement of the sensor nodes is continuous and random. The mobile sensor nodes may be used to monitor the environment or for the marine surveillance. The protocol is designed to establish the routing path among the moving nodes to forward the data to the gateway with minimum end-to-end delay. The network is divided into clusters to minimize the number of hops. The CHs are equipped with two modems, operating at different frequencies, to communicate with the other CHs and the OSNs simultaneously. The formation forwarding path between the CHs is initiated by the GW by broadcasting a BCN packet. The BCN packet traverses through all the network to get all CHs connected. The clusters are formed by OSNs selecting the CH based on the distance. The distance between a CH and OSN is computed using RSS by an OSN. In future, the performance of the protocol can be improved by decreasing the end-to-end delay using more efficient queuing algorithm at the CHs and medium access control method between the OSNs and the CHs.

6.2. Future work

The work done in underwater sensor networks using fuzzy based schemes can be extended to concepts of Fuzzy Neural Networks, Intelligent decision making among clusters using machine learning and artificial intelligence. The decision making and optimization is based on sensor node performance. The decision can be made for autonomous underwater vehicles etc. Machine learning methods established using fuzzy logic can be used to obtain relationships developed as rules from a dataset. Automated decision making and selection of relay nodes will make UWSN nodes much more powerful in terms of energy efficiency and battery life of the sensor nodes.

Appendix A

Curriculum Vitae

Experience

- **Lecturer**, Department of Telecommunication Engineering, Dawood University of Engineering and Technology, Karachi from February 2016 – Till date
- **Lecturer**, Hamdard University Karachi, from August 2014-Feburary 2016
- **Lab-Engineer**, Hamdard University Karachi, from March 2012-August 2014
- **BSS Commissioning Engineer**, Alcatel Lucent, Pakistan from May 2011-Feburary 2012

Education

- **Doctor of Philosophy** (Communication Engineering), Universidad de Malaga, 2018-2023
- **Post Graduate Diploma** in Statistics, University of Karachi, Pakistan 2017
- **Master's in Telecommunication Engineering**, Hamdard University Karachi May 2014
- **Bachelor's in Telecommunication Engineering**, Mehran University of Engineering and Technology, Jamshoro Pakistan. 2010

Journal Publications

- **2023:** S. Sagar, A. Mahmood, K. Wang, Q. Z. Sheng, **J. K. Pabani** and W. E. Zhang, "Trust–SIoT: Towards Trustworthy Object Classification in the Social Internet of Things," in *IEEE Transactions on Network and Service Management*, doi: 10.1109/TNSM.2023.3247831.

- **2022:** W. Hyder, **J. Kumar**, M. -Á. Luque-Nieto, A. A. Laghari and P. Otero, "Self-organized ad hoc mobile (SOAM) underwater sensor networks", in *IEEE Sensors Journal*, doi: 10.1109/JSEN.2022.3224993.

- **2022: Kumar, J.**; NISAR, A.; Hyder, W.; Sagar, S.; Shaikh, M.Z. "System architecture for the internet of things (IoT) based smart agriculture monitoring". *J. Inf. Commun. Technol*. JICT 2022, 16

- **2022: Kumar, J.**; Luque-Nieto, M.-Á.; Hyder, W.; Ariza, A. "Energy-efficient routing protocol for selecting relay nodes in underwater sensor networks based on fuzzy analytical hierarchy process". *Sensors* 2022, 22, 8930. https://doi.org/10.3390/s22228930.

- **2022**: Jatoi, G. M., Das, B., Karim, S., **Kumar, J.**, Krichen, M., Alroobaea, R., & Kumar, M. (2022). "Floating nodes assisted cluster-based routing for efficient data collection in underwater acoustic sensor networks". *Computer Communications*, *195*, 137-147.

- **2021**: **Kumar, J.**; Luque-Nieto, M.-Á.; Hyder, W.; Otero, P. "Energy-efficient packet forwarding scheme based on fuzzy decision-making in underwater sensor networks". *Sensors* **2021**, *21*, 4368. https://doi.org/10.3390/s21134368.

Conference Publications

- **2023:** Das, Bhagwan, Syed Mazhar Ali, Muhammad Zakir Shaikh, Abdul Fattah Chandio, Mashtaque Ahmed Rahu**, Jitander Kumar Pabani**, and Mujeeb Ur Rehman Khalil. "Linear Regression Based Crop Suggestive System for Local Pakistani Farmers." In *2023 Global Conference on Wireless and Optical Technologies (GCWOT)*, pp. 1-6. IEEE, 2023.

- **2022:** Hyder, W.; **Kumar, J.**; Luque-Nieto, M.-Á.; Sheikh, A.A.; Shaikh, M.M. "CLUSMOB protocol based on clusters for mobile underwater networks". In Proceedings of the 2022 Global Conference on Wireless and Optical Technologies (GCWOT); IEEE, 2022; pp. 14

- **2022:** Mahboob, K.; Khursheed, S.; Jameel, S.M.; Uddin, V.; Shukla, S.; **Kumar, J.** "A novel medical image de-noising algorithm for efficient diagnosis in smart health environment". In Proceedings of the 2022 Global Conference on Wireless and Optical Technologies (GCWOT); IEEE, 2022; pp. 15

- **2021: J. Kumar.** "System architecture for internet of things (IoT) based smart agriculture monitoring" published in 11th International Conference on Distributed Computing, Information Systems and Internet of Things (ICDCII) from Oct 20-21, 2021 held at ILMA University Karachi.

- **2021**: **J. Kumar.** "(EEPFSFDM-UWSNs) "Energy-efficient packet forwarding scheme based on fuzzy decision-making in underwater wireless sensor networks", published in congress for young researchers of the sea at Motril Granada from 6-9 September 2021.

- **2020**: S. Sagar, A. Mahmood, **J. Kumar**, and Q. Z. Sheng, "A time-aware similarity-based trust computational model for social internet of things", GLOBECOM 2020 - 2020 IEEE Global Communications Conference, 2020, pp. 1-6, doi: 10.1109/GLOBECOM42002.2020.9322540.

- **2019**: S.K. Hindu, **J. Kumar**, M.Á. Luque-Nieto, J. Poncela, and P. Otero. "Multihop based scalable routing protocol (MSRP) for underwater acoustic sensor networks." 1-4 Oct 2019, Malaga Spain.

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