Towards Cooperative Routing in Underwater and Body Area Wireless Sensor Networks

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CIIT/SP12-PEE-002/ISB

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I Sheeraz Ahmed, CIIT/SP12-PEE-002/ISB hereby declare that I have produced the work presented in this thesis, during the scheduled period of study. I also declare that I have not taken any material from any source except referred to wherever due that amount of plagiarism is within acceptable range. If a violation of HEC rules on research has occurred in this thesis, I shall be liable to punishable action under the plagiarism rules of the HEC.

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It is certified that Sheeraz Ahmed, CIIT/SP12-PEE-002/ISB has carried out all the work related to this thesis under my supervision at the Department of Electrical Engineering, COMSATS Institute of Information Technology, Islamabad and the work fulfills the requirement for award of PhD degree.

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DEDICATION

To My Family

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ABSTRACT

Towards Cooperative Routing in Underwater and Body Area Wireless Sensor Networks

Wireless Sensor Networks (WSNs), particularly Wireless Body Area Networks (WBANs) and Underwater Wireless Sensor Networks (UWSNs) are important building blocks of upcoming generation networks. Sensor networks consist of less expensive nodes having the features of wireless connectivity, very less transmission power, limited battery capacity and resource constraints. Due to low cost and small size, sensor nodes allow very big networks to be installed at a viable price and develop a link between information systems and the real globe. Cooperative routing exploits the transmission behavior of wireless medium and communicates cooperatively by means of neighboring nodes acting as relays. Prospective relays as well as the destination nodes are chosen from a set of near-by sensors that use distance and Signal-to-Noise Ratio (SNR) of the link conditions as cost functions – this contributes to significant reduction in path-loss and enhanced reliability.

In this dissertation, we propose three schemes Link Aware and Energy Efficient protocol for wireless Body Area networks (LAEEBA), Incremental relay-based Cooperative Critical data transmission in Emergency for Static wireless BANs (InCo-CEStat) and Cooperative Link Aware and Energy Efficient protocol for wireless Body Area networks (Co-LAEEBA). These protocols are efficient in terms of link-losses, reliability and throughput. Consideration of residual energy balances load among sensors, and separation and SNR considerations entrust reliable data delivery. As a promising technique to mitigate the effect of fading, cooperative routing is introduced in the functionality of LAEEBA and Co-LAEEBA protocols. Similarly, incremental relaying in InCo-CEStat account for reliability. Simulation results show that our newly proposed schemes maximize the network stability period and network life-time in comparison to other existing schemes for WBANs.

In Underwater Acoustic Sensor Networks, demand of time-critical applications leads to the requirement of delay-sensitive protocols. In this regard, this dissertation presents five routing protocols for UWSNs; Cooperative routing protocol for Underwater Wireless Sensor Networks (Co-UWSN), Cooperative Energy-Efficient model for Underwater Wireless Sensor Networks (Co-EEUWSN), Analytical approach towards Reliability with Cooperation for Underwater sensor Networks (ARCUN), Reliability and Adaptive Cooperation for Efficient UWSNs (RACE) and Stochastic Performance Analysis with Reliability and COoperation for UWSNs (SPARCO). In these protocols, physical layer's cooperative routing is explored for the design of network layer routing schemes that prove to be energy-efficient as well as path-loss aware. The concentration is focused on Amplify-and-Forward (AF) scheme at the relay nodes and Fixed Ratio Combining (FRC) technique at the destination nodes. Nodes cooperatively forward their transmissions taking benefit of spatial diversity to reduce energy consumption. Simulations are conducted to validate the performance of our proposed schemes in comparison to the selected existing ones. Results demonstrate the validity of our propositions in terms of selected performance metrics.

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Chapter 1

Introduction

In the upcoming era, wireless networks will totally change the means by which the people are accessing the information today. These networks will be a source of facilitation by integrating the Internet with the physical world. Wireless technology is quickly shifting its paradigm from communication systems to embedded real-world scenarios. Example of such a scenario includes an automated meter reading system utilizing sensor nodes. In this application, nodes regularly monitor the electric meter reading without any human intervention. This is done periodically (e.g. monthly) and the information is then transmitted to a processing center. Another such application includes the detection of dangerous tsunami waves in underwater environments by dropped wireless nodes. Wireless nodes can be installed on a soldier body to regularly monitor vital signs during action in the battlefield.

1.1 Wireless sensor networks

Wireless Sensor Networks (WSNs) are types of networks comprising of various of far separated small devices equipped with sensors. These devices have the capability that monitor quantities in our environment for physical or environmental phenomena. They are able to work autonomously and are logically connected by self-organizing mechanisms. WSNs are special type of Ad-hoc networks i.e. a collection of wireless sensors that communicate via a common wireless channel. Network is called ad-hoc or temporary as it has no dependency on a pre-defined infrastructure and have the ability of self-organizing. Every sensor of the network is responsible in forwarding the data to other sensors, so the search of nodes which will route the packets is done dynamically on the basis of linkage. Hence, each sensor has a wireless transceiver, is capable to function as a router and to forward data to their sinks. Common Ad-hoc networks and WSNs differ in their areas of applications. For WSNs, monitoring and collecting data are of primary importance, whereas Ad-hoc networks concentrate more on the communication sides.

A WSN consists of sensor nodes in large number that are an effective tool for collecting data in different scenarios. In a typical WSN, sensor nodes are usually powered with limited batteries but are also much less complex. These sensor nodes sense a variable parameter from the physical environment and then transfer the sensed information to multiple sinks usually through multiple hops. The unattended operative mechanism of small-sized sensor nodes not only decreases the cost of the application but also eliminates the risk to a human life. As a sensor node is very limited computation, communication and energy resources, hence these sensor nodes must be deployed in very large numbers so as to cover a large area feasibly. This also adds in to raise the fidelity of the sensed data [1]. Once deployed, these nodes should stay in access to each other so that the coordination of their actions while performing a task, and then forwarding the sensed data to end users is quite feasible. Hence, the inter-sensor connectivity has a profound effect on the performance of WSNs and must be maintained throughout [1]. The sensor nodes regularly monitor and sense the data from the environment and then forward that data to a sink node. A sink node can be an external sensor node with much higher capabilities of storage, processing, communication and longer battery life, or it can be a base station. The sink receives all the sensed data, aggregates it and then transmits it an end user for further processing [2]. Sinks have higher responsibilities of achieving reliable performance of the network. Figure 1.1 shows a terrestrial WSN environment consisting of various sensor nodes transferring data to an end user via internet.

1.2 Sensor deployment strategy factors

Various factors are taken into account while considering the sensor node deployment strategies. These are reviewed as follows:

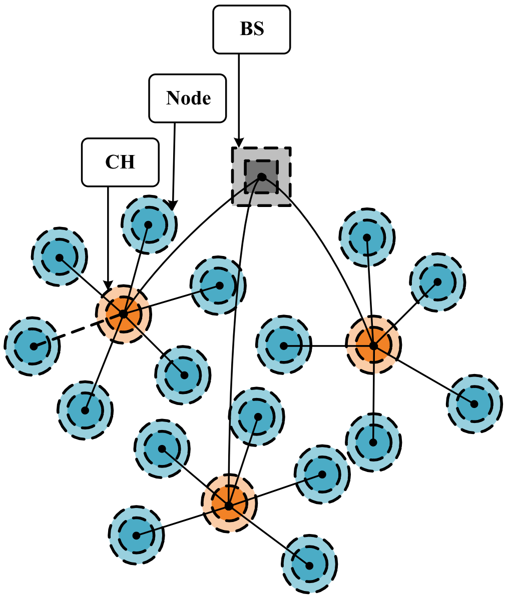

FIGURE 1.1: WSN environment

1) ***Range of sensing:*** Sensing range is defined as the range out or distance for which a sensor node is capable of sensing a particular phenomenon [3].

2) ***Range of communication:*** The maximum allowable range between two senors which keeps them communicating with each other is called the communication range [3].

3) ***Node redundancy:*** The degree to which an area of desire is covered by one or more nodes is called node redundancy. If k sensors are involved in the sensing of an area then it is also known as the $k - coverage$ [4].

4) ***Link redundancy:*** Link redundancy is defined as the degree by which more than one data transferring paths are present for a unit sensor node. If k sensors are available within a specified range of communication, then it is also known as the $k - connectivity$ [5].

5) ***Range dependence:*** Physical location of a sensor node has a profound effect on both the sensing range and communication range of the sensors and this effect is referred to as the range dependency [6].

6) ***Energy awareness:*** All the techniques which are adopted on part of deployment strategy for conservation of energy for the network is called energy awareness

[7].

7) ***Obstacle awareness:*** The mechanisms adopted in the deployment strategy of sensor networks or modifications made so that obstacles interfering in the sensing range or communication range are fully avoided [8].

1.3 Applications of WSNs

There are various types of WSNs but the major applications include the following:

1. Terrestrial WSNs
2. Underwater WSNs (UWSNs)
3. Underground WSNs
4. Wireless Body Area Networks (WBANs)
5. Mobile WSNs
6. Multimedia WSNs
7. Vehicular Adhoc Networks
8. Visual Sensor Networks

and many more [9].

1.4 WBANs

Dynamic topology and distributed nature of WSNs introduce specific requirements in routing protocols to be fulfilled. Various challenges are faced in the design of the routing protocol for WSN like optimal energy consumption with greater end-to-end throughput. Sensor nodes which are implanted inside or attached to the body, constitute a WBAN. Core concept of WBANs is to provide the inaccessible observing of human body's functions and its contiguous environment. Advancements in technology make it possible to integrate the whole system on a single chip which is affordable and comfortable for the person under observation. Another fascinating aspect of WBANs is the integration of such networks with the emerging technologies like mobile phones and PDAs etc., which makes their use more appealing in terms of quick, reliable and accurate delivery of information. Provisional to the desired factors to be sensed, various nodes and network topologies are needed [10]. Figure 1.2 shows a WBAN environment consisting of various sensor nodes deployed on a human body transferring data to an end user via internet.

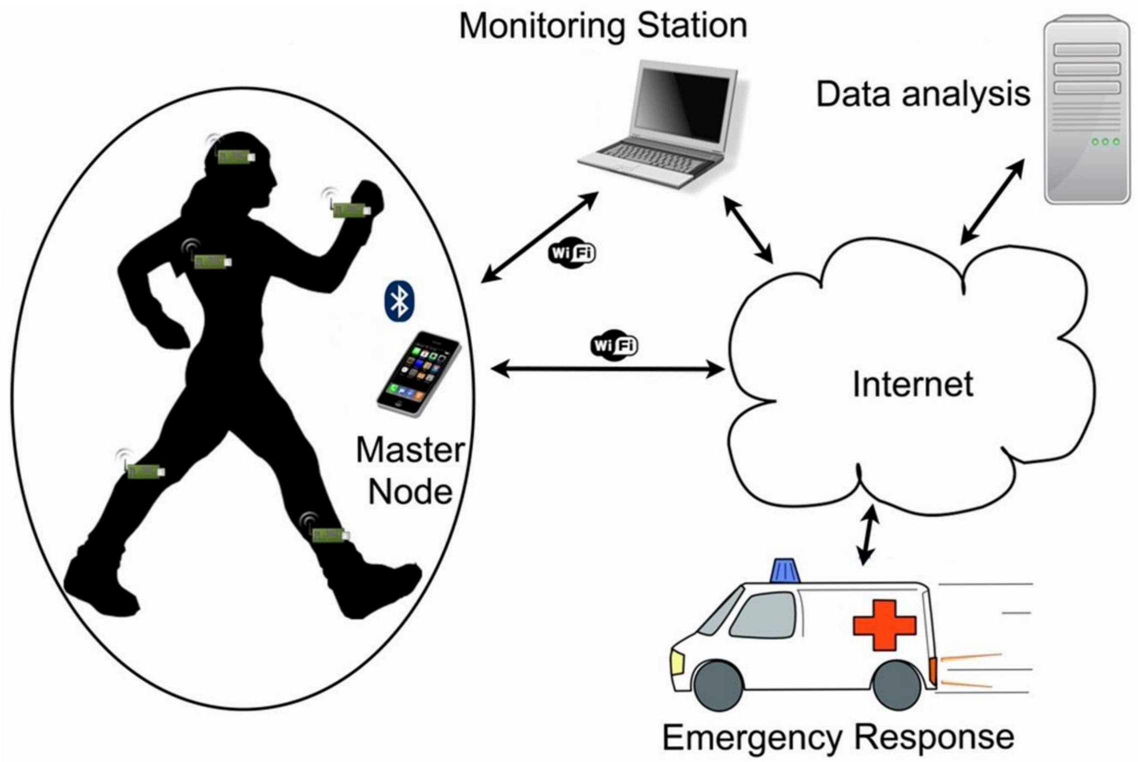

FIGURE 1.2: WBAN environment

WBANs are required to perform correctly for long periods without any battery replacements, particularly for implanted (in-body) nodes. Hence, energy management is a primary concern for WBAN schemes [11]. Continuous data monitoring and broadcast, and large separations between communicating sensors cause more energy utilization. In single-hop communications, sensors are at larger distances from the sink and will die rapidly due to more energy consumption in distant transmission, while multi-hop communications make raise in the energy utility of forwarding sensors nearer to the sink. One of the major challenges in designing an efficient routing protocol is to maximize network lifetime and stability period by using the merits of both multi-hop and single-hop communication. Efficient selection of forwarding nodes is done on the least hop count mechanism. Larger separations between sensors cause more energy to be utilized, so much nearer sensor is selected for data routing. Another performance parameter that needs to be enhanced is throughput.

Major issues in WBANs are energy management and reliable data delivery. Due to small dimensions, sensor nodes have limited energy resources. In WBANs, sensors are small in number and it is uncomfortable to replace them frequently. Much of the energy in the network is utilized during communication between nodes. Hence, a well designed network topology may significantly improve the stability period of a node and may prevent the wastage of energy. Multi-hop communication in WBANs is usually utilized to save the energy of nodes. Using nodes as relays to forward information to the base station/sink is very efficient method to increase network life time. Whereas, in single-hop or direct communication, nodes at larger distance from the destination die faster due to more energy consumption.

In the meantime, a cooperative communication is grasped to be a competent skill to attain greater energy savings, consistent transport of information and to overcome the sound effects of fading and noise in communication system. Network throughput may be improved by employing broadcast nature of wireless conduit by spreading independent signal via diverse paths. The main impression behind this is if a signal practices a noise on a sure path at specific instant, then other independent path may convey the same signal with less noise or fading. By presenting the thought of cooperative diversity, both Signal to Noise Ratio (SNR) and Bit Error Rate (BER) of signal can be enhanced at receiver end. Cooperative links, given a certain limitation on BER target level, are employed to increase overall network throughput and energy feeding by sensors.

1.5 UWSNs

From the very beginning, oceans are essential way of transportation, military actions and distributed tactical surveillance. For all these applications, UWSNs employ sensor nodes to detect physical attributes such as temperature, pressure, etc. There are vast applications of UWSNs such as assisted navigation, ocean sampling, mine reconnaissance and pollution monitoring, which demand time-critical and delay-sensitive routing protocols [12]. These applications surpass the requirements of energy-efficient and delay-tolerant routing designs. Therefore, there is a need of delay-sensitive routing protocols in UWSNs, which forward the sensed data towards the Base Station (BS) with a minimal time lag. There is also a requirement of routing protocols in large-scale distributed networks to tackle the high propagation delays in localization-free environment as the underwater activities encompass hundreds to thousands of kilometers. Underwater routing protocols can be categorized in two major types: (i) localization-free and (ii) localization-based routing protocols. Those routing protocols which are localization-free do not require location information of nodes for data forwarding, however, localization-based protocols route data towards the base station on the basis of location information of the sensor nodes [13]. Figure 1.3 shows a UWSN environment consisting of various sensor nodes underwater transferring data to an end user via internet.

UWSN forms an upcoming technology that promises to enhance major applications of oceanic research like data collection, tactical surveillance, pollution monitoring, and disaster prevention. Unlike conventional terrestrial sensor nodes, a large quantity of UnderWater (UW) sensors are dropped to the region of desire to create a Sensor Equipped Aquatic (SEA) Swarm. Every sensor is furnished with a low bandwidth acoustic modem and a distinct antenna. It can regulate its depth through a fish-like bladder device and a pressure tester. The swarm is escorted by sinks (sonobuoys) at the surface of the ocean that are furnished with both radio

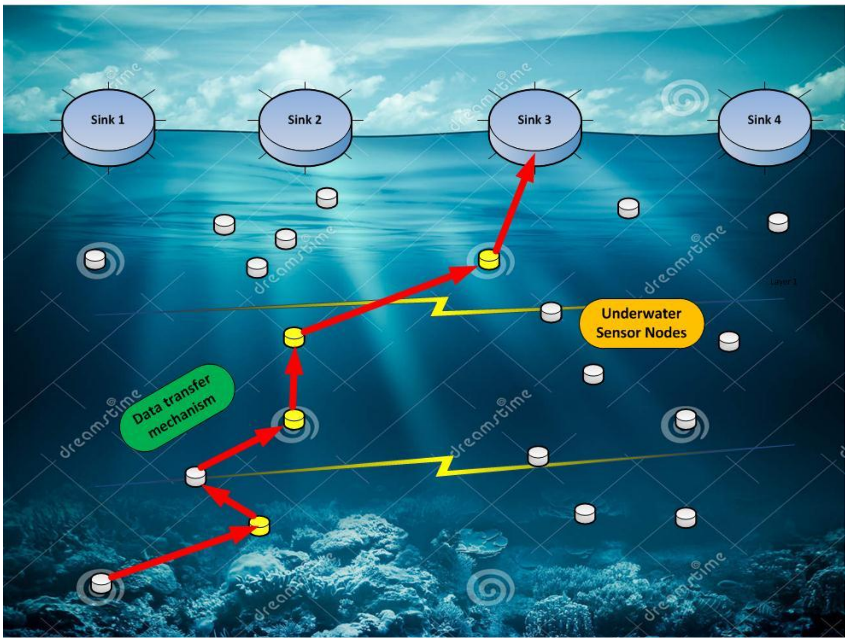

FIGURE 1.3: UWSN environment

and acoustic communications. Each sensor, in a SEA swarm architecture, monitors UW activities and reports time-critical data to sinks located at the surface using multi-hopping.

The UnderWater Acoustic (UWA) WSN has become a prominent area of research in the field of acoustic communications. Such a kind of sensor network has a special physical layer which affects acoustic waves. Acoustic waves are the only and most accurate means of gaining adequate range and data communication rate in UW broadcasts. Radio waves get absorbed in water very quickly and cannot handle adequate range and data. Similarly light experiences high dispersion in UW environments and has the same issues. Nevertheless, new developments attained in UWA transportations make consistent data conduction across several meters imaginable. Many studies have been investigated on developing solutions for UWA networks, including acoustic channel modeling and physical layer transmission analysis as well as routing protocols.

In communications, the delay spread is a measure of the multipath richness of any channel. It can be interpreted as the difference between the time of arrival of the earliest significant multipath component (typically the LoS component) and the time of arrival of the latest multipath components. UW acoustic waves have longer path length difference compared with microwave in terrestrial communication because velocity of UW acoustic wave is much slower than that of microwave. This physical phenomenon will be caused Inter Symbol Interference (ISI) and so aggravated performance of communications. Therefore, analysis on the time delay characteristics take precedence in order to realize UWSNs. Path-loss in case of radio channels depends solely on link length; but UW acoustic waves encounter both frequency and distance effective path-losses [14]. Acoustic waves also get dispersed widely because of suspended particles and small bubbles. Also, reflections from the surface as well as sea bottom raise the channel fading. All these factors must be taken into account in the design of UWA wireless systems. Hence in this case, range and bandwidth are peculiar bottlenecks.

Noise spawned in ocean is classified into two sets: man-made noise and ambient noise. In deep sea, man-made noise is ignorable, while, in existence of shipping actions or adjacent to coast, man-made noise upsurges the total noise. On the other hand, geysers, earthquakes, heat, and some marine animals are reflected as sources of ambient noise [14]. Entire noise in the UW acoustic atmosphere is connected to signal carrier frequency. As path loss and noise power are frequency reliant, SNR in UWA communications is associated to frequency. Therefore, SNR is subjective by two major bounds: link length and frequency.

1.6 Cooperative communication

Having now sufficient technological advancements made in the field of radio communications, researches are trying to enhance the working of UW systems using modern techniques adopted from radio communications. A promising technique is cooperative communication, already being used in terrestrial WSNs. It is a potential approach for distributed UWSNs to upgrade the quality of link connecting sensors as well as the reliability in both point-to-point and multi-point environments, having multiple relays doing cooperation [15]. Wireless network designs take into account the diversity to improve the overall successful transmissions by allowing duplicate signals at the receiver. In contrast to this approach, Multiple-Input Multiple-Output (MIMO) technique also uses a promising mechanism to improve SNR by enhancing diversity gain. But, the technique needs extra equipment cost for each sensor with much complexity.

A different approach for gaining diversity is to utilize several sensors cooperating with each other to upgrade the quality of communication channel. In variation to an individual sensor having an antenna array, duplicate data is forwarded by an array of distributed antennas comprised of several sensors to reach the end-point but introducing some delay [16]. Spatial diversity concept has directed to regular efforts to its use in wireless networks particularly in WSNs. If various paths existing between two end devices are not dependent on each other and have adequate working, channel efficiency can be improved by forwarding multiple duplicates of data along these links and merging them at the destination [17]. The total error probability decreases since the paths are independent, which makes the channel and system performance increase. However in general case of WSNs, nodes are very small to that needed for the support of such distributed antennas. Hence to combat such issues, the idea of cooperative routing is proposed. Cooperation is defined as a cluster of units working together to attain a mutual aim whereas sharing each other resources. In these systems, transmitter onwards one copy of data packets to a sensor performing as relay. The relay then decodes or amplifies each data packet, as the scheme suggests and re-forwards it to the final receiver. Relay node uses a path which is generally different from the direct path. The destination merges or utilizes both the received signals to extract the forwarded information.

Cooperative diversity, an alternative to combat fading in wireless channels, allows distributed users aid in relaying data of each other to explore inherent spatial diversity present in links [18]. In variant to a sole user with an array antenna, duplicated data is relayed by distributed antennas (also known as virtual antenna array) by various sensors to reach sink after some delay. Various cooperation-based protocols have been proposed in literature like fixed relaying protocol, adaptive relaying protocol, user cooperation protocol and coded cooperation schemes. In fixed relaying schemes, such as Amplify and Forward (AF) and Decode-and-Forward (DF), relays provide assistance to provide the source information. In AF scheme, the relays amplify and forward the information [18], whereas in DF scheme, the relays decode the received data and then re-encode it and transmit it to the receiver. Although in DF, the relay routes the decoded data to the receiver; however, this scheme has adequate degradation in performance if the relay does not decode the transmitter's information properly [19].

Cooperative communication has recently gained attention because of its tendency to utilize the broadcast nature of the wireless medium in designing energy-efficient routing protocols [20]. This type of routing scheme permits more regular data collection with the support of adjacent sensors, hence data loss is least expected. Transmissions from different sensors are generally influenced by different and statistically independent fading. Hence, the final sink sensor can aggregate the received signals using common combining techniques such as Fixed Ratio Combining (FRC), Maximal Ratio Combining (MRC) or Selection Combining (SC) and obtain diversity against the killing effects of fading. Diversity attained by the use of multipath transmissions is known as cooperative diversity. It is a dominant procedure to upsurge strength contrary to channel fading.

1.7 Dissertation break-up

Chapter 2 gives a detailed review of the related literature studied for the implementation of various UWSN and WBAN schemes proposed in this dissertation.

In chapter 3, we have addressed the model for underwater acoustic channel considering the attenuation, propagation delay and the various types of noise present in the channel. Also the relations for SNR for underwater channel are also given. The chapter also describes the basic equations utilized for cooperation. Role of relay node and the combining strategy at the sink are also evaluated mathematically.

In chapter 4, we have proposed improved delay-sensitive versions of Depth Based Routing (DBR), Energy Efficient DBR (EEDBR) and Adaptive Mobility of Courier nodes in Threshold-optimized DBR (AMCTD) to make them adaptable for time-critical applications. This work is an extension of [21]. These new schemes are verified and validated through simulations in the UWSNs. We have applied delay and channel loss models in depth-based routing protocols of DBR, EEDBR and AMCTD to examine their effects in delay-sensitive routing. The main concern is to minimize huge propagation delays along with maintaining other parameters such as network lifetime and number of transmissions. We prefer localization-free routing protocols as sensor nodes move with a speed of 2-3 knots and it is difficult to identify their location information. It is important to examine the deficiencies of these flooding-based protocols as they depict the practical acoustic conditions.

In chapter 5, a cooperative routing protocol is presented for UWSNs to enhance the network performance called Analytical approach towards Reliability with Cooperation for UWSNs (ARCUN). The protocol is energy-efficient and high-throughput for UWSNs. Efficient relays are chosen from a set of adjacent sensors that utilize SNR and distance calculation of the UW link. Both single-hop and multi-hop routing methods are considered that contribute to significant reduction in path-loss. Cooperation balances load in the network to prolong the network stability period.

The main focus of chapter 6 is a routing scheme that transmits data effectively from a mobile node to any sink on the sea surface. Here, we propose a Cooperative routing protocol for UWSNs (Co-UWSN), and compare its working with other non-cooperative routing protocols. However, this is a challenging task due to noisy environment and limited energy and bandwidth resources. An UWA channel has low bandwidth and propagation latency five orders of magnitude more than the radio channel. These limitations make the network susceptible to bottleneck due to packet collisions. Under these conditions, curtailing the number of packet conduction is significant for not only lessening congestion but also to lessen energy feeding. Cooperative routing is one of the answers to this problem, through which data damage is evaded by using transmission nature of wireless connection. Such a routing marks use of multi-cast approach in which a sole source node conveys its data to more than one sensor by developing more than one links at the same time. Planning a competent cooperative routing protocol may lead to a substantial rise in network throughput. Cooperative routing in wireless networks has newly gained much consideration due to its inclination to exploit the broadcast nature of the wireless medium in scheming energy-efficient routing algorithms. This sort of routing structure permits more recurrent data collecting due to backing of adjoining nodes, hence data harm is least anticipated.

Reliability is a key factor for application-oriented UWSNs which are planned to achieve certain objectives for efficient data routing schemes. Chapter 7 presents Reliability and Adaptive Cooperation for Efficient UWSNs (RACE). Multiple nodes coordinate their broadcasts to take advantage of spatial diversity in conserving energy. Cooperative diversity at physical layer and multi-hop routing at network layer aids in designing minimum energy routing as a combined optimization of the broadcast power at physical layer and path selection at the network layer. Results show that RACE routing scheme performs quite well in terms of stability period, packet delivery ratio, end-to-end delay, and energy consumption comparative to routing protocols Adaptive Cooperation in EEDBR (ACE) and AMCTD.

Cooperative Energy-Efficient model for UWSNs (Co-EEUWSN) is proposed in chapter 8, in which a scheme to route information via UW networks with minimum path-loss over the channel; and the attributes of single-hop and multi-hop are taken into account. The presented protocol considers UW noises that follow Gaussian distribution and the channel is stable for some time period. UW channel is formulated by path-loss model in terms of distance and frequency. The probability of error is also computed for a specific modulation at a particular value of SNR. Experimental results reveal that Co-EEUWSN scheme has considerably enhanced the network stability period with much lowered effects of path-loss. The research considers a distributed UWA environment in the ocean, where the channel is heavily affected by multi-path fading. Data packets from sensor nodes arrive at the sink which further communicate with the onshore base station through long range radio frequency link. Signal may be modeled by a Rayleigh random variable. In this research we shall be considering FRC for signal combining. Cooperative diversity is especially useful when time, frequency and spatial diversity through multiple antennas are not feasible. Proper measures need to be taken into account for any present vulnerability in the cooperative scheme.

Cooperative routing is a promising technique which utilizes the broadcast feature of wireless medium and forwards data with cooperation using sensor nodes as relays. In chapter 9, we present a cooperation-based routing protocol for UWSNs to enhance their performance called Stochastic Performance Analysis with Reliability and Cooperation (SPARCO). Cooperative communication is explored in order to design an energy-efficient routing scheme for UWSNs. Each node of the network is assumed to be consisting of a single omnidirectional antenna and multiple nodes cooperatively forward their transmissions taking advantage of spatial diversity to reduce energy consumption. Both multi-hop and single-hop schemes are exploited which contribute to lowering of path-losses present in the channels connecting nodes and forwarding of data. Simulations demonstrate that SPARCO protocol functions better regarding end-to-end delay, network life-time, and energy consumption comparative to non-cooperative routing protocol improved AMCTD (iAMCTD). The performance is also compared with three cooperation-based routing protocols for UWSN, Cognitive Cooperation (Cog-Coop), Cooperative Depth-Based Routing (CoDBR) and Cooperative Partner Node Selection Criteria for Cooperative Routing (Coop Re and dth). In SPARCO scheme, we suggest an approach to forward information through UWSNs with much lower path-loss over a link. The protocol uses a cost function, computed using node distances from the destination and their residual energies. Simulations depict that SPARCO scheme enhances the network stability period with much reduced path-loss, to a large extent.

Chapter 10 presents Incremental relay-based Cooperative Critical Data Transmission in Emergency in Static WBANs (InCo-CEStat) protocol for WBANs. This protocol is proposed to enhance the performance of existing schemes for WBANs, Cooperative Critical Data Transmission in Emergency in Static WBANs (Co-CEStat) and Advanced Co-CEStat (ACo-CEStat). Proposed protocol utilizes cooperative transmission to achieve reliable and quick data delivery and greater network stability period. Incremental relay-based cooperation is utilized to improve energy efficiency of the network. At relays, Detect-and-Forward (DF) technique is used, whereas, Switched Combining (SC) technique is utilized at sink.

In chapter 11, we propose a new cooperative routing protocol; Cooperation in Link-Aware and Energy Efficient scheme for WBANs (Co-LAEEBA) which is a successor of Link-Aware and Energy Efficient scheme for WBANs (LAEEBA) protocol [56]. We compare its working with LAEEBA and another existing BAN protocols Mobility aware Adaptive Threshold based Thermal-aware Energy-efficient Multi-hop ProTocol (M-ATTEMPT) and Stable Increased-Throughput Multi-hop Protocol for Link Efficiency (SIMPLE). Many contemporary cooperation using routing schemes are designed by utilizing the shortest path algorithm and then performance is improved using cooperation. The suggested cooperative routing model, promises better throughput with least energy consumption with the introduction of the cooperation at the node level and then implementing the shortest path route algorithm. A detailed mathematical model is also presented in this chapter which is based on a linear three-node arrangement in which AF technique is employed at the relay and a combining strategy, FRC is utilized at the sink. Certain losses are also considered in this model, the most important being shadowing or slow-fading, path-loss and cumulative noise effects.

Finally chapter 12 describes the conclusions in regard to this dissertation and the future work which will be carried in continuity of the research tasks accomplished for this dissertation.

Chapter 2

Literature review

2.1 UWSNs

Earlier attempts to analyze UWSN behavior were based on the technology developed for terrestrial WSNs. Despite similar functionality, the design of appropriate network architecture for UWSNs is complicated by the conditions of communication system. As a consequence, the overall network is required to supply an appropriate network service for the demanding applications in such an unfriendly underwater communication environment.

Extensive research has been done on UWSN routing protocols in recent years due to their worth applications. Their primary requirement is adaptability with the delay-tolerant and delay-sensitive applications. Furthermore, the drawback of any specific method is viewed as an advantage to its contrasting scheme.

2.1.1 Non-location based schemes

Notable proposals in UW routing schemes investigate lack of global load balancing in the network to achieve extended network lifetime. Wireless networks can be random or deterministic deployed in physical environments to collect information from an area of interest in a robust and autonomous manner. In most of the cases, the sensor nodes update themselves with the number of nodes in their neighbourhood which makes them aware of the density of the network periodically. An efficient technique of localization-free type is DBR [23], based on data routing by the use of low-depth sensors. DBR proposes flooding based approach in which sensor nodes forward data solely on the basis of their depth information. It is one of the best localization-free routing schemes of UASN which utilizes acoustic signals to tackle error-prone underwater conditions. Energy-Efficient Depth-Based Routing scheme (EEDBR)[24] is another framework for enhancing the network stability period by considering both depth and residual energy of the sensors. It lowers down the end-to-end delay along with better energy consumption of the low-depth sensors. Both of these schemes try to deal with lowering the burden on medium-depth sensors in dense situations. There is a lack of load balancing in these schemes because of unequal load distribution among sensors. EEDBR extends the network lifetime and improves path loss by computing holding time (H_T) on the bases of residual energy of sensors.

The research paper in [25] recommends an AMCTD scheme to extend the network lifetime in UWSN. The considerations are supportive in decrementing the energy consumption of low-depth sensor nodes in the stability period. Optimal weight computation not only provided the global load balancing in the network, but also gave proficient holding-time calculation for the neighbors of source nodes. AMCTD encourages the deployment of courier nodes and devises efficient weight functions (W_F) to increase the stability period of the network. It also provides a paradigm to minimize noise and other attenuation losses for sensor nodes positioned in a low-depth region of UWSN. Abdul Wahid and Dongkyun [26] investigated UWSN routing schemes and classifies them according to their priorities in UWSN. Sherif et al. [27] proposed Delay Tolerant network (DTN) routing protocol to tackle continuous node movements and utilize the single-hop and multi-hop routing. They also attempt to minimize collision overhead at the Medium Access Control (MAC) layer. Hanjiang Luo [28] proposes energy balancing strategies in an underwater moored monitoring system in order to deal with sparse conditions. They provide a mathematical model to investigate the power consumption of sensor nodes. These schemes provide higher stability period at the cost of higher delay or increased path loss.

2.1.2 Medium-access control schemes

Furthermore, there are also some energy-efficient protocols in all types of UWSNs such as Round-Based clustering (RBC)[29] and Link-State Based routing (LSB)[30].

The main designing concern of these schemes is the minimization of energy consumption of the sensor nodes. These protocols propose different technical solutions for this purpose at physical, MAC and routing layer. These schemes assume the water condition, according to the depth of the sender and receiver node as there is a large difference between the parameters of shallow and deep water. At the MAC layer, the major problem is the large number of transmission collisions which can also be handled by the routing protocols. The study in [29] promises to overcome the UWSN confines by resolving the transmission of redundant data in the network. The protocol worked in rounds, with each round consisting of four phases; utilizing suitable mechanisms in each round. The proposed clustering scheme reduces network consumption, increasing network throughput. Moreover, the minimum percentage of received data at the base station is guaranteed. The research in [30] proposes a time-based priority forwarding mechanism and utilizes downstream node table to prevent flooding. A credit-based routing table update mechanism is adopted to avoid energy consumption caused by frequent update of routing table. Simulation results indicate the performance of routing protocol in terms of packet delivery ratio, average end-to-end delay and energy consumption. Chao [31] minimize the transmission collisions by proposing an efficient multichannel MAC layer protocol. Moreover, RBC minimizes the amount of redundant data transmission by utilizing cluster formation. The authors propose a contention-free multi-channel protocol for UWSNs that performs effectively even when the nodes are experiencing bursty traffic loads. Results verified that the protocol conserves energy and is suitable for a heavy-loaded environment. Authors in [32] derive a cut-set upper bound on the capacity scaling. They show that there exists either a bandwidth or power limitation, according to the path-loss attenuation regimes, thus yielding the upper bound that follows three different information transfer arguments. Also, an achievable result based on the multi-hop transmission is presented for dense networks.

2.1.3 Delay-sensitive schemes

In addition, to the above mentioned schemes, there are also some delay-sensitive protocols proposed for UWSN. Mobicast Routing Protocol (MRP) [33] suggests adaptive mobility of Autonomous Underwater Vehicle (AUV) to collect data with a minimum end-to-end delay. It applies "*Appleslice*" technique to solve the coverage hole problem with varying node density. Simulation results confirm the performance enhancement of packet delivery rate, power consumption, and message overhead. Stefano et. al [34] minimize the packet latency and energy consumption of the sensor nodes by optimized packet size selection along with examining its effects on MAC layer protocols.

Dario Pompili [35] suggests the paradigms for both delay-sensitive and delay-insensitive techniques in UWSN by formulating Integer Linear Programming models. Zhong et. al [36] suggest Multi-path Power control Transmission (MPT) protocol to ensure a guaranteed end-to-end delay and minimum BER in challenging acoustic channels. It formulates optimal energy distribution models for unipath and multipath communication. In [37], the authors devise multi-subpath routing to minimize propagation delays along with improving packet delivery ratio in UWSN.

H2-DAB [38] implements the dynamic addressing scheme among sensor nodes without requiring the localization information. Another efficient scheme R-ERP2R [39] employs the routing metric based on the physical distances between the nodes and exercises it to accomplish higher throughput in UWSN. It also provides the energy efficient solution for data forwarding along with better link quality. The sensor nodes compute the holding time based on their depth during the optimal forwarder selection to eradicate the needless flooding of data packets.

2.1.4 Forwarding-function based schemes

In [40], a communication path based routing protocol by the name of Relative

Distance Based Forwarding (RDBF) is presented whose focus is to provide transmission efficient, energy-saving, and low delay routing. Only a small fraction of nodes were involved in forwarding process, which reduced the energy consumption and end-to-end delay. RDBF also controlled the transmission time of the multiple forwarders to reduce the duplicates of the packets. In [41], the authors have addressed the problems of localization by expressing UW transmission loss via the Lambert W function. Real device implementation demonstrated the accuracy and efficiency of the proposed equation in distance calculation, computation stability, and shorter processing time. The simulation results showed that Lambert W function was more stable to errors than Newton-Raphson inversion.

ACOA-AFSA fusion routing algorithm is proposed in [42] which possesses the advantages of Artificial Fish Swarm Algorithm (AFSA) and Ant Colony Optimization Algorithm (ACOA). The fusion algorithm reduced the existing routing protocols transmission delay, energy consumption and improve routing protocols robustness theoretically. A novel approach to localization and mapping of wirelessly connected Underwater Robotic Fish (URF) is presented in [43]. It is based on both Cooperative Localization Particle Filter (CLPF) scheme and Occupancy Grid Mapping Algorithm (OGMA). Using the probabilistic framework, CLPF has the major advantage that no prior knowledge about the kinematic model of URF is required to achieve accurate 3D localization. Results verify the feasibility and effectiveness of the proposed strategy. Using the probabilistic framework, CLPF had the major advantage that no prior knowledge about the kinematic model of URF was required to achieve accurate 3D localization. Results verified the feasibility and effectiveness of the proposed strategy. In [44], the authors have proposed a Forwarding-function based routing protocol improved Adaptive Mobility of Courier nodes in Threshold-optimized Depth-based routing (iAMCTD) for UWSNs. It maximizes the life-time of reactive UWSNs by optimized mobility pattern of sink.

2.1.5 Power-aware routing schemes

Another efficient scheme for UWSN, Coop (Re and dth) [45] employs cooperative routing which involves data transmission via partner node/relay towards sink. In this paper, two different partner node selection criteria are implemented and compared. The authors have considered source node Depth-threshold (dth), potential relays depth, Residual energy (Re) as one criterion and SNR of the link connecting source node with relay or destination as another criterion for selection parameters. The research paper in [46] tackles the problem of tracking underwater moving targets. For three-dimensional underwater maneuvering target tracking, the interacting multiple model method is combined with the particle filter to cope with uncertainties. Simulation results show that the proposed method is a promising substitute for traditional imaging-based or sensor-based approaches.

The Remotely Powered Underwater Acoustic Sensor Networks (RPUASN) paradigm is introduced in [47], whereby sensor nodes harvest and store the power supplied by an external acoustic source, indefinitely extending their lifetime. The required number of RPUASN nodes and the volume which was guaranteed to be covered by the nodes were analyzed in terms of electrical power, range, directivity, and transmission frequency of the external acoustic source, and node power requirements. Researchers in [47] address the challenges faced in an UWA environment and the advancements being in progress. According to them, due to the cost of sea trials and the lack of standards, there are no operational underwater networks, but only experimental demonstrations. Capacity of an acoustic network is a major question to be answered. Efficient and scalable protocols are needed if bigger deployments are to be expected.

In [48], the authors describe physical layer of a new acoustic modem called ITACA for UWSN. The modem architecture includes an ultra-low power asynchronous wake-up system implementation for UWA transmission based on a low-cost off-the-shelf radio frequency identity peripheral integrated circuit. This feature enables a reduced power dissipation of 10W in stand-by mode and registers very low power values during reception and transmission. The modem also incorporates Clear Channel Assessment (CCA) to support CSMA-based Medium Access Control (MAC) layer protocols. Application-oriented UWSNs are planned to achieve certain objectives in [49]. In this paper, the authors propose chain-based routing schemes for application-oriented cylindrical networks and also formulate mathematical models to find a global optimum path for data transmission. After finding local optimum paths in separate chains, they try to find global optimum paths through their interconnection and develop a computational model for the analysis of end-to-end delay. The 4-chain based scheme performs better than the other two chain based schemes due to better load balancing and optimal neighbor selection among the sensor nodes. In [50], the authors introduce the prototype of an aquatic sensor node equipped with an embedded camera. Based on this sensing platform, the authors propose a fast and accurate debris detection algorithm, based on compressive sensing theory to consider the unique challenges in UWA environments. They used an efficient sparse recovery algorithm in which a few linear measurements need to be transmitted for image reconstruction. The experimental results demonstrate that their approach is reliable and feasible for debris detection using camera sensors in underwater environments.

2.1.6 Localization-aware routing schemes

In [51], the authors propose two localization algorithms based on color filtering technology called Projection-Color Filtering Localization (PCFL) and Anchor-Color Filtering Localization (ACFL). Both algorithms aim at collaboratively accomplishing accurate localization of UWA nodes with minimum energy expenditure. They both adopt the overlapping signal region of task anchors which can communicate with the mobile node directly as the current sampling area. PCFL employs the projected distances between each of the task projections, while ACFL adopts the direct distance between each of the task anchors and the mobile node. By comparing the nearness degrees of the RGB sequences between the samples and the mobile node, samples can be filtered out. The normalized nearness degrees are considered as the weighted standards to calculate coordinates of the mobile nodes. Simulation results show that the proposed methods have excellent localization performance and can timely localize the mobile node.

In [52] and [53], the authors show that acoustic sensors deployed on the sea floor can be localized using a broadband sound source travelling along a linear trajectory at a constant velocity and a constant depth below the sea surface. They show that the projection of the source trajectory onto the xy-plane is described by three motion parameters: the source speed together with the time and horizontal range at which the source is at the Closest Point of Approach (CPA). The relative positions of all other sensors, are estimated by measuring the temporal variation of the Differential Time-of-Arrival (DTOA) of the signal emitted by the moving source at each pair of sensors and then minimizing the sum of squared deviations of the noisy DTOA estimates from their predicted values over a long period of time for all pairs of sensors. The proposed sensor localization method is applied to real acoustic data recorded in a shallow water experiment. Assuming that the absolute positions of two of the sensors are known, the effectiveness of the method is verified by comparing the estimated absolute positions of other sensors with their nominal values. In [54], a novel approach to provide full autonomy in the control and synchronization of multiple payload sonar systems is described, facilitating the close-proximity integration and concurrent operation of multiple high-frequency acoustic sensors on an unmanned UW vehicle. Recent advances in computational technology and real-time programming techniques afford the ability to process bathymetric data in situ to react to real-time environment data. The novel approach presented interrogates real-time bathymetric data to predict the transmission-reception timing of payload sensor acoustic pulses, thus permitting the ability to synchronize the trigger of the instruments such that neighboring return signals of other sonar are not saturated by sensor crosstalk.

As delay tolerant applications are the major intention of UWSN, the notable proposals in underwater routing protocols investigate lack of global load balancing in the network to obtain extended lifetime of network. Authors in [55] have implemented a novel cooperative routing protocol for UWSN called ACE. ACE aims to reduce high error rate and enhance throughput via retransmission through cooperative relay nodes. Retransmission is performed only when destination receives erroneous copy in direct transmission from the source node. Relay nodes are selected on the basis of depth and residual energy of sensor nodes. Co-DBR [55] is a cooperation based routing protocol proposed to enhance network performance. Potential relays are selected on the basis of depth information. Data from source node is cooperatively forwarded to the destination by relay nodes.

2.2 WBANs

Many energy efficient and reliable routing protocols are designed for WBANs. Different techniques are utilized to make efficient use of available resources.

2.2.1 Non-cooperation based schemes

Many routing protocols for WBANs are designed by considering some major objectives, such as energy efficiency, quick and reliable delivery of data, bandwidth utilization, efficient use of available resources etc like in LAEEBA protocol [56]. In [57], authors propose a routing protocol for heterogeneous WBSNs; Mobility-supporting Adaptive Threshold-based Thermal-aware Energy-efficient Multi-hop ProTocol (M-ATTEMPT). A prototype is defined for employing heterogeneous sensors on human body. Direct communication is used for real-time traffic (critical data) or on-demand data while multi-hop communication is used for normal data delivery. A protocol for WBANs named as Stable Increased-throughput Multi-hop Protocol for Link Efficiency (SIMPLE)is presented in [58]. They propose a cost function to select parent node or forwarder which has high residual energy and minimum distance to sink. Residual energy parameter balances the energy consumption among the sensor nodes while distance parameter ensures successful packet delivery to sink.

Authors in [59], design a routing protocol which is energy efficient and supports body mobility. The scheme is also thermal aware and able to change the route in case of hot-spot detection. Here, authors present a protocol in which positive features of both single-hop and multi-hop communications are utilized. Priority based routing is done for normal and critical data transmissions. Routes are selected on the basis of minimum-hop count which reduces delay in transmission. However, there is a space for energy management.

In [60], a reliable ANYCAST routing protocol for Zigbee-based wireless patient monitoring is proposed. Mobile sensor nodes select the closest sink to forward their data in a Wireless Mesh Network (WMN). It reduces the number of control messages with fast re-routing. In [61], an analysis of performance of UWA networks is presented in the presence of interference. The node-to-node channel is modeled using frequency dependent path loss and Ricean fading. The authors adopt a communication theoretic approach and study the number of hops through the network as an indicator of connectivity, along-with power and bandwidth requirements. They show that a desired level of connectivity can be achieved through a judicious selection of the operating frequency, power and bandwidth. They propose a hierarchical UWA sensor network architecture in which the sensors and the collector stations operate in distinct layers. The sensors and the collector stations are consequently allocated different operating frequencies. The analysis is performed under the assumption that there is interference from other nodes within the same layer of the hierarchy.

2.2.2 Cooperation-based schemes

Authors in [62] have proposed a scheme Co-CEStat which exploits the broadcast nature of wireless medium and transmits cooperatively using sensor nodes as relays. The protocol utilizes the merits of both direct/single-hop and cooperative transmission to achieve higher stability period and end-to-end throughput with extended network lifetime. The relative distances between relay and other nodes have a large effect on the performance. Authors in [63], focus on the possible advantages of cooperative transmission for implanted sensors. Spatial diversity of multiple single-antenna terminals is exploited to reduce total power consumed by sensors.

Authors in [64], propose cooperative WBAN protocol that is able to support multi-hop communication along with cooperation. This protocol extends the cooperation at MAC layer to cross-layered gradient based routing. A WBAN routing protocol is designed in [65] in which incremental relay-based cooperation is used to improve energy efficiency. Energy efficiency of direct and cooperative communication is considered with the effect of packet error rate. In [66], different WBAN techniques and design problems are provided. Energy efficient routing protocols are classified as flat, hierarchical, query-based, coherent and non- coherent based, negotiation-based, location-based, mobile agent-based, multipath-based and QoS-based. It is stated that location based protocols are useful in increasing the network lifetime. Implementation of appropriate routing protocol also ensures the network connectivity and reliable data delivery. A protocol is presented in [67] which considers the possibility of outage between two communicating nodes. For bandwidth efficiency, incremental relaying cooperation strategy is used in this paper.

Many other energy efficient routing protocols for WSNs and WBANs are proposed by considering different applications and topologies in [68][69][70][71][72][72] and [73].

Table 2.1: Comparison of the UWSN schemes

Technique	Features	Domain	Flaws/Deficiencies	Results Achieved
DBR [23]	Dimensional location information of sensors not required	UWSNs, 3D UW monitoring, Depth based routing, Handles dynamic networks	More energy consumption, Unequal load balancing, Redundant Data, Does not support sparse and high dense networks	Better network lifetime, High data delivery ratio, Low end-to-end delay
EEDBR [24]	Energy efficient, No location information required, Controlled flooding	UWSNs, Supports 3D UW monitoring and surveillance	High energy consumption in dense networks, Low packet delivery ratio, High packet drop	Better network lifetime, Minimum energy consumption, Improved End-to-end delay
AMCTD [25]	Adaptive Mobility, Energy efficient, Uses weight function for data routing	2D-UWSNs,Underwater monitoring applications, Distributed routing mechanism	Imbalanced energy consumption, Resistant to node mobility, Routing information may not be updated, High end-to-end delay	Increased network lifetime, Minimized energy consumption
AFR [30]	Time-based priority approach, Credit-based routing table	UWSNs, Prevent flooding, Utilization of downstream node	Frequent updation of routing table, Redundant transmissions due to packets dropping, Lower stability period results as nodes die earlier	Better packet delivery ratio, Less energy consumption, Improved end-to-end delay.
MRP [31]	Delay-sensitive approach, Adaptive feedback routing	3D UWSNs, Coverage Hole problem addressing	More energy consumption due to high computations, Unsatisfactory performance in multimode	Packet delivery rate, Power consumption, Message Overhead
Mobicast [33]	Geocast problem investigation, Apple-slice technique, For maximum data collection	3D-UWSNs, Networks with Hole problem	Message Overhead, delay is also introduced	Better data delivery rate, Less Power consumption
H2-DAB [38]	Energy efficient, Full dimensional location information not required	2D-UWSNs, Critical UW monitoring missions	Imbalance load balancing and energy consumption, Nearer to sink nodes deplete more energy, High end-to-end delay	Improved data delivery ratio, Better Network lifetime
R-ERP2R [39]	Energy efficient, Physical distance and residual energy based routing	3D UWSNs, UW monitoring and location-based routing	More energy consumption with increased node mobility, More routing paths, Redundant packets transmission	More network lifetime, Reduced end-to-end delay, Minimized energy consumption
RDBF [40]	Minimum hop counts involved, No use of control messages	3D UWSNs, UW monitoring and target tracking, Location-based routing	Forwarding area for packets not restricted, Redundant data transfer by nodes with same distance to sink	Improved network lifetime, Better packet delivery ratio, Minimum end-to-end delay
TLLF [41]	Immune to errors, RSS a practical tool for distance measurement	UWSNs, Localization of sensors	Limited computation to only 2 nodes, Limitations of RSS technique	Distance calculation with fewer iterations, computation stability, and shorter processing time
ACOA-AFSA [42]	Fusion routing algorithm, Improve routing protocols' robustness	UWSNs, Local knowledge required, Self-adaptive mechanism	Imbalance energy consumption, High end-to-end delay	Better energy consumption, Lower packet loss rate, Less delay
URF [43]	3D Localization approach, Hybrid approach, No prior information needed	UWSNs, Cooperation based networks, 3D environment	Not suitable for 2D networks, More energy consumption due to probabilistic framework	High data delivery ratio, Better network lifetime
iAMCTD [44]	Forwarding-function based routing protocol, Adaptive mobility of courier nodes, Depth-based	UWSNs, Courier-based network, Threshold-optimized	No consideration of channel modelling, more computations consume more energy	Reduced transmission losses, Enhanced network lifetime, Improved end-to-end delay
Coop (Re and dth) [45]	Cooperative routing, Partner node selection criteria	UWSNs, Suitable for Uneven and Bursty traffic loads	Not suitable for sparse networks, More energy consumption	Contention free data delivery, Supports Multichannel approach
RPUASN [47]	Energy efficient, Location information not needed	UWSNs, Critical UW targeting missions	Nodes nearer to sink deplete energy earlier, High end-to-end delay	Better data delivery ratio, Improved network lifetime
ITACA [48]	Low cost, Reduced power dissipation, MAC protocol	3D underwater terrain monitoring, Asynchronous wake-up system	High energy consumption while transmitting at long distance, Formation of transmission loops	Network lifetime, Balanced energy consumption
RSSI/energy-CC [52]	Cooperative Routing, Consideration of QoS and energy consumption, Use of MRL algorithm	WSNs, Wildfire Monitoring, Shadowing effect of trees	More percentage of delayed packets, More average delay to sink, Restricted to a single sink	Better energy consumption, More Network lifetime
ACE [55]	Cooperation based, Energy efficient, Limited forwarder nodes	3D-UWSNs, UW monitoring and detection	Improper load balancing, High packet drop, More end-to-end delay, Static network topology	Improved network lifetime, Reduced energy consumption
SLIT [58]	Mathematical model for path-loss of surface-level nodes	WSNs, flat and irregular outdoor terrain	Restricted to 400MHz range, Not suitable for indoor environment	Much reduction in path-loss of the network and fading

Table 2.2: Comparison of the WBAN schemes

Technique	Features	Domain	Flaws/Deficiencies	Results Achieved
LAEEBA [56]	Equal power and computational capabilities, Multi-hop communication	WBANs, Link-aware routing, Handles various detection	Energy wastage, Unequal load balancing, Limited number of nodes	Better network lifetime, High data delivery ratio, Low path-loss
M-ATTEMPT [57]	Mobility supportive, Adaptive threshold-based routing	WBANs, Thermal-aware routing, Multi-hop scheme	Use of heterogeneous sensors leads to high energy consumption, Low packet delivery ratio, High packet drop	Better network lifetime, effective use of both single-hop and multi-hop communication
SIMPLE [58]	Cost-function based routing, Increased-throughput scheme	WBANs, Multi-hop scheme, optimum selection of forwarding node	Improper load balancing, High packet drop, Static network topology	Improved network lifetime, Reduced energy consumption
Co-CEStat[59]	Cooperative Routing, Multi-hoping technique	WBANs, Static Body networks	Imbalance load balancing and energy consumption, Nearer to sink nodes deplete more energy, High end-to-end delay	Higher stability period, End-to-end throughput, Better network lifetime
RE-ATTEMPT[60]	Singl-hop and Multi-hop communication, Continuous data transmission	WBANs, Adaptive threshold-based routing	More energy consumption due to continuous and repeated transmissions, Redundant packets transmission	More network lifetime, Minimized energy consumption
Zig-bee based scheme[61]	Reliable routing, Based on wireless mesh networks	WBANs, Anycast routing scheme, Mobile sensors used	Use of control messages, Complexity increase rises energy consumption	Reduced control messages, Better packet delivery ratio
Co-Critical data[62]	Cooperation based scheme, Merits of single-hop and multi-hop utilized	WBANs, Static WBAN and emergency situations	Limited computation to limited, Does not support mobility,	Higher stability period, End-to-end throughput, Extended network lifetime
Opportunist transmission scheme [63]	Power-aware scheme, Cooperation-based approach	WBANs, Competitive/opponent mechanism	More energy consumption due to high computations, Unsatisfactory performance in multimode environment	Improved Accuracy, Better end-to-end delay
Incremental Relay-based [65]	Cooperative Routing, Consideration of energy consumption, Use of incremental algorithm	WBANs, does not take into effect path-loss	More percentage of delayed packets, More average delay to sink, Restricted to a single sink	Better energy consumption, Reduced packet error rate
DARE[69]	Distance-aware routing, Multi-hop environment	WBANs, Local knowledge required, Self-adaptive mechanism	Imbalance energy consumption, High end-to-end delay	Better energy consumption, Lower packet loss rate, Less delay

2.3 Cooperation-based terrestrial WSNs

In [74] and [75], a comprehensive survey on different design problems and techniques in WSNs is provided. In this paper, energy-efficient routing protocols are classified as flat, hierarchical and query-based, coherent and non-coherent based, location-based, multipath-based, mobile agent-based and QoS-based. It discusses that location based protocols are more useful in increasing network lifetime. Implementation of appropriate routing protocol also ensures network connectivity and reliable data delivery.

In [76], Mohamed Maalej et al. propose cooperative communication routing protocol based on both energy consumption and QoS. The QoS is measured by absolute Received Signal Strength Indicator (RSSI). To integrate these two parameters in the routing protocol, a competitive/opponent mechanism is implemented at each node by utilizing Multi-agent Reinforcement-Learning (MRL) algorithm. Proposed algorithm [77] ensures better performance in terms of end-to-end delay and packet loss rate, taking into account the consumed energy by the network. The main idea of cooperative communication is to utilize the resources of more than one node to transmit data. Thus, by sharing resources between nodes, the transmission quality is enhanced.

In [78], Jin Woo Jung and Mary Ann Ingram formulate the lifetime optimization problem of cooperative routing using Linear Programming (LP). They achieve optimal life-time of multi-hop WSNs by the use of cooperative routing. They then compare the performance and lifetime of existing routing protocols with contemporary protocols. In [79], Ahmed S. Ibrahim et al. present a cooperation-based routing algorithm, Minimum Power Cooperative Routing (MPCR) algorithm and utilize cooperative communication. The MPCR algorithm constructs the minimum-power route, which guarantees certain throughput. Authors in [80], propose Residual-Energy-Activated Cooperative Transmission (REACT) and give the idea of range extension by using less burdened nodes as next hope to reduce load on highly burdened nodes. Unused energy of the network is utilized to extend network lifetime.

In [81], the author has explored the benefits of cooperative diversity for a linear arrangement of WSN, using AF protocol at the relay sensor node and a lightweight combining strategy at the receiver. In [82], a wireless sensor protocol utilizing cooperation and relay deployment is proposed to improve the network lifetime. In [83], the authors present a comprehensive measurement of path-loss and fading characteristics for surface-level sensor nodes in the 400 MHz band in both flat and irregular outdoor terrain and propose a new mathematical path loss Surface Level Irregular Terrain (SLIT) model.

Cog-Coop [84] is an efficient scheme for maximization of network lifetime using residual energy of the nodes. It improves the spectrum sensing performance along with having better energy consumption of the sensors. Optimal conditions are attained based on the standard optimization methods, to find the priority of sensors for spectrum sensing. They showed that cooperation among cognitive sensors is necessary for lowering the fading as well as shadowing effects, and hence, correct sensing.

The authors in [85] presented a cooperation-based Harvest-Then-Cooperate (HTC) scheme for WSNs in which the source and relay harvest energy from the access point in the downlink and work cooperatively in the uplink for the source information transmission. The impacts of the system parameters, like relay number, time allocation and relay position, on the throughput performance were investigated. Modified Double-Threshold Energy Detection (MDTED) scheme is presented in [86] which is a cooperative spectrum sensing scheme for WSNs. The paper incorporates location and channel to improve the clustering mechanism and hence collaborative sensing ability.

Chapter 3

Modeling of UWSNs

Extensive research has been done on UWSN routing protocols in recent years due to their worth applications. Their primary requirement is adaptability with the delay-tolerant and delay-sensitive applications. Furthermore, the drawback of any specific method is viewed as an advantage to its contrasting scheme. Sensor networks feature low-cost sensor devices with wireless network capability, limited transmit power, resource constraints and limited battery energy. Usage of cheap and small-sized wireless sensors allow very large networks to be deployed at a feasible cost to provide a bridge between information systems and the physical world. Cooperative routing exploits the broadcast nature of wireless medium and transmits cooperatively using nearby sensor nodes as relays. It is a promising technique that is a mixture of a routing protocol and cooperative communication to improve the communication quality of single-antenna sensor nodes.

3.1 Underwater acoustic channel

Simulating UWSN communications requires modeling the acoustic wave propagation while a sensor node in UWA tries to transmit data to another one. Several models are proposed in the literature from simplest ones based on sound propagation theory to more elaborated and complex models based on the physics of acoustic sound propagation.

3.1.1 Attenuation and propagation delay

Sound propagates in the underwater environment at approximate speed of $c = 1500m/s$. As a signal propagates and is received by a node, its energy dissipates and it is distorted by noise. For wireless radio links, the attenuation function is approximated as $A(d) \propto d^{-\alpha}$, where α is a constant decay factor. For underwater acoustic links, both link distance d and signaling frequency f have impact on the attenuation function denoted by $A(d, f)$. Consequently, for a transmitted signal with a sufficiently narrow bandwidth which is centered around carrier frequency

f with unit power, the received signal has a frequency-dependent SNR denoted by $\rho(d, f)$ [66]. UWA channel is affected by spreading loss and absorption loss which cause significant attenuation. For a distance d (km) from a source to a destination at a frequency f (kHz) and spreading coefficient k, the attenuation $A(d, f)$ is described by Urick [90] given as

$$A(d, f) = A_0 d^k a(f)^d \tag{3.1}$$

where A_0 is a normalizing constant. k is the spreading factor whose value is $k = 1$ for cylindrical, $k = 2$ for spherical space, and in practical spreading $k = 1.5$. The absorption coefficient $a(f)$ is modeled by the Thorps formula as [97]

$$10loga(f) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + \frac{2.75f^2}{10^4} + 0.003[dB/km] \tag{3.2}$$

3.1.2 Noise presence in underwater channels

Assuming the absence of site-specific noise, the receiver is affected by colored ambient noise only, with its overall power spectral density in units of dB re μ Pa (i.e., in decibels relative to a micro Pascal) in kHz. Underwater communication is affected by many sources such as (N_t), (N_s), (N_w) and (N_{th}) which may be modeled by Gaussian statistics and the Power Spectral Density (PSD) of those ambient noises (in dB re μ Pa per Hz) as described in [67]:

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f) \tag{3.3}$$

where

$$10logN_t(f) = 17 - 30logf \tag{3.4}$$

$$10logN_s(f) = 40 + 20(s - 0.5) + 26logf - 60log(f + 0.03) \tag{3.5}$$

$$10logN_w(f) = 50 + 7.5\sqrt{w} + 20logf - 40log(f + 0.4) \tag{3.6}$$

$$10logN_{th}(f) = -15 + 20logf \tag{3.7}$$

where s is shipping activity factor, whose value ranges between 0 and 1 for low and high activity, respectively; and w is the wind velocity ranging from $0-10m/s$.

3.1.3 SNR in underwater channels

The SNR characteristic of a narrow-band signal with transmit power $P[watts]$, carrier frequency f and bandwidth $B[Hz]$ received at distance d for a link $i-j$ is

$$SNR(d, f) = \rho(d, f) = \frac{P}{A(d, f)N(f)B} \tag{3.8}$$

where $A(d, f)$ is the attenuation in UWA channel and $N(f)$ is the noise amplitude. The SNR of an emitted UW signal with unit transmit power $\hat{p}(t)(watts)$ at the receiver is given by:

$$SNR(d, f) = \rho(d, f) = SL - A(d, f) - N(f) - DI \tag{3.9}$$

where $A(d, f)$ is the attenuation in UW channel and $N(f)$ is the net noise amplitude as from equations (3.1) and (3.3) respectively. Assuming omni-directional antennas, directivity index $DI = 0$. The Source Level (SL) is given by:

$$SL = \frac{20logI}{1\mu Pa} \tag{3.10}$$

where I is the intensity at 1 m from the source in $watt/m^2$, given by:

$$I = \frac{\hat{p}(t)}{2\pi H} \tag{3.11}$$

where H is the water depth in meters. Signals in UW channels (T_d) experience frequency and link length dependent path-loss which is more complicated than radio channels and is modeled as [31]

$$T_d = 10log_{10}d + 10^{-3}a(f)d \tag{3.12}$$

where $a(f)$ has the relation as given in equation (3.2). First term of the equation (3.12) stands for power consumptions of signals transmitted from source to destination in wireless channels. Second term corresponds to absorptions of traveling wave power in UW caused by mechanical nature of acoustic waves [92].

3.1.4 Cooperation model

In cooperative sensor network environment, each sensor can act as a source that sends information on its route, or as a relay that helps forward information of other sensors on other routes. A two-phase transmit scheme is considered here which allows a non-overlapping transmission for the source node and the relay node. Here we are considering a single source-relay pair separated by a distance d_1.

In phase 1, S transmits its information to both R and D simultaneously; whereas in phase 2, R transmits received information to D. The distance between the relay and destination is d_2 and hence the total distance between the source and destination is $d_1 + d_2$ as shown in figure 3.1

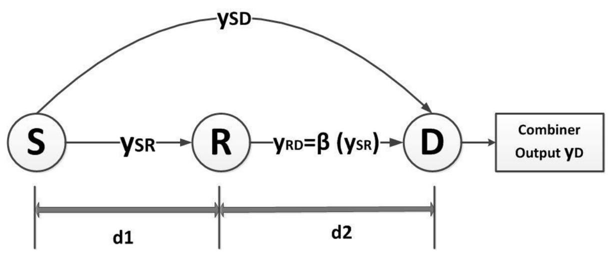

FIGURE 3.1: Linear three-sensor-node system model

The information received at R and D from the transmission in phase 1 can be written as [82]:

$$y_{SR} = h_{SR}x_S + n_{SR} \tag{3.13}$$

$$y_{SD} = h_{SD}x_S + n_{SD} \tag{3.14}$$

where x_S is the transmitted information symbol, h_{SR} and h_{SD} are the fading coefficients from the source to relay and source to destination, respectively [82]. Typically, the fading coefficients are multiplicative in nature and noise components are additive in nature. Hence h components are in multiplication with the transmitted information symbol and n components are added with them. These co-efficients are modeled as complex Gaussian random variables with zero mean and variance σ^2 expressed as $\mathcal{CN}(0, \sigma^2)$.

In phase 2, R retransmits the signal to the destination D received from phase 1, after applying some processing. Hence the information received at D from phase 2 can be expressed as [82]

$$y_{RD} = h_{RD}x_S f(y_{SR}) + n_{RD} \tag{3.15}$$

where $f(y_{SR})$ is the function applied on the received signal from source by the relay and then forwards to the destination. n_{SR}, n_{SD} and n_{RD} are the noise components present in the links of source-relay, source-destination, relay-destination respectively.

3.1.5 Channel capacity computation

Assuming that the channel is estimated at the receiver, the adaptive techniques require a feedback path between the transmitter and receiver and some complexity in the transmitter. The optimal adaptive technique uses variable-rate and power transmission, and the complexity of its decoding technique is comparable to the complexity of decoding a sequence of Additive White Gaussian Noise (AWGN) channels in parallel. We do not consider the case when the channel fade level is unknown to both the transmitter and receiver. Capacity under this assumption can be obtained for the Gilbert Elliot channel in [102] and for more general Markov channel models in [103]. If the statistics of the channel variation are also unknown, then channels with deep fading will typically have a capacity close to zero. This is because the data must be decoded without error, which is difficult when the location of deep fades are random. In particular, the capacity of a fading channel with arbitrary variation is at most the capacity of a time-invariant channel under the worst case fading conditions. More details about the capacity of time-varying channels under these assumptions can be found in the literature on Arbitrarily Varying Channels [104], [105].

When the average number of nodes in the forbidden range is greater than one, a typical outage event is when aggregate interference/noise from many nodes exceeds the threshold. The aggregate noise can be approximated by a Gaussian random variable. We derive a simpler way to find the cumulants of the aggregate noise [106].

When the average number of nodes in the forbidden range is slightly smaller than one, a typical outage event is when the combination of a few nearest nodes interference/noise exceeds the threshold. Neither the nearest node approximation nor Gaussian one is accurate in this case. Higher order cumulants approximations or others are required [106].

In this dissertation it is assumed that the noises follow Gaussian distribution and the channel is stable for some interval of time that is known as the coherence time. The channel capacity of a Gaussian channel with infinite bandwidth represents the upper bound on the amount of information that can be transmitted successfully over a communication channel. This can be expressed by the Shannon-Hartley theorem [107]:

$$C(d,f) = Blog_2(1+\rho(d,f)) \tag{3.16}$$

where $C(d, f)[bits/sec]$ is the channel capacity dependant on both frequency and distance. If it is assumed that the transmission rate at each node is $R[bits/sec]$, than the signal is considered to be transmitted successfully over fading channels if the channel capacity is equal to or greater than the transmission rate, expressed as:

$$C(d, f) \geq R \tag{3.17}$$

This condition may be used to assess the quality of incoming signal at the receiver side. This approximates the link efficiency in wireless systems without any requirement in complex coding, detecting, and decoding procedures [31].

3.1.6 Relay strategy

The relay node R multiplies the received signal from S by an amplification factor β before forwarding it to the destination node D, i.e., $y_{RD} = \beta(y_{SR})$. In equation (3.15), we have defined $f(y_{SR})$ as a function applied on the signal received from the source node to be forwarded to the destination. This function is applied at the relay side. As we consider AF technique in this research work, hence this function is amplification applied on the received signal from the source before forwarding to the destination node. The main downfall of this method lies in the fact that noise contained in the signal is amplified as well and is often used when time delay caused by the relay to decode and encode the message has to be minimized or when there is limited computing time/power available at the relay side. The amplification of the incoming signal is employed block-wise which can be regarded as a multiplication with an amplification factor β which normalizes the received power. If P_s and P_r are the transmission powers at S and R respectively, then the factor β can be written as [57]:

$$\beta = \sqrt{\frac{P_r}{P_s|S_{SR}.PL_{SR}|^2 + N_0}} \tag{3.18}$$

where N_0 is the noise spectral density at the relay node. This relay gain is also called Channel State Information (CSI) assisted AF relay gain since the relay node requires to estimate the instantaneous channel information of the S-R channel. Gain β provides amplification at R to counter the effect of the channel fading and prevents the relay gain from saturating when the S-R link undergoes deep fade. As power is defined as energy per unit time, hence expressing the transmission powers of S and R in terms of energy, equation (3.19) can be expressed as

$$\beta = \sqrt{\frac{E_r}{E_s|S_{SR}.PL_{SR}|^2 + N_0.\Delta t}} \tag{3.19}$$

Fading is generally independent of time, therefore $N_0.\Delta t \cong N_0$, and β can be re-written as

$$\beta = \sqrt{\frac{E_r}{E_s|S_{SR}.PL_{SR}|^2 + N_0}} \tag{3.20}$$

In this analysis, the amplitude of the received signal i.e., S to D, S to R and R to D is modeled as a Rayleigh distribution and the links are assumed to be independent and modeled as Rayleigh fading.

3.1.7 Combining strategy

Destination sensor node D implements a diversity combining technique to combine the received signals coming from source S and relay R. In case of BAN (as under consideration), FRC is used as the combining strategy because it shows better performance as compared to the other combining techniques like Maximum Ratio Combining (MRC), Equal Ratio Combining (ERC), SNR Combining (SNRC), etc [89]. ERC is the easiest combining method for signals, but with low performance. All received signals are just added up due to either an inability to estimate channel quality or a shortage of computing time. FRC achieves a much better performance than ERC. Instead of just being adding up, the received signals are weighted with a constant ratio which will not change a lot during the whole communication instance. In this thesis, a ratio of 2:1 is used. Distance between different stations is considered since that affects the average channel quality due to shadowing and other effects. In case of a single- relay node, FRC can be expressed as

$$y_d = w_1 y_{SD} + w_2 y_{RD} \tag{3.21}$$

where y_d represents the combined output signal of the destination node D, w_1 and w_2 are the weights of the two links and the expression can be extended for any number of relay nodes. These weights are a function of distance and their ratio can be expressed as

$$\frac{w_1}{w_2} = \frac{d_1 + d_2}{d_2} \tag{3.22}$$

An optimal value of the weights ratio is $2 : 1$ in case of AF technique and $3 : 1$ in the case of DF technique [56].

3.2 Conclusion of the chapter

In this chapter, we have discussed the model for underwater acoustic channel considering its attenuation, propagation delay and various types of noise present in the channel. Also the relations for SNR in underwater channel are also given. The chapter also described the basic equations utilized for cooperation. Role of relay node and the combining strategy at the sink are also evaluated mathematically. The next chapter proposes improved delay-sensitive versions of DBR, EEDBR and AMCTD to make them adaptable for time-critical applications. Delay and channel loss models are incorporated in depth-based routing protocols of DBR, EEDBR and AMCTD to examine their effects in delay-sensitive routing. Concern is to minimize huge propagation delays along with maintaining other parameters such as network lifetime and number of transmissions. The presented schemes in chapter 4 are all non-cooperation based in contrast to cooperation-based schemes presented in rest of the following chapters.

Chapter 4

Delay-sensitive routing schemes for UWSNs

4.1 Summary of the chapter

UWSNs offer their practicable applications in seismic monitoring, sea mine detection and disaster prevention. In these networks, fundamental difference between operational methodologies of routing schemes arises due to the requirement of time-critical applications therefore, there is a need for the design of delay-sensitive techniques. In this chapter, Delay-Sensitive DBR (DSDBR), Delay-Sensitive EEDBR (DSEEDBR) and Delay-Sensitive AMCTD (DSAMCTD) protocols are proposed to empower the depth-based routing schemes. The performance of the proposed schemes is validated in UWSNs. All of the three schemes formulate delay-efficient Priority Factors (PF) and Delay-Sensitive Holding time (DSH_T) to minimize end-to-end delay with a small decrease in network throughput. These schemes also employ an optimal weight function (W_F) for the computation of transmission loss and speed of received signal. Furthermore, solution for delay lies in efficient data forwarding, minimal relative transmissions in low-depth region and better forwarder selection. Simulations are performed to assess the proposed protocols and the results indicate that the three schemes largely minimize end-to-end delay along with improving the transmission loss of network.

4.2 Motivation

We have selected DBR, EEDBR, and AMCTD for the analysis because these are depth-based routing protocols. In this chapter, the main focus is on the improvement of notable depth-based routing protocols in UWSNs. There is a large end-to-end delay in these protocols due to calculation of holding time and long transmission distance between sender and receiver node. Having minimized delay, these protocols perform well in the delay-sensitive applications of UWSNs. Moreover, EEDBR and AMCTD have high network throughput, whereas the major deficiency is high end-to-end delay which has been overcome by their delay-sensitive

TABLE 4.1: List of notations used in chapter

Notation	*Definition*
N_i	Number of neighbours of node i
R_i	Residual energy of node i in joules
D_i	Depth of node i in meters
E_{ini}	Initial energy of any node in joules
H_{Tmax}	Maximum H_T for any node in seconds
D_{max}	Maximum depth of network in meters
PF_H	Priority factor for nodes in high network density (DSAMCTD)
PF_M	Priority factor for nodes in medium network density (DSAMCTD)
PF_L	Priority factor for nodes in low network density (DSAMCTD)
α	A constant value assigned according to network size (DSAMCTD)
α_1	Lower limit for number of dead nodes (DSAMCTD)
α_2	Upper limit for number of dead nodes (DSAMCTD)
$T_{s,i}^{s,b}$	Propagation delay of packet transmitted by source to forwarder i
$T_{i,j}^{s,b}$	Propagation delay of packet transmitted by forwarder i to forwarder j
$T_{j,b}^{s,b}$	Propagation delay of packet transmitted by forwarder j to BS
$T_{i,b}^{s,b}$	Propagation delay of packet transmitted by forwarder i to BS

versions. DBR is the initial routing protocol in the category of depth-based routing and its major deficiency is also a high delay due to large nodal delay.

4.3 Underwater channel model

In this section, we analyze the effects of acoustic channel characteristics on the speed and end-to-end delay of the signal. We propose an analytical model to compute the propagation delay in data transmissions. Figure 4.1 shows the propagation delay in a multi-hop communication environment whereas table 4.1 identifies the list of notations used in this chapter.

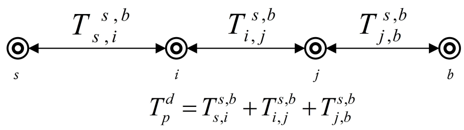

FIGURE 4.1: Propagation delay in multi-hop communication

As we discussed in section 1.5, acoustic waves travel five times faster in water than air; and hence experience large delay spreads due to multi-path and fading effects, and depends on the attenuation coefficient due to high BER in aqueous environment. The end-to-end delay between the sender and receiver is given by:

$$T_{E-E} = (n+1)(T_{tx}) + n(T_{rx}) + T_p^d, \tag{4.1}$$

where, T_{tx} and T_{rx} are the transmission and receiving time consumed by a sensor node for a packet in seconds. n is the number of hops for a specific packet. In terms of transmission time, n is taken as $(n+1)$ as we consider one hop more for a packet to reach the receiver. T_{E-E} is the end-to-end delay whereas, T_p^d is the overall propagation delay of packets between the source and BS expressed as:

$$T_p^d = T_{s,i}^{s,b} + \sum_{i,j \in n} T_{i,j}^{s,b} + T_{j,b}^{s,b} \qquad n \geq 2 \wedge i,j \in n \tag{4.2}$$

$$T_p^d = T_{s,i}^{s,b} + T_{i,b}^{s,b} \qquad n = 1 \wedge i \in n \tag{4.3}$$

$$T_p^d = T_{s,b}^{s,b} \qquad n = 0 \tag{4.4}$$

Equations (4.2), (4.3) and (4.4) show the computations of propagation delay for multi-hop, single-hop and direct communication respectively.

In equation (4.5), we compute the propagation delay T_p between any two nodes of the network. Propagation delay is the time consumed by the signal to cover the distance between sender and receiver node. We assume d as the Euclidean distance between the two nodes and v as the speed of received acoustic signal which depends upon different parameters such as depth difference of sender and receiver etc. Propagation delay between two nodes calculated in [81] is given as:

$$T_p = d/v, \tag{4.5}$$

where d is the distance between the sender and receiver in m and v is the speed of signal in m/s which is calculated as follows [82]:

$$\begin{aligned} v = 1449.05 + 45.7t - 5.21t^2 + 0.23t^3 \\ +(1.333 - 0.126t + 0.009t^2)(S - 35) \\ +16.3z + 0.18z^2, \end{aligned} \tag{4.6}$$

$$t = T/10 \tag{4.7}$$

In the above equations, T is the temperature in $°C$, S is salinity in ppt and z is the depth in km. Above discussed equations compute the overall delay of packets between the source nodes and BS, by considering signal speed with the depth of water.

4.3.1 Acoustic attenuation models

Underwater channel efficiency depends primarily on the attenuation coefficient for the inter-nodal distances. This coefficient is characterized by different factors such as depth of sensor nodes and distances between them. Furthermore, path loss increases with the increase in frequency of signal. We have thoroughly reviewed the attenuation losses in both Thorps [39] and Monterey-Miami Parabolic Equation (MMPE) [41] models. Thorp's computes the total attenuation loss $A(l, f)$ by the summation of absorption effects and the spreading loss, which can be expressed as:

$$10logA(l, f) = k10log(l) + l10log(\alpha(f)). \tag{4.8}$$

In equation (4.8), the first term refers to spreading loss and the second term denotes the absorption loss, which are measured in dB re 1μ Pa. The spreading coefficient k describes the geometry of the signal propagation (i.e., $k = 1$ is cylindrical, $k = 2$ is spherical, and $k = 1.5$ is particle spreading [83]) and $\alpha(f)$ is bandwidth efficiency measured in dB/km. l is the distance between the sender and receiver in km and f is the frequency of signal in kHz.

Research shows that the molecular movement of acoustic signal is highly affected by the random noise and wave motion, which can be detected by increasing the complexity of the improved models along with their enhanced accuracy. MMPE [84] model computes the Transmission Loss (TL) as:

$$TL = m(f, s, d_A, d_B) + w(t) + e(n) \tag{4.9}$$

where:

$m(f, s, d_A, d_B)$: Propagation loss due to haphazard and periodic constituents; incurred from the regression of MMPE data.

f: Frequency of acoustic signal in kHz.

d_A: Depth of sender node A in m.

d_B: Depth of receiver node B in m.

s: Euclidean distance between node A and node B in m.

$w(t)$: Periodic function to estimate signal loss due to wave movement.

$e(n)$: Signal loss function caused by random noise error.

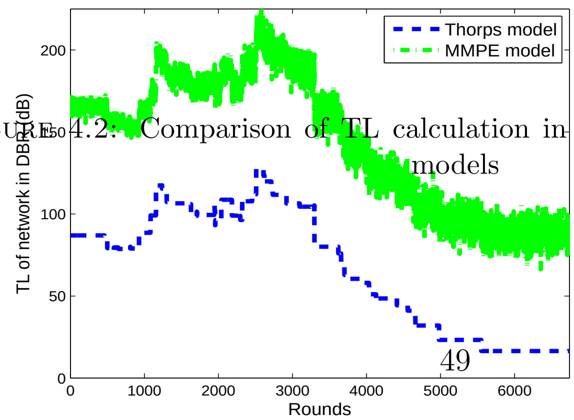

FIGURE 4.2: Comparison of TL calculation in DBR by Thorps and MMPE models

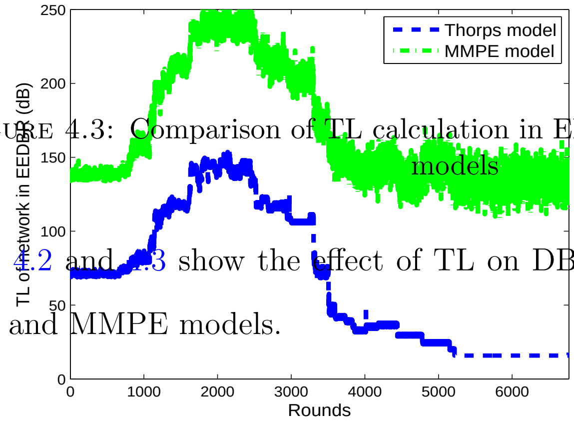

FIGURE 4.3: Comparison of TL calculation in EEDBR by Thorps and MMPE models

Figures 4.2 and 4.3 show the effect of TL on DBR and EEDBR as predicted by Thorps and MMPE models.

4.4 Problem statement

Depth-based routing protocols use natural characteristics of acoustic communication as they do not require localization information and completely depend upon the depth information of sensor nodes. There is high end-to-end delay in DBR, EEDBR and AMCTD which is unsuitable for delay-sensitive routing applications. Therefore, in terms of high end-to-end delay, the following major observations were noticed in the above mentioned protocols:

- In DBR, there are distant transmissions between the sensor nodes specifically in the medium-depth region introducing large propagation delay.
- In EEDBR, the delay conditions are improved than in DBR, however, there is lack of load balancing in the low-depth region due to multiple forwarding and number of transmissions of data packets.
- Presence of courier nodes improves the throughput in AMCTD, however, do not minimize end-to-end delay of network remarkably.

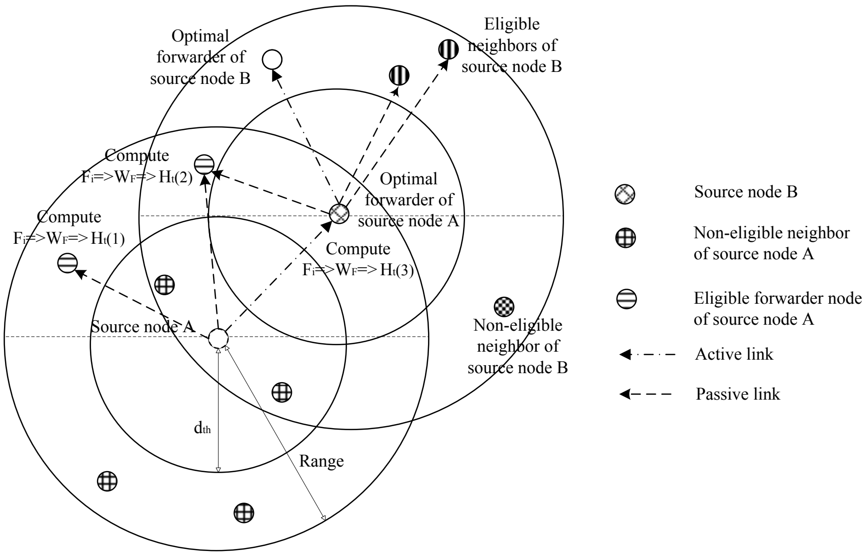

FIGURE 4.4: Data Transmission in DSDBR

In this chapter, we propose improved delay-sensitive versions of DBR, EEDBR and AMCTD to remove above-discussed deficiencies.

4.5 Delay-sensitive DBR

Delay Sensitive Depth-Based Routing (DSDBR) is an improved version of DBR, which not only performs routing on the basis of depth information but also employ Holding time (H_T) and Depth threshold (d_{th}). Each sensor node transmits the sensed data within its transmission range as shown in figure 4.4. The neighbor node, at a depth lower than the source node and is located outside its d_{th} limit, computes H_T for received data packet. d_{th} limit is given as:

$$d_{th} < d_p - d_c \tag{4.10}$$

d_c and d_p denote the depths of the current and previous node respectively during transfer of a packet. H_T depends upon (W_F) of the received data packet as discussed in next subsection.

Figure 4.4 shows the mechanism of transmission in DSDBR. It shows that as the source node A transmits the packet, all the nodes in its transmission range receive the packet. These nodes compare the depth of A with their depth. The three neighbors in the figure having more depth than A discard the packet. Now the other four neighbors check that whether their depth falls under the limit of depth threshold or not? In figure, a single neighbor in depth threshold limit also discards the packet. The other three eligible neighbors compute the Forwarding value (F_i) and (W_F) of the received packet using the parameters of received signal such as Transmission loss. By using W_F, each eligible node computes the H_T for the received packet. H_T is the time duration to hold the packet in queue. We found out that one of the neighbors having a depth between the other two eligible neighbors has less H_T than the other two nodes. It transmits the packet earlier than the other nodes. Other two nodes receive the packet during their H_T and discard it due to overhearing process. The same process continues until the packet reaches the sink.

4.5.1 Data forwarding phase

DSDBR works on the principle of greedy algorithm and nodes with a lower depth forward data towards BS. Each eligible neighbor computes Forwarding value F_i for the received packet as follows:

$$F_i = \left(\frac{(TL)_i v_i}{\eta} \right) \tag{4.11}$$

where, v_i is the speed of the received data packet in m/s and $(TL)_i$ is the TL of the received data packet i in dB. η is a scaling factor for F_i which is assumed as 1000. F_i depends upon TL and q of received data packet which is used to find intermediate forwarder in transmission range. Furthermore, F_i is used to compute

W_F for received packet, which is expressed as:

$$W_F = \alpha - F_i \ , \tag{4.12}$$

where, α is used as a constant and depends upon the network size. The value of α determines the difference between the F_i values of neighbors of the source node, which is further applied to calculate H_T. Nodes having high F_i will have low W_F as well as H_T, and is computed as:

$$H_T = \left(\frac{W_F H_{Tmax}}{v_{AC} T_{min}} \right) \tag{4.13}$$

Using equation (4.13), each node calculates H_T for received packet during which it keeps data packet in buffer. T_{min} is the minimum TL between any two nodes in dB and v_{AC} [85] is the speed of acoustic signal in m/s. H_{Tmax} is the maximum value of H_T for any received packet.

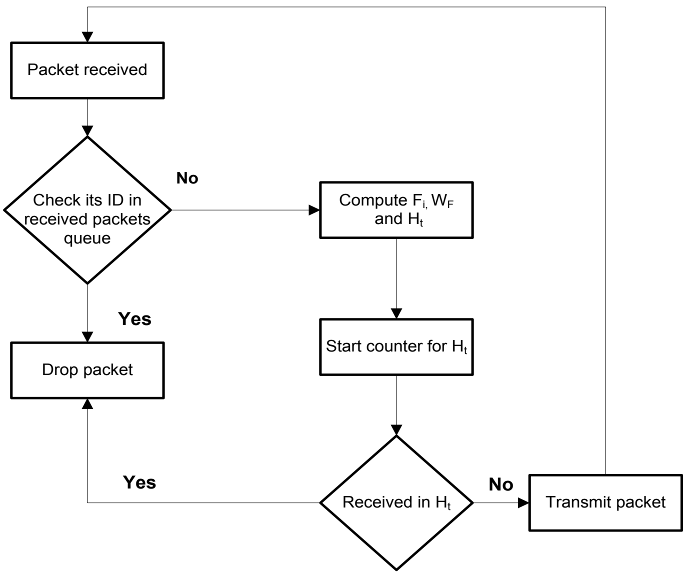

FIGURE 4.5: Forwarding mechanism of DSDBR

An optimal value of H_T is used to minimize multiple transmissions of same packets, as nodes overhearing the received packets from low-depth nodes will not transmit these packets. Thus, DSDBR aims to minimize end-to-end delay in DBR to make

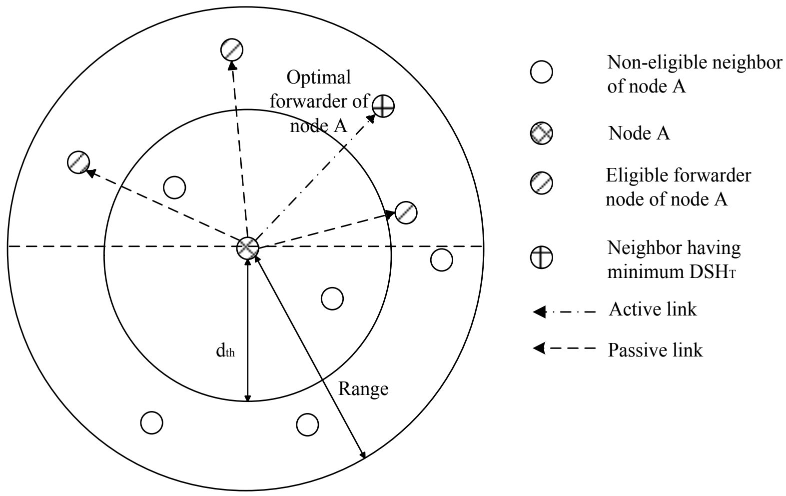

FIGURE 4.6: Data transmission in DSEEDBR

it adaptable to time-critical applications by improving H_T computations criteria and W_F formulation. However, there is a trade-off between end-to-end delay and throughput in the stability period. Figure 4.5 depicts the forwarding mechanism of DSDBR.

4.6 Delay-sensitive energy-efficient DBR

Delay-Sensitive Energy-Efficient DBR (DSEEDBR) provides enhanced network lifetime along with delay sensitivity to EEDBR by implementing Delay-Sensitive Holding time (DSH_T) and adaptive variations in d_{th} for sensor nodes. DSH_T is heart of depth-based routing model as it removes the inadequacy of multiple retransmissions in EEDBR. Every receiving node before forwarding the data packet, computes the TL and noise loss of the channel, and depth difference in order to predict the time-lag of the packet to be forwarded. Figure 4.6 shows the mechanism of data transmission in DSEEDBR.

Figure 4.6 shows that all the nodes in the range of source node A receive the packet. The four neighbors having more depth than A discard the packet. Now the other five neighbors compare their depth with the limit of depth threshold. A single neighbor falling in depth threshold limit discards the packet. The other five eligible neighbors compute the DSH_T of the received packet using the parameters of received signal such as Attenuation loss. We found out that one of the neighbors has less DSH_T than the other three nodes. It transmits the packet earlier than the other nodes. The link between this node and source node A is termed as active link. Other two nodes receive the packet during their DSH_T and discard it due to overhearing process.

4.6.1 Variations in d_{th}

DSEEDBR exploits the inefficient approach of constant d_{th} in the entire network which causes more delay in the low-depth region. Transmissions by sensor nodes in the low-depth region cause high propagation delays. These transmissions may reduce the load on medium-depth region nodes on the cost of high noise losses in the upper region. We compute these losses along with considering the residual energy of medium-depth nodes and apply variable d_{th} for nodes according to their depth information. The sensor nodes deployed in low-depth and medium-depth regions have smaller d_{th} values than the high-depth nodes, therefore, they will have increased number of neighbors avoiding distant transmissions.

4.6.2 DSH_T estimation

DSEEDBR proposes faster data forwarding mechanism than EEDBR by estimating DSH_T for forwarding data packets. After receiving these packets, eligible forwarders consider attenuation loss A_L [86] in computing DSH_T. Since, our scheme is energy efficient (as it utilizes residual energy of the forwarder node), thus, DSH is computed as:

$$DSH_T = \left(\frac{A_L D_d R_i}{L_N v_{AC} E_{ini}} \right) \tag{4.14}$$

where A_L denotes attenuation loss of received data packet in dB, D_d is the depth difference between sender and receiver node in m and R_i is the residual energy of a receiver node in $Joules$. L_N [87] is the combined noise loss due to shipping, wind, turbulence and thermal activities in dB and E_{ini} shows the initial energy of nodes in $Joules$. Nodes having low A_L and D_d will have lesser DSH_T than the other neighbours and will be selected as suitable forwarder.

4.7 Delay sensitive AMCTD

Delay-Sensitive AMCTD (DSAMCTD) employs variations in d_{th} with the changing depth of sensor nodes. In this scheme, courier nodes largely minimize the delay factor as sensor nodes adapt their priority of data forwarding according to the presence of courier nodes. Nodes apply different Priority Factor (PF) formulae for data forwarding with the help of which they compute their H_T with varying network density. This parameter is based on the availability of neighbor nodes, depth information and residual energy of source node. Our scheme prioritizes distant transmissions with decreasing network density to facilitate the quick movement of courier nodes.

4.7.1 System model and network initialization

AMCTD formulates energy-efficient W_F to forward data along with availability of courier nodes. We have utilized d_{th} variations according to depth information of sensor nodes. Nodes with higher depth have more d_{th} than the other nodes. This increase distant transmissions in high-depth regions, however, reduce them in low-depth region. Flow diagram in figure 4.7 depicts the variation of d_{th} in DSAMCTD. In this figure, ε_1 and ε_2 represent the lower and upper limits for d_{th} variations whereas, D_{th1}, D_{th2} and D_{th3} represent the values for d_{th} at varying depths in meters.

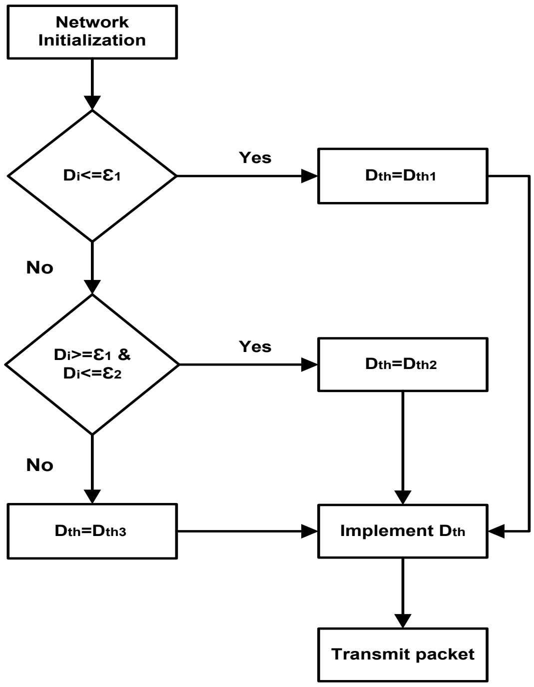

FIGURE 4.7: Variations of d_{th} in DSAMCTD

4.7.2 PF formulation

DSAMCTD devises PFs for sensor nodes to manage delay-efficient data transmission. During initialization phase, each sensor node estimates the number of neighbors within its transmission range and finds its H_T on the basis of PF formulae. There are three different PF formulae designed to enhance availability of neighbors for selection of optimal data forwarders. These formulae are used for efficient data forwarding in the proposed scheme. Figure 4.8 shows the mechanism of data transmission in DSAMCTD. Nodes having high PF value will have shorter H_T than the other nodes. Furthermore, nodes forward data using PF_H in high network density, PF_M in medium density and PF_L in last rounds of network; when the network density gets sufficiently low.

$$PF_H = \left(\frac{H_{Tmax} N_i \times R_i D_{max}}{D_i E_{ini}} \right) \tag{4.15}$$

PF_H encourages high availability of neighbours and residual energy instead of depth information in forwarder selection.

$$PF_M = \left(\frac{H_{Tmax}(D_{max} - D_i)N_i E_{ini}}{D_i D_{max}}\right) \tag{4.16}$$

During instability period, PF_M manages data forwarding by considering depth as a decision factor in the network.

$$PF_L = \left(\frac{H_{Tmax} R_i D_i}{D_{max} E_{ini}}\right) \tag{4.17}$$

In extreme sparse situation, PF_L monitors the network by selecting nodes with high residual energy as optimal forwarder. Figure 4.9 shows that if the number of dead nodes is less than α_1, then the sensor nodes compute their H_T for the received data packets using PF_H. They utilize PF_M between α_1 and α_2 for forwarder selection, and in sparse conditions, PF_L provides better performance for time-critical applications when number of dead nodes is greater than α_2.

Figure 4.8 shows the mechanism of transmission in DSAMCTD. It shows that as the four neighbors having more depth than A discard the packet after receiving packet. Now, a single neighbor in depth threshold limit also discards the packet. The other three eligible neighbors check out the number of alive nodes and network density by using the received information from the sink. If the network density is high, the three eligible nodes compute the PF_H of the received packet using the parameters of received signal. By using PF_H, these nodes compute the H_T for the received packet. We found out that one of the neighbors has less H_T than the other two nodes. It transmits the packet earlier than the other nodes. Other two nodes receive the packet during their H_T and discard it due to overhearing process. If the network density is medium, the three eligible nodes compute the

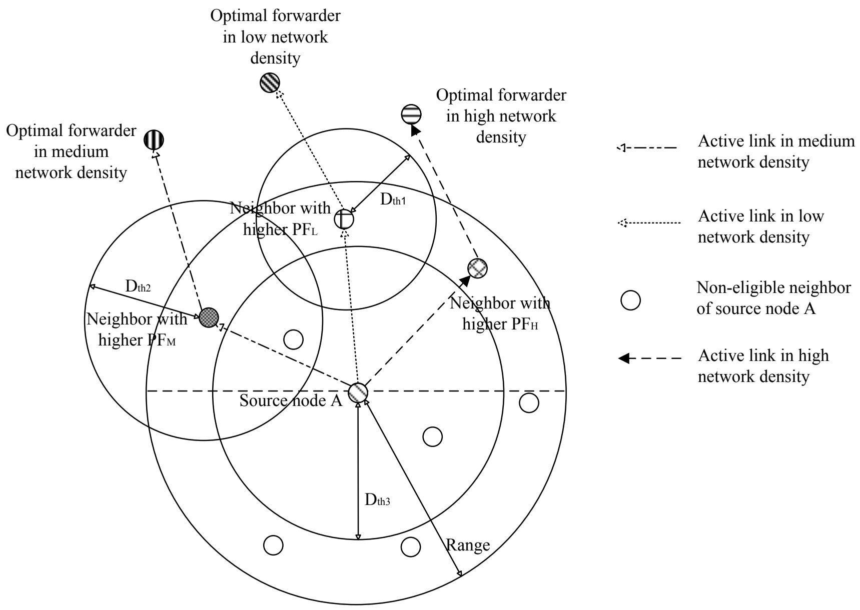

FIGURE 4.8: Data transmission in DSAMCTD

PF_M of the received packet. By using PF_M, these nodes compute H_T for the received packet. Neighbor having less H_T than the other two nodes transmits the packet earlier than the other nodes. If the network density is low, the three eligible nodes compute the PF_L of the received packet. By using PF_L, these node compute H_T for the received packet. Neighbor having less H_T than the other two nodes transmits the packet earlier than the other nodes. Therefore, there are three different data forwarders according to the network density.

4.8 Performance evaluation and analysis

In this section, we examine the performance of DSDBR, DSEEDBR and DSAMCTD and analyze their simulated effects in realistic acoustic conditions. All the three proposed schemes improve the end-to-end delay in the routing protocols of DBR, EEDBR and AMCTD by allowing small decrease in network throughput. Using these performance parameters, we estimate the TL specifically in the low-depth region in order to provide efficient data forwarding. Effects of combined

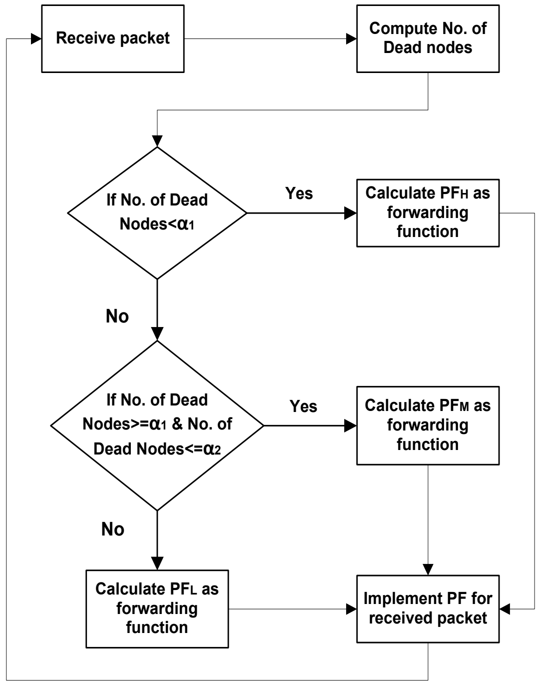

FIGURE 4.9: PF computation in DSAMCTD

noise caused by shipping, turbulence and thermal activity have been calculated. Same simulation scenario and specifications are employed for all the proposed protocols.

4.8.1 Simulation scenario

In all simulations, we have assumed a network dimension of 500m x 500m x 500m with multiple sinks deployed on the surface of water, with a random deployment of 225 sensor nodes. Each sensor node has a transmission range of 100 meters. Following the convention of existing depth-based routing schemes, we used acoustic modem of LinkQuest UWM1000 [88] having a bit rate of 10kbps. According to the specifications of modem, the power consumption in transmitting, receiving, and idle mode are 2W, 0.1W, and 10mW respectively. The size of data packet is 50 bytes, while that of control packet is 8 bytes. Moreover, we minimize collisions at MAC layer by implementing 802.11-DYNAV [25] protocol as a core MAC protocol. The initial energy of the sensor node is set as 20 joules. The simulations are conducted in MATLAB to check the performance of our presented schemes.

4.8.2 Simulation results and analysis

This section is devoted for the performance evaluation, verification, validation and comparison of our three proposed protocols with the conventional ones in WSNs (particulary UWSNs). In the following subsections, each enhanced scheme is compared with the existing one.

4.8.2.1 Comparison of DBR and DSDBR

First of all, we compare DBR and DSDBR to analyze the functioning of our proposed scheme in terms of different performance parameters. The default transmission time and receiving time of data packet for all sensor nodes is 40ms and that of control packets is 10ms. We also assume that sensor nodes employ a frequency of 25 kHz for acoustic communication. In figure 4.10, we analyze the total energy consumption in DBR and DSDBR. DSDBR faces tradeoff between decreased end-to-end delay (figure 4.12) and increased total energy consumption, however, it allows a small decrease in network throughput (figure 4.11). In the earlier rounds of DBR, there is an increase in number of transmissions which increases the network throughput along with end-to-end delay. In DSDBR, the network attempts to remove distant transmissions by selecting optimal data forwarders on the basis of their received packet's TL and q. Figure 4.11 depicts that in DBR, number of

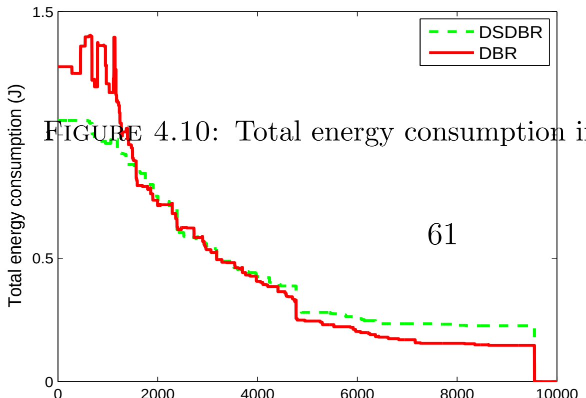

FIGURE 4.10: Total energy consumption in DBR and DSDBR

packets received by sink are higher than DSDBR. In the initial rounds, throughput of DSDBR is lower than DBR. In DBR, high throughput in the initial rounds reduces the number of available forwarding nodes during instability period. In later rounds of DBR, there is a quick average energy consumption of sensor nodes causing creation of energy holes in the network.

Figure 4.12 illustrates the average decrement in delay of our proposed scheme in comparison to DBR. After 5000 rounds, there is a major decrease in delay of DSDBR at the cost of small decrement in network density. However, in DBR, there is increase in end-to-end delay which is primarily due to high *TLs* for remaining distant nodes. Furthermore, end-to-end delay depends upon salinity, temperature,

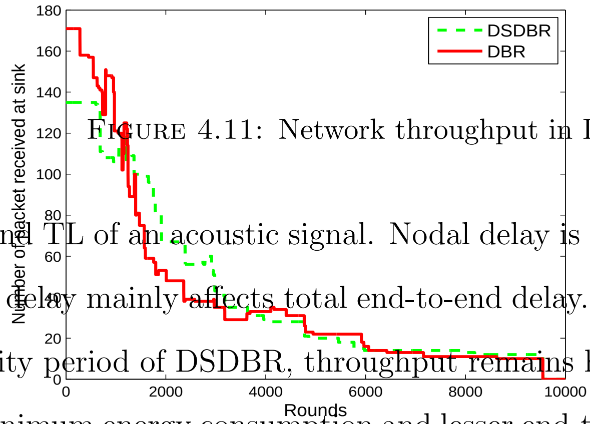

FIGURE 4.11: Network throughput in DBR and DSDBR

depth and TL of an acoustic signal. Nodal delay is also important, however, propagation delay mainly affects total end-to-end delay. After 1000 rounds, during the instability period of DSDBR, throughput remains higher than that of DBR along with minimum energy consumption and lesser end-to-end delay as shown in figures 4.9, 4.10 and 4.11. The key cause of reduced delay in DSDBR in later rounds is low network density and availability of suitable data forwarders. Therefore, DSDBR is 48 % more efficient than DBR in terms of end-to-end delay by compromising on low throughput and less stability period.

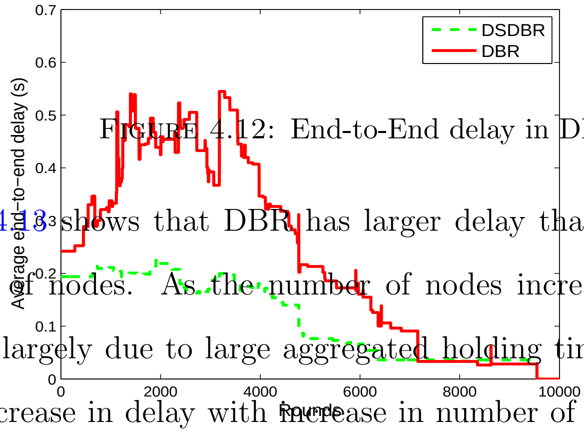

FIGURE 4.12: End-to-End delay in DBR and DSDBR

Figure 4.13 shows that DBR has larger delay than DSDBR with the change in number of nodes. As the number of nodes increases, the delay in DBR is increased largely due to large aggregated holding time. In DSDBR, there is not a large increase in delay with increase in number of nodes due to selection of data forwarders at the intermediate depth difference from the sender.

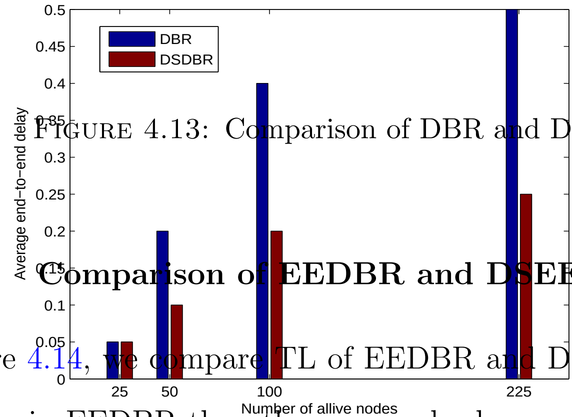

FIGURE 4.13: Comparison of DBR and DSDBR in terms of delay

4.8.2.2 Comparison of EEDBR and DSEEDBR

In figure 4.14, we compare TL of EEDBR and DSEEDBR. It illustrates that TL is higher in EEDBR than the proposed scheme, which is caused by a large number of transmissions and multiple retransmissions for same packets. In EEDBR, due to high network density in initial rounds, there is less transmission loss which

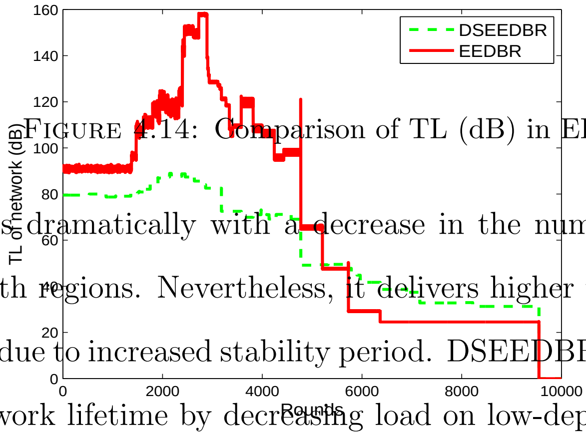

FIGURE 4.14: Comparison of TL (dB) in EEDBR and DSEEDBR

increases dramatically with a decrease in the number of available forwarders in low-depth regions. Nevertheless, it delivers higher throughput than our proposed scheme due to increased stability period. DSEEDBR maintains low TL throughout the network lifetime by decreasing load on low-depth nodes, however, it compromises on network throughput in the initial rounds.

Figure 4.15 depicts average end-to-end delay in EEDBR and DSEEDBR. It shows gradual decrease in delay of DSEEDBR along with changes in TL (figure 4.16) of the network. It illustrates slower network activity in EEDBR which is not suitable for time-critical applications. After 2000 rounds, there is a sharp increase in delay of EEDBR due to quick energy consumption of nodes deployed in medium-depth region. DSEEDBR decreases end-to-end delay of the network by incrementing d_{th} in high-depth area for forwarder selection considering low attenuation and noise losses in this region. Figure 4.16 shows the comparison of number of transmissions in EEDBR and DSEEDBR. It also shows that in spite of low throughput in stability period before 2000 rounds, there is a high number of transmissions in EEDBR which increase rapidly in the later rounds.

Our proposed protocol minimizes delay by reducing the number of transmissions in the network. It compromises on network throughput to achieve low T_p. Global load balancing is achieved in DSEEDBR which results in an almost same number of transmissions throughout the entire lifetime. Simulations show that DSEEDBR

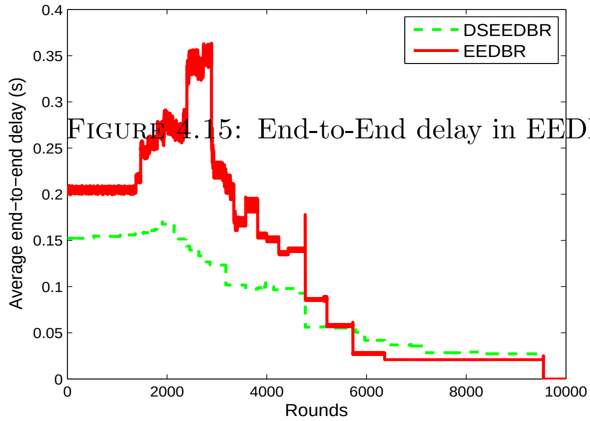

Figure 4.15: End-to-End delay in EEDBR and DSEEDBR

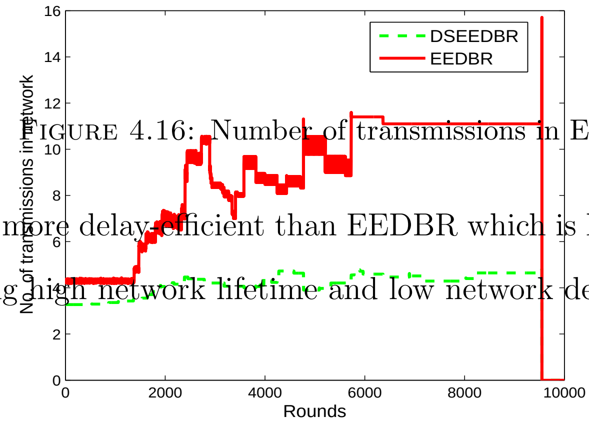

Figure 4.16: Number of transmissions in EEDBR and DSEEDBR

is 68 % more delay efficient than EEDBR which is highly suitable for applications requiring high network lifetime and low network delay.

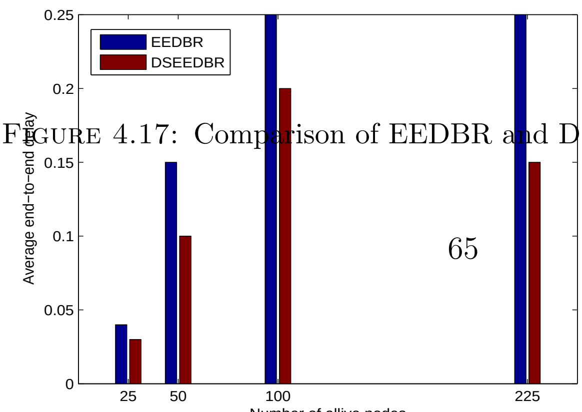

Figure 4.17: Comparison of EEDBR and DSEEDBR in terms of delay

Figure 4.17 shows that DSEEDBR has decreased end-to-end delay than EEDBR. It is due to the fact that speed of received signal defines the holding time. Neighbors having high depth difference, but low Euclidean distance is selected as the data forwarder of the source node. It has less holding time than the other neighbors which causes decrease in delay. As the number of nodes is 225, there is a large improvement in delay condition in DSEEDBR due to efficient holding time computation.

4.8.2.3 Comparison of AMCTD and DSAMCTD

Figure 4.18 shows the comparison of end-to-end delay between AMCTD and DSAMCTD. The delay in AMCTD is already less than that of DBR and EEDBR due to the involvement of courier nodes, however, there is a high variation in end-to-end delay of AMCTD which is removed in our proposed scheme by introducing W_F. Sensor nodes having higher number of neighbors have a greater W_F than

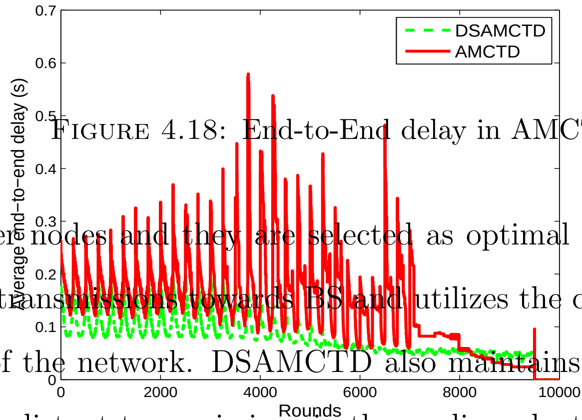

Figure 4.18: End-to-End delay in AMCTD and DSAMCTD

the other nodes and they are selected as optimal data forwarders. This reduces distant transmissions towards BS and utilizes the courier nodes in the high-depth region of the network. DSAMCTD also maintains reasonable stability period by avoiding distant transmissions in the medium-depth region.

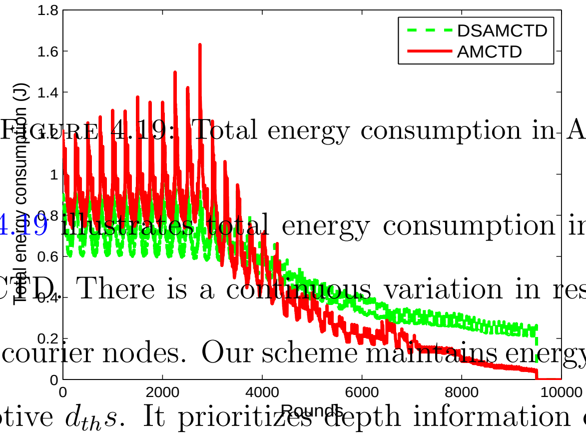

FIGURE 4.19: Total energy consumption in AMCTD and DSAMCTD

Figure 4.19 illustrates total energy consumption in the schemes of AMCTD and DSAMCTD. There is a continuous variation in results of AMCTD due to movement of courier nodes. Our scheme maintains energy consumption in entire lifetime by adaptive $d_{th}s$. It prioritizes depth information of sensor nodes to compute its W_F.

Figures 4.20 and 4.21 clearly show the trade-off between the throughput and end-to-end delay of DSAMCTD. Moreover, AMCTD has much higher throughput in the stability period however, high variation in energy consumption of sensor nodes. We employed the mobility of courier nodes to achieve minimal delay without increasing network throughput. However, higher network throughput is maintained in the later rounds. According to our computations, DSAMCTD is 56 % more

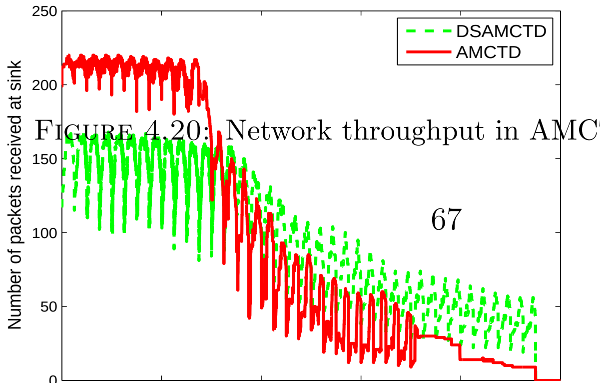

FIGURE 4.20: Network throughput in AMCTD and DSAMCTD

efficient than AMCTD in terms of end-to-end delay in the network.

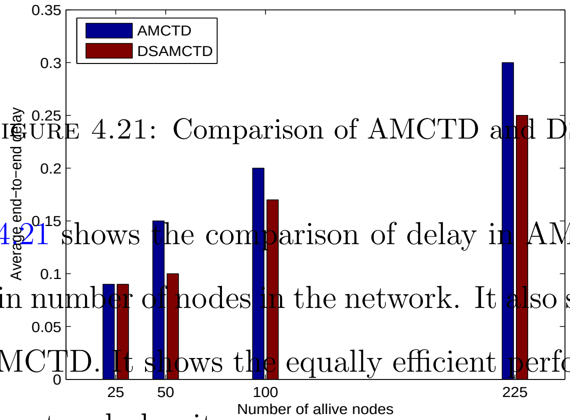

FIGURE 4.21: Comparison of AMCTD and DSAMCTD in terms of delay

Figure 4.21 shows the comparison of delay in AMCTD and DSAMCTD with the change in number of nodes in the network. It also shows the improved performance of DSAMCTD. It shows the equally efficient performance of PFs in high, medium and low network density.

4.9 Conclusion of the chapter

In this chapter, we proposed delay-sensitive protocols as an improvement to localization-free routing schemes of DBR, EEDBR and AMCTD. The proposed schemes are validated and verified through extensive simulations in UWSNs. In DSDBR, we used F_i and W_F to devise better forwarder selection. In DSEEDBR, we introduced d_{th} variation and provided an analysis to estimate DSH_T. It is observed that distant transmissions in the low-depth region are the major causes of high propagation delays. Therefore, we eliminated large number of transmissions caused by turbulence and thermal activities. In the improved version of AMCTD, we devised PF formulae for sensor nodes with varying network density and selecting a sensor node with higher neighbors as an optimal forwarder for data packets. We succeeded in guaranteeing minimal end-to-end delay by employing adaptive mobility of courier nodes allowing a slight decrease in network throughput.

In the next chapter, a cooperative routing protocol is presented for UWSNs to enhance the network performance called ARCUN. The protocol is energy-efficient and high-throughput for UWSN. Single-hop and multi-hop routing methods both are considered which contribute to significant reduction in path-loss present in the channels linking nodes and forwarding of data. Ideal role of cooperation delivers load balancing in the network and offers weighty enhancement in network stability period.

Chapter 5

ARCUN

5.1 Summary of the chapter

Cooperative routing is a hybrid approach utilizing routing techniques and cooperative communication to improve the communication quality of single-antenna sensor nodes. It exploits the broadcast nature of wireless medium and transmits cooperatively using nearby sensor nodes as relays. In this research, a cooperative transmission scheme is proposed for UWSNs to improve the network performance called ARCUN. The protocol is an energy-efficient and high-throughput routing scheme for UWSN. Potential relays are selected from a group of neighbor nodes that utilize SNR and distance computation of the underwater channel. Both single-hop and multi-hop routing techniques have been utilized which contribute to sufficient decrease in path-losses occurring in the links connecting sensors and transferring of data. Optimal role of cooperation provides load balancing in the network and gives profound improvement in network stability period.

5.2 Motivation

In ARCUN protocol, we propose a mechanism to route data through UW networks with minimum path-loss over the link; and the merits of single-hop and multi-hop are utilized. The proposed scheme uses a cost function to select the most appropriate route to sink. This cost function is calculated on the basis of their distance from the sink and their residual energy. The channel for acoustic link is described by path loss model in terms of frequency and distance. Simulation results show that ARCUN protocol has considerably enhanced the network stability time with reduced effects of path-loss.

The research takes into account an underwater environment, where channel is heavily affected by multi-path fading. Data packets from nodes arrive at sink which further communicate with the base station through radio frequency link.

The presented scheme leads to enhance the reliability of the channel through co-operation. Cooperative diversity, obtained with single antennas, is especially useful when time, frequency, and spatial diversity through multiple antennas are not feasible. This motivated us to introduce cooperation scheme in UW environment, and study its impact on system performance.

5.3 ARCUN: The proposed protocol

Multi-hop communication is used as the maximum transmission range of a sensor node is not long enough to cover the entire network. Simulating UWSN communications requires modeling the acoustic wave propagation while a sensor node in UWA tries to transmit data to another one.

5.3.1 Network topology

Sensed data from the source node S is gathered at one of the sinks D. It is considered that nodes except for sink nodes are energy constrained. Network is assumed to be composed of heterogeneous nodes, as shown in the figure 5.1, with each node having only one antenna. Relay nodes R1, R2 and R3 are advanced nodes having more energy than the normal nodes. Source nodes are transmitting the data to the higher level nodes as well through the relay nodes. The process goes on till the data reaches D at the surface of the water. Relay nodes have the dual responsibility of data relaying of the neighbor nodes and the transmission of their own data. In case of normal delivery, data from S always follows the relay node path in a cooperation mode but if the relay node link is not reliable or the relay node is dead, then there is a direct link path available for the data transfer.

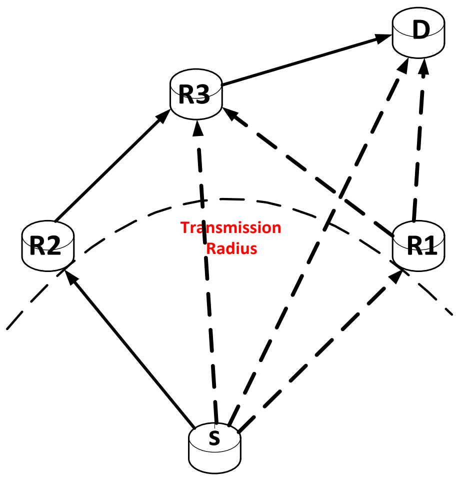

FIGURE 5.1: Multi-hop routing

5.3.2 Initialization phase

Three different types of tasks are performed in this phase. Each node is informed about its neighbors, location of sinks on the surface of water and all the possible routes to various sinks are also evaluated. Sensors update their depth to its neighbors and sinks when each node broadcasts an information packet containing its node identity, depth and energy status. Employing hello packets transmission, each node identifies its neighbors in transmission range and maintains the separate queue of neighbors under depth threshold to identify the finest forwarder for its data transmission. Each node calculates its weights using the formula given below:

$$W_i = \frac{max(\rho(d_{S_iR_i}, f), \rho(d_{S_iD_i}, f)) + max(R.E_{R_i}, R.E_{D_i})}{min(|d_{S_iR_i}|^2, |d_{S_iD_i}|^2)} \tag{5.1}$$

where $\rho(d_{S_iR_i}, f)$, $\rho(d_{S_iD_i}, f)$ are the SNR of the corresponding node's links from S_i to R_i and S_i to D_i respectively, $R.E$ is the residual energy of the corresponding nodes, $d_{S_iR_i}$ and $d_{R_iD_i}$ are the distances between the corresponding source to its relay and immediate destination respectively.

5.3.3 Co-operation phase

A two-phase transmission scheme is utilized here as shown in figure 5.1. In phase 1, one of the sources S_i forwards its data to both relay R and destination D simultaneously; whereas in phase 2, R re-transmits the received data to D. Information received at R and D from source in phase 1 can be expressed mathematically as [57]:

$$y_{S_iR_i} = \sqrt{P_1} h_{S_iR_i} x_{S_i} + N_{S_iR_i}(f) \tag{5.2}$$

$$y_{S_iD_i} = \sqrt{P_1} h_{S_iD_i} x_{S_i} + N_{S_iD_i}(f) \tag{5.3}$$

where P_1 is the transmitted power at the source, x_{S_i} is the transmitted information symbol from S_i. $h_{S_iR_i}$ and $h_{S_iD_i}$ are the gains of the wireless medium from S_i to R_i and S_i to D_i, respectively. These co-efficients are modeled as a complex Gaussian random variable with zero mean and variance σ^2 expressed as $\mathcal{CN}(0, \sigma^2)$ rather than normal variables because these represent the channel characteristics which vary from time to time. These characteristics are dependent not only on frequency but also other features affecting channel modelling. $N_{S_iR_i}$ and $N_{S_iD_i}$ are the noise components introduced in the links from S_i to R_i and S_i to D_i, respectively [57]. The channel variance σ^2 is modeled as:

$$\sigma^2 = \eta d_{ij}^{-\alpha} \tag{5.4}$$

where d_{ij} denotes the distance between any two nodes i and j, α is the propagation loss factor and η is a constant whose value depends on the propagation environment.

In phase 2, the relay forwards the amplified symbol with power P_2 to the destination. The received signal then can be modeled as [57]:

$$y_{R_iD_i} = \sqrt{P_2'} h_{R_iD_i} x'_{S_i} + N_{R_iD_i}(f) \tag{5.5}$$

where $\tilde{P}_2' = P_2$ if the relay receives the transmitted symbol correctly, otherwise $\tilde{P}_2' = 0$, x'_{S_i} is the signal which is received at the destination node after passing from $S - R$ link which may be faded and may not be the same as x_{S_i} and h_{RD} is the channel coefficient from R_i to D_i. The noise terms are complex Gaussian random variables with mean zero and variance N_0.

Destination node D_i aggregates the received signals from S_i and R_i. If the total received power at D_i is P then $P_1 + P_2' = P$.

5.3.4 Relay selection phase

Selection of relay node relies on instantaneous channel conditions, the weight factor computed in equation (5.1), SNR for each link from source to its neighbor, the residual energy of the nodes and the distances between the nodes. The source node finds an optimal relay among its neighbors by comparing their weights. The neighbor having the highest value of W_i is elected as the relay and after receiving the packet it waits for holding time before upward data transmission. It discards the packet on receiving the same packet from any other neighbor node or the direct link from the source during the holding time duration. If a corresponding destination node receives the packet, it transmits acknowledgment to other neighbors of source node to eliminate needless forwarding by any other neighbor node. Relay nodes continue to forward the packet of the source node until it reaches to one of the sink at the surface of the water.

If multiple relay nodes are available in the path and a source node has a sink node as its next-hop node, then a relay node will never trigger co-operation. It will help to maximize the minimum residual energy left after data transmission. This can be accomplished through the following condition:

$$\begin{cases} \text{if} \quad E_{re}(S_i) > E_{re}(R_i), & \text{then direct transfer} \\ \\ \text{else} \quad E_{re}(S_i) \leq E_{re}(R_i), & \text{then relay path} \end{cases}$$

5.3.5 Relay strategy

In this research, as we are considering the AF technique, the relay node R multiplies the received signal from S by an amplification factor β before forwarding to the destination node D i.e. $y_{RD} = \beta(y_{SR})$, following equations (3.15), (3.16) and (3.17).

5.3.6 Attenuation and propagation delay

For to compute the attenuation and propagation delay for an underwater, we will follow the same model as given in section (3.1), and hence following the equations (3.1) till (3.7).

5.3.7 SNR in UWA channels

The SNR of an emitted UW signal with unit transmit power $\hat{p}(t)(watts)$ at the receiver is given by section (3.1.3).

5.3.8 Outage formulation in UW acoustic channel

Channel capacity of a Gaussian channel with infinite bandwidth presents an upper limit for on the amount of information being transmitted successfully over a communication path. This can be expressed by the equations (3.12) and (3.13) and this condition is used to assess the quality of incoming signal at the receiver side. In contrast to equation (3.13), outage occurs when the transmission rate R exceeds C, i.e.

$$Outage = C(d, \rho) < R \tag{5.6}$$

It is assumed here that probability of error is approximately nil when channel is not in outage. Hence, the outage probability $P_{outage}$is given by:

$$P_{outage} = P\{C(d, \rho) < R\} \tag{5.7}$$

$$P_{outage} = P\{Blog_2(1 + \rho(d, f)) < R\} \tag{5.8}$$

5.3.9 Reliability in UW acoustic channel

There are a variety of techniques for prevention of losing data when the channel is in outage, like coding over a long period of time, or obtaining transmitter side channel information [75]. Here, reliability of a link is obtained by isolating diversity through routing, and then results be applied in combination with other diversity techniques. The event of successful end-to-end transmission from S to D is the one in which all transmissions are successful. The end-to-end Reliability $\mathfrak{R}$ is defined as the probability of this event [75]. Hence, $\mathfrak{R}$ can be written as:

$$\mathfrak{R} = 1 - P_{outage} \tag{5.9}$$

5.3.10 Combining strategy

Each node D implements a diversity combining technique to combine the received signals coming from S and R. Here FRC is used as the combining strategy. In FRC, instead of just adding up the incoming signals, they are weighted with a constant ratio. This ratio should reflect the average channel quality and influences on channel due to shadowing and other effects. In case of a single-relay node, FRC can be expressed as

$$y_d = k_1 y_{SD} + k_2 y_{RD} \tag{5.10}$$

where y_d represents the combined output signal at the destination node D, k_1 and k_2 are the weights of the two links and the expression can be extended for any number of relay nodes. These weights are a function of power and channel co-efficients and their ratio can be expressed as [82]

$$\frac{k_1}{k_2} = \frac{\sqrt{P}_1 h_{SD}}{\sqrt{P}'_2 h_{RD}} \tag{5.11}$$

An optimal value of the weights ratio is 2 : 1 in case of AF technique [57].

where

$$k_1 = \frac{\sqrt{P}_1 h_{SD}}{N_0} \tag{5.12}$$

and

$$k_2 = \frac{\sqrt{P}'_2 h_{RD}}{N_0} \tag{5.13}$$

If the transmitted symbol x_s has an average energy of unity, then the SNR of the FRC output is [82]

$$\rho = \frac{P_1|h_{SD}|^2 + P'_2|h_{RD}|^2}{N_0} \tag{5.14}$$

5.4 Performance evaluation of ARCUN

To evaluate the performance of ARCUN, it is compared with the existing schemes AMCTD and EEDBR. In the simulation, nodes have been deployed randomly in every simulated technique. With 10 sinks deployed on the surface of the water, 225 nodes are randomly deployed in the network. The transmission range of sensor node is 250 meters. In each round, all alive nodes transmit threshold-based data towards sink. After equal intervals of time, nodes compute their distance from the neighbor nodes. The nodes transfer their data to the upper layer using cooperation of neighbor nodes till the data reaches the sink. The introduction of cooperation and variations in depth threshold make ARCUN scheme as a feasible contender for data-critical applications.

Figure 5.2 illustrates that ARCUN scheme improves the stability period of network by avoiding the forwarding of unnecessary data along with maintaining lower transmission loss. In the simulations shown, first node in EEDBR dies after 1000 secs, in AMCTD it dies after 1100 secs whereas in our scheme it dies after 3000 seconds thereby increasing the stability period. Due to the introduction of cooperation scheme, load balancing is achieved thereby increasing the stability period.

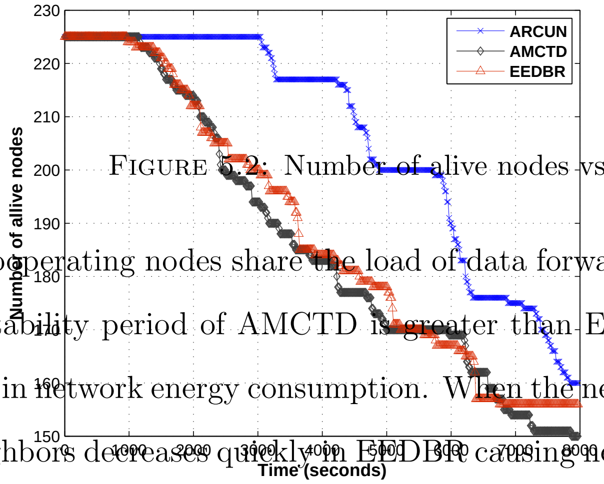

Figure 5.2: Number of alive nodes vs Network lifetime

The cooperating nodes share the load of data forwarding of distant transmissions. The stability period of AMCTD is greater than EEDBR, as there is gradual increase in network energy consumption. When the network becomes sparse, number of neighbors decreases quickly in EEDBR causing network instability. In AMCTD, the consideration of two forwarding attributes; depth and residual energy, causes a trade-off between the network lifetime and transmission loss which is not suitable for reactive applications. Lifetime of ARCUN is increased due to lower throughput by responsive network. In our suggested scheme, employment of Thorp energy model specifies the detailed channel losses, useful for selective data forwarding in responsive networks. Increase in stability period also confirms reduction in redundant transmissions.

Packet Delivery Ratio (PDR) is the ratio of data packets received at destination to those generated by the source. The plots in figure 5.3 show the PDR comparison of ARCUN with that of AMCTD and EEDBR. Performance of the EEDBR is reduced whereas the delivery ratios of AMCTD and ARCUN show a similar pattern of plots; although the drop in PDR in ARCUN is much less than that of AMCTD. When the inter-arrival time of packets is less, higher traffic is sent from source nodes. This increases the rate of packet collision leading a lower PDR. ARCUN

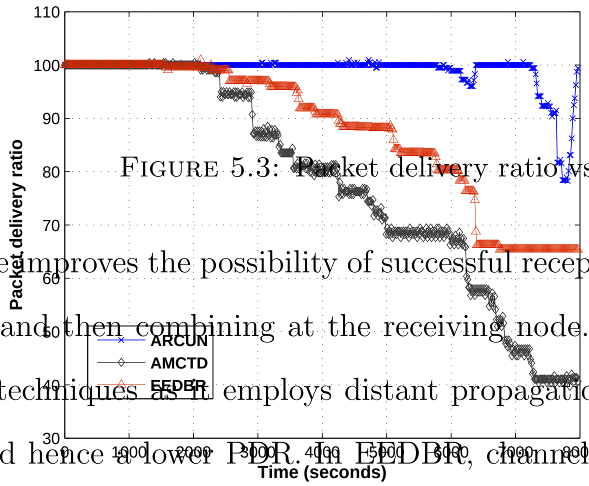

FIGURE 5.3: Packet delivery ratio vs Network lifetime

scheme improves the possibility of successful reception of data packets on multiple paths and then combining at the receiving node. AMCTD has higher loss than other techniques as it employs distant propagations as well as multiple forwarding and hence a lower PDR. In EEDBR, channel loss conditions are better than AMCTD, as the weight function computations consider both depth and residual energy of forwarding nodes, therefore the propagations remain stable. The figure shows that there is sufficient drop in PDR after 7000 seconds but it again rises after 7750 seconds. This accounts for the fact that as the simulations go on, the energy of nodes go on decreasing and nodes farther from the sink start dying but after 7750 seconds, only those nodes are left which are nearer to the sink. At this stage, only these nodes will be available for data sensing and transfer to sink.

Figure 5.4 describes the comparison between the path-loss (dB) of ARCUN with the other two schemes. In our scheme, path-loss of links is much reduced because the use of cooperation makes the data forwarding much better with the help of relay nodes and load balancing is also achieved. ARCUN is mainly concerned with the requirement of time-critical applications and hence addresses the problem of path-loss reduction by utilizing cooperation and depth difference between data forwarders. The weakness of ARCUN protocol is also obvious from the plots

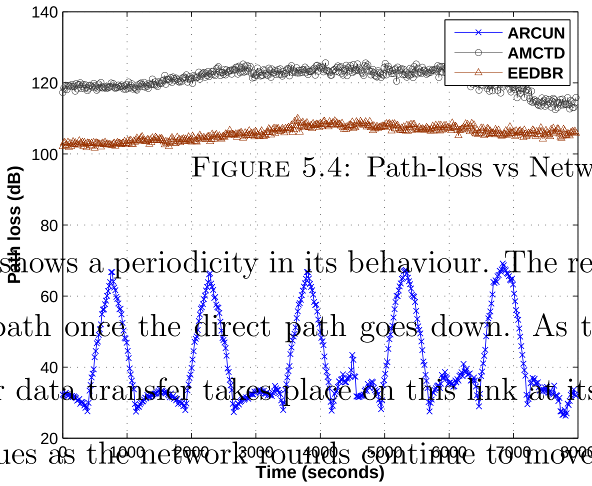

FIGURE 5.4: Path-loss vs Network lifetime

which shows a periodicity in its behaviour. The reason is its selection of alternate relay path once the direct path goes down. As the direct link is re-established, further data transfer takes place on this link at its priority and the same activity continues as the network rounds continue to move ahead.

5.5 Conclusion of the chapter

In this work, we have suggested ARCUN routing protocol to maximize network lifetime and reduce energy consumption in UWSNs. Utilization of cooperation and SNR enhances the stability period and packet delivery ratio especially for delay-sensitive applications and even in sparse conditions. The transmission schemes without cooperation are based on channel estimation. These try to improve the received packet quality at receiver node. However, transmission using a single link can be affected when the channel quality changes. Relay selection mechanism considers the instantaneous path conditions and distance among neighbours to relay packets successfully to destination in constrained UWSN. Variations in depth threshold increase the number of eligible neighbors, thus minimizing critical data loss. Features of single-hop and multi-hop communication techniques have been utilized for the reduction of path-loss effects and increasing stability period as well as network lifetime. Optimal weight computation and role of cooperation not only provides the load balancing in the network, but also gives proficient improvement in the network stability period.

In the next chapter, we introduce a routing scheme Co-UWSN, that transmits data effectively from a mobile node to any sink on the sea surface. However, this is a challenging task due to noisy environment and limited energy and bandwidth resources. These limitations make the network susceptible to bottleneck due to packet collisions. Cooperative routing is one of the answers to this problem, through which data damage is evaded by using transmission nature of wireless connection. This sort of routing structure permits more recurrent data collecting due to backing of adjoining nodes, hence data harm is least anticipated.

Chapter 6

Co-UWSN

6.1 Summary of the chapter

In this chapter, we propose a cooperative transmission scheme for UWSNs to enhance the network performance. Cooperative diversity has been introduced to combat fading. Co-UWSN is proposed, which is a reliable, energy efficient and high throughput routing protocol for UWSN. Destination and potential relays are selected from a set of neighbor nodes that utilize distance and signal-to-noise ratio computation of the channel conditions as cost functions. This contributes to sufficient decrease in path-losses occurring in the links connecting sensors in UWSN and transferring of data with much reduced path-loss. Simulation results show that Co-UWSN protocol performs better in terms of end-to-end delay, energy consumption and network life-time. Selected protocols for comparison are non-cooperative routing protocols EEDBR and iAMCTD and a cooperative routing protocol for UWSN, Cooperative Partner Node Selection Criteria for Cooperative Routing (Coop Re and dth).

6.2 Motivation

In most applications the network consists of battery-powered nodes. Due to low transmit power, these nodes have limited communication range. Thus, cooperative communication, in which nodes share their resources, is essential for these networks. Replacing long and weaker links with short and stronger links can reduce the burden on the link. Alternative routes between the users and the base-station provide robustness against shadowing and multi-path fading, and introduce new design options for scheduling and routing.

In Co-UWSN protocol, a cooperation-based mechanism is proposed to route data through underwater networks with minimum path-loss over the link; and the merits of single-hop and multi-hop are utilized. The proposed scheme uses a cost function to select the most appropriate route to sink. This cost function is calculated on the basis of their distance from the sink and their residual energy. The channel for acoustic link is described by path loss model in terms of frequency and distance. Simulation results show that Co-UWSN protocol has considerably enhanced the network stability time with reduced effects of path-loss.

EEDBR uses local depth information along with residual energy of sensor nodes to select the optimal forwarder for achieving load balancing. Redundant transmissions are controlled by introducing holding time for forwarding nodes. It is a receiver based approach in which the nodes having smaller depth participate in forwarding the data packets. But, redundant transmissions consume a lot of energy. EEDBR is a non-cooperative routing protocol. Hence, data is routed from source to destination over a single noisy link in a multihop fashion. Due to noise and multipath fading in underwater environment, signal suffers high BER. In iAMCTD, a routing scheme is proposed to maximize the lifetime of reactive UWSNs. iAMCTD considers signal quality along with residual energy as routing metrics. It is a network prototype in localization-free and flooding based routing for underwater applications. It improves the network throughput and largely minimizes PDR by using its formulated forwarding functions. iAMCTD faces redundant transmissions which result in major energy consumption. Coop (Re and dth) aims to solve the issues of EEDBR and iAMCTD via cooperative diversity. This protocol involves data transmission through the use of partner nodes/relays that cooperatively forward data to the destination. It increases the rate of successful data delivery to the destination because in case of link failure, at least one link is capable of delivering the data successfully to the destination. The scheme considers a node link state information along with its depth and residual energy as selection parameters. So, Coop (Re and dth) is consuming more transmission energy than iAMCTD and EEDBR. This shows the tradeoff between energy conservation and reliability. Also, the protocol does not consider any transmission impairments present in the underwater environment. In order to address the issues of all these three protocols, we have tried to propose a new protocol by the name of Co-UWSN.

The chapter considers a distributed UWA environment in the ocean, where the channel is heavily affected by multi-path fading. Data packets from sensor nodes arrive at the sink which further communicate with the onshore base station through long range radio frequency link. Each node can monitor and detect events from local environment in many applications such as oceanographic data collection, environmental monitoring, climate recording, etc. Signal may be modeled by a Rayleigh random variable. The presented scheme leads to enhance the reliability of the underwater channel through cooperative transmission scheme. In this research we shall be considering FRC for signal combining. Cooperative diversity is a kind of spatial diversity that can be obtained without use of multiple antennas. It is especially useful when time, frequency, and spatial diversity through multiple antennas are not feasible. This motivated us to introduce the cooperation in UWA environment, and study its impact on system performance.

6.3 Co-UWSN: The proposed protocol

A node that uses cooperation shares its data packet with its neighbour nodes, and a group of these nodes can transmit the packet to the intended receiver or destination. The destination node can use a physical-layer diversity combining scheme to combine multiple signals. Cooperative routing improves SNR over the traditional Single-Input-Single-Output (SISO) case, which does not utilize cooperation. This SNR improvement can save transmit power, increase data rate, and extend the communication range. The aim of the chapter is to apply multihop networking in UWA environment through the use of cooperation. In this chapter, we are considering a simple network model, in which data packets originating from a source node at the base of the river bed are forwarded hop by hop to a destination node at the surface of the sea. A relay node is employed at the joint of every two consecutive hops. It receives the incoming packets, amplifies them, and re-transmits them on to the destination.

6.3.1 Network topology

Network capacity, energy consumption, and the reliability of a network depends on network topology. Multi-hop communication is used as the maximum transmission range of a sensor node is not long enough to cover the entire network. Sensed data from the source node is gathered at one of the sinks. It is considered that sink has no energy constraint that may communicate with any of the nodes without cooperation. Nodes except for sink nodes are energy constrained. Network is assumed to be divided into layers going deep into underwater; and is composed of heterogeneous nodes, as shown in the figure 6.1, with each node having only one antenna. The yellow coloured nodes are advanced nodes having more energy than the normal nodes which are white in color. The source nodes are transmitting the data to the higher level nodes as well through the relay nodes shown yellow in color. The process goes on till the data reaches the sink at the surface of the water. The relay nodes are advanced nodes as they have the dual responsibility of data relaying of the neighbor nodes and the transmission of their own data. In case of normal data, the source node data always follows the relay node path in a cooperation mode but if the relay node link is not reliable or the relay node is dead, then there is a direct link path available for the data transfer.

6.3.2 Initialization phase

Three different types of tasks are performed in this phase; each node is informed about its neighbors, location of sinks on the surface of water is identified and all the possible routes to various sinks are also evaluated. Sensors update their depth to its neighbors and sinks when each node broadcasts an information packet

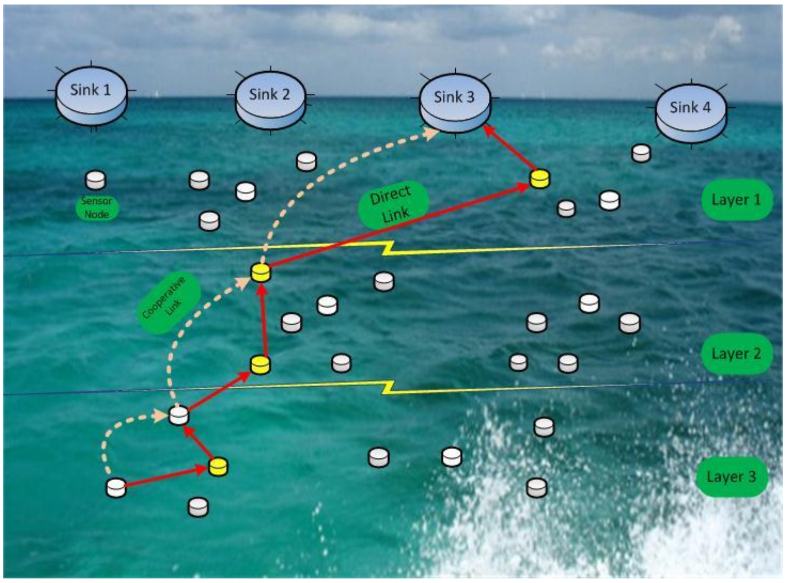

FIGURE 6.1: Nodes' deployment in an underwater environment

containing its node ID, depth and energy status. Sink sends hello packet to all the nodes to get their vital information. Employing hello packets transmission, each node identifies its neighbors in transmission range and maintains the separate queue of neighbors under depth threshold to identify the finest forwarder for its data transmission. Each node calculates its weights using the formula given below:

$$W_i = \frac{max(\rho(d_{S_iR_i}, f), \rho(d_{S_iD_i}, f)) + max(R.E_{R_i}, R.E_{D_i})}{min(|d_{S_iR_i}|^2, |d_{S_iD_i}|^2)} \tag{6.1}$$

where $\rho(d_{S_iR_i}, f)$, $\rho(d_{S_iD_i}, f)$ are the SNR of the corresponding node links from S_i to R_i and S_i to D_i respectively, $R.E$ is the residual energy of the corresponding nodes, $d_{S_iR_i}$ and $d_{R_iD_i}$ are the distances between the corresponding source to its relay and immediate destination respectively.

In cooperative networks, the source node is in charge of selecting the cooperators also known as relays. It is also in charge of sharing its data with the selected relay and doing the cooperative routing. The maximum number of cooperating nodes N_c^{max} cannot exceed the maximum number of channels N_d, and therefore, $N_c^{max} \leq N_d$. Also, a source can select up to $(N_c^{max} - 1)$ cooperators, and

$2 \leq N_c \leq N_c^{max} \leq N_d$. If a node decides to do cooperation, it becomes an "initiator". Cooperators of a node are its neighbors that are selected by the node to do cooperation. An initiator should share its data with its cooperators called the "cooperative sharing". Figure 6.2 shows complete flow-chart for the Co-UWSN scheme with different stages incorporated.

6.3.3 Cooperation phase

A two-phase transmit scheme is considered as shown in figure 6.3 which allows a non-overlapping transmission for source node and relay node. The whole process of cooperation is done in two phases. In phase 1, one of the sources S_i transmits its information to both relay R and destination D simultaneously; whereas in phase 2, R transmits received information to D. Distance between the relay and source is d_1 and the distance between the relay and destination is d_2 as shown in figure 6.3. The information received at R and D from source in phase 1 can be written as [30]:

$$y_{S_iR_i} = \sqrt{P_1} h_{S_iR_i} x_{S_i} + N_{S_iR_i}(f) \tag{6.2}$$

$$y_{S_iD_i} = \sqrt{P_1} h_{S_iD_i} x_{S_i} + N_{S_iD_i}(f) \tag{6.3}$$

where P_1 is the transmitted power at the source, x_{S_i} is the transmitted information symbol from one of the i^{th} source S_i, $h_{S_iR_i}$ and $h_{S_iD_i}$ are the characteristics of the wireless medium from S_i to R_i and S_i to D_i, respectively. These co-efficients are modeled as a complex Gaussian random variable with zero mean and variance σ^2 expressed as $\mathcal{CN}(0, \sigma^2)$. The channel variance σ^2 is modeled as:

$$\sigma^2 = \eta d_{ij}^{-\alpha} \tag{6.4}$$

where d_{ij} denotes the distance between any two nodes i and j, α is the propagation loss factor and η is a constant whose value depends on the propagation environment. $N_{S_iR_i}$ and $N_{S_iD_i}$ are the noise components introduced in the links from S_i

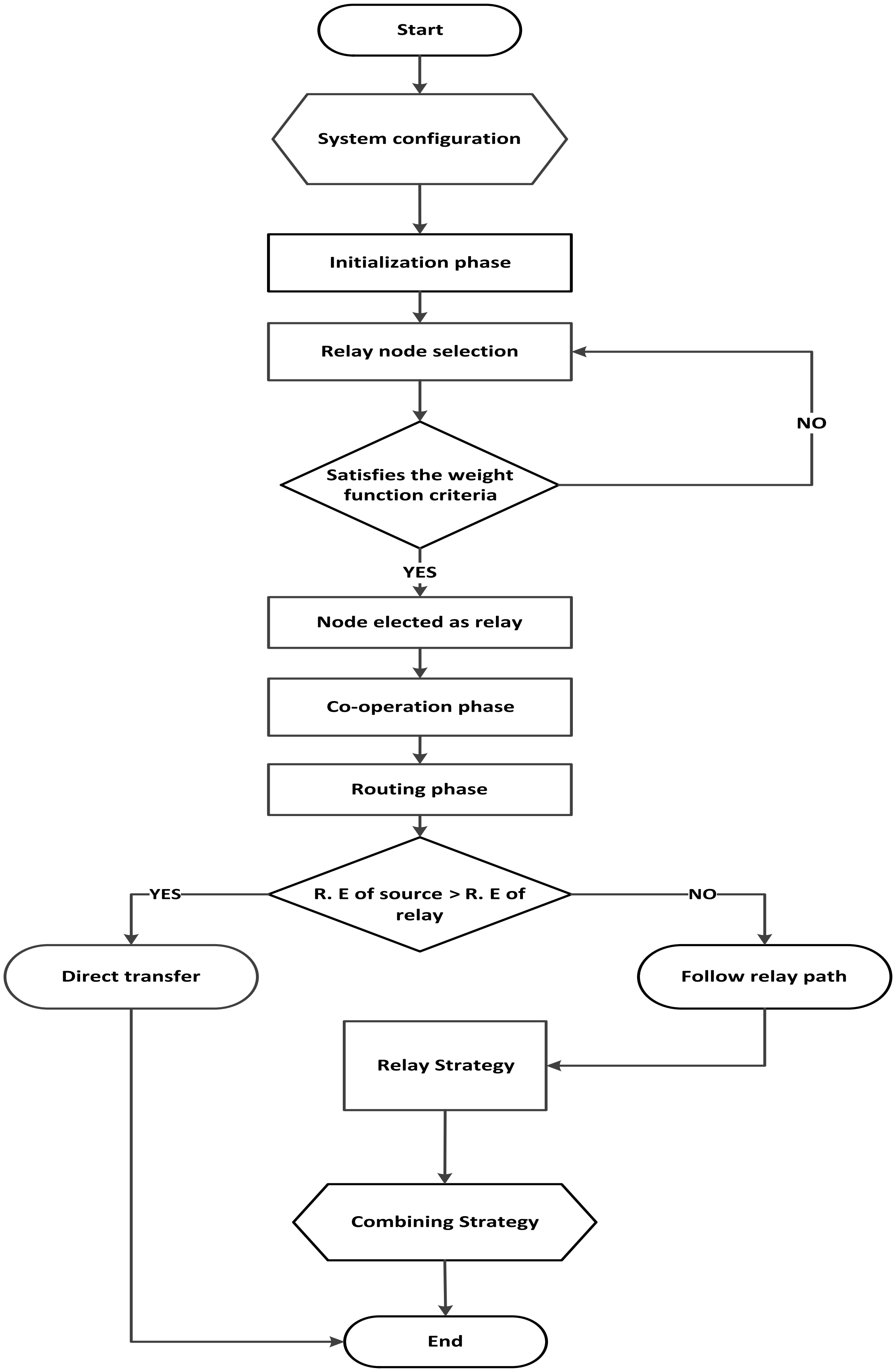

FIGURE 6.2: Flow-chart for the Co-UWSN scheme

to R_i and S_i to D_i, respectively [30] and has the value in terms of the components as given in equation (6.3). In phase 2, the relay forwards the amplified symbol

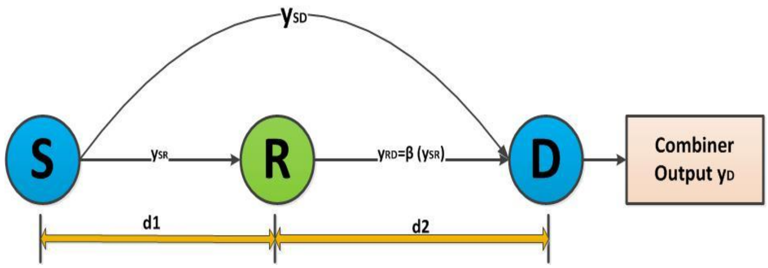

FIGURE 6.3: Linear three-sensor-node system model

with power P_2 to the destination. Received signal at the destination in phase 2 can be modeled as [30]:

$$y_{R_iD_i} = \sqrt{P_2'} h_{R_iD_i} x'_{S_i} + N_{R_iD_i}(f) \tag{6.5}$$

where $P_2' = P_2$ if the relay receives the transmitted symbol correctly, otherwise $P_2' = 0$, x'_{S_i} is the signal which is received at the destination node after passing from $S - R$ link which may be faded and may not be the same as x_{S_i} and h_{RD} is the channel coefficient from R_i to D_i. The noise terms are modeled as zero-mean complex Gaussian random variables with variance N_0.
Destination node D_i combines the received signals from S_i and R_i and using FRC technique. Total transmitted power is P such as $P_1 + P_2' = P$.

6.3.4 Relay selection and routing phase

A source node S_i has n surrounding nodes in its neighborhood as shown in figure 6.1. Any of the source relies on the instantaneous channel conditions to determine which of the neighbor will be most reliable to relay its information towards the sink. Selection of relay node relies on instantaneous channel conditions, the weight factor computed in equation (6.1), SNR for each path from source to each its neighbor, the residual energy of the nodes and the distances between the nodes. The source node finds an optimal relay among its neighbors by comparing their weights. The neighbor having the highest value of W_i is elected as the relay and after receiving the packet it waits for holding time before upward data transmission. It discards the packet on receiving the same packet from any other neighbor node or the direct link from the source during the holding time duration. After every 50 rounds, the sinks broadcast hello packet in the network to find the number of dead nodes [67]. It is used to cope with the changing conditions of the network and computations of network parameters. If a corresponding destination node receives the packet, it transmits acknowledgment to other neighbors of source node to eliminate needless forwarding by any other neighbor node. Source node broadcasts data and then relays are identified. Relay nodes continue to forward the packet of the source node until it reaches to one of the sink at the surface of water.

If multiple relay nodes are available in the path and a source node has a sink node as its next-hop node, then a relay node will never trigger co-operation. It will help to maximize the minimum residual energy left after data transmission. This can be accomplished through the following condition:

$$\begin{cases} \text{if} \quad E_{re}(S_i) > E_{re}(R_i), & \text{then direct transfer} \\ \\ \text{else} \quad E_{re}(S_i) \leq E_{re}(R_i), & \text{then relay path} \end{cases}$$

6.3.5 Relay strategy

In this research, as we are considering the AF technique, the relay node R multiplies the received signal from S by an amplification factor β before forwarding to the destination node D i.e. $y_{RD} = \beta(y_{SR})$, following equations (3.15), (3.16) and (3.17).

Hence, accordingly the signal received at D in phase 2 can be re-written as

$$y_{RD} = \sqrt{P_2'} h_{RD} \beta x_S N_{RD} \tag{6.6}$$

where P_2' is the power of the R-D link and is different in wattage from that of P_s and P_r. In this analysis, the amplitude of the received signal i.e., S to D, S to R and R to D is modeled as a Rayleigh distributed and the links are assumed to be independent and modeled as Rayleigh fading.

6.3.6 Combining strategy

Destination sensor node D implements a diversity combining technique to combine the received signals coming from source S and relay R. In case of BAN, as under consideration, FRC is used as the combining strategy and follows the equations (3.18) and (3.19).

6.4 Performance evaluation of Co-UWSN

6.4.1 Performance metrics

Some major terminologies and performance metrics that are used in this chapter are defined in section 5.6 and the rest as below:

- *Network lifetime:* It is defined as the total network operational time.
- *Packet delivery ratio:* Packet Delivery Ratio (PDR) is defined as the ratio of data packets received by the destination to those generated by the source.
- *Transmission-loss:* It shows the average transmission loss between a source node and sink in one round. It is measured in decibels (dB).

6.4.2 Results and discussions

To evaluate the performance of Co-UWSN, it is compared with the existing schemes of EEDBR, iAMCTD and Coop (Re and dth). In the simulation of 10000 rounds, nodes have been deployed randomly in every simulated technique. By following multiple-sink model of conventional methods with 5 sinks deployed on the surface of the water, 225 nodes are randomly deployed in the network field of 500m×500m.

In each round, all alive nodes transmit threshold-based data towards sink. Each node shares the vital physical metrics, like depth threshold and weight with its neighbors to keep informed with the changing circumstances of the network. After every 100th round, nodes compute their distance from the neighbor nodes. Source nodes transfer their data to the upper layer using cooperation of neighbor nodes till the data reaches sink. The sink supervises the depth thresholds and adaptive mobility of cooperating nodes. Introduction of cooperation, cooperative diversity and variations in depth threshold make Co-UWSN scheme as a feasible contender for data as well as time-critical applications. The changes in the channel model are not so rare, thereby, we take 10 simulation runs to show the average behavior of the simulated routing protocols.

Figure 6.4 represents a comparison between the end-to-end delay of Co-UWSN, iAMCTD, EEDBR and Coop (Re and dth). Their plots show that end-to-end delay of network in Co-UWSN is less than the other three techniques due to minimum forwarding distances between the nodes in both dense and sparse conditions. In iAMCTD, delay is much higher in final rounds due to distant data forwarding. It increases gradually with the sparseness of the network after about 4000 rounds and the network causes data forwarding at minimum distance. End-to-end delay in iAMCTD is better than EEDBR as both threshold variations and weight functions perform load balancing. But in Coop (Re and dth), there is a minimum possible time lag due to consideration of SNR, depth-threshold between sender and relay nodes and introduction of cooperation. iAMCTD and EEDBR forward packets with minimum hops but the low quality UWA channel can increase packet loss at the destination, therefore the packets need to be retransmitted. This intensifies the end-to-end packet delay. While all the four schemes are based on channel estimation, packets are forwarded with higher reliability, leading to lower retransmissions, especially in the case of the cooperative schemes Coop (Re and dth) and Co-UWSN. Hence, the packets reach the sink with a lower delay in Co-UWSN as it also considers the transmission impairments in case of underwater channels.

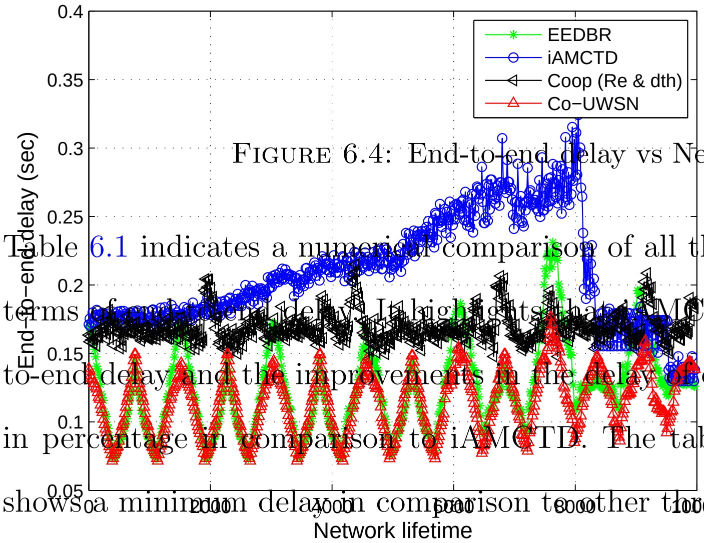

FIGURE 6.4: End-to-end delay vs Network lifetime

Table 6.1 indicates a numerical comparison of all the four compared protocols in terms of end-to-end delay. It highlights that iAMCTD shows the maximum end-to-end delay and the improvements in the delay of other three protocols is shown in percentage in comparison to iAMCTD. The table 6.1 shows that Co-UWSN shows a minimum delay in comparison to other three protocols.

TABLE 6.1: End-to-end delay after equal intervals

Protocol	**Average efficiency (%)**	**2000 rounds**	**4000 rounds**	**6000 rounds**	**8000 rounds**	**10000 rounds**
EEDBR	68	0.08	0.12	0.175	0.22	0.15
iAMCTD	100	0.175	0.22	0.25	0.32	0.13
Coop (Re and dth)	83	0.2	0.18	0.17	0.175	0.185
Co-UWSN	39	0.05	0.1	0.105	0.075	0.10

Figure 6.5 illustrates that Co-UWSN scheme improves the stability period of network by avoiding the forwarding of redundant and unnecessary data along-with maintaining lower transmission loss. In the simulations of 10,000 rounds, first node in EEDBR dies at 1185th round, in iAMCTD it dies at at 3185th, in Coop (Re and dth), it dies at 3275th round. In our scheme, although the first node dies at 1850th round but the network remains stable upto 6225th round. Due

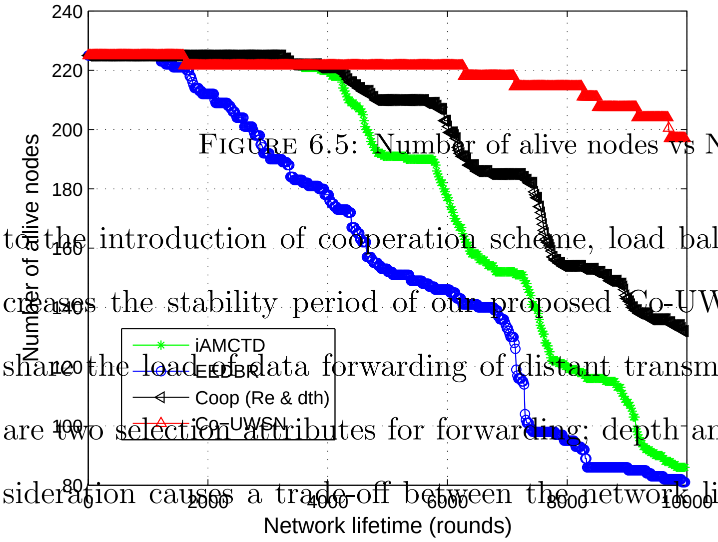

FIGURE 6.5: Number of alive nodes vs Network lifetime

to the introduction of cooperation scheme, load balancing is achieved which increases the stability period of our proposed Co-UWSN. The cooperating nodes share the load of data forwarding of distant transmissions. In Co-UWSN, there are two selection attributes for forwarding; depth and residual energy. This consideration causes a trade-off between the network lifetime and transmission loss which is not suitable for reactive applications. Cooperation between nodes causes load balancing both in Co-UWSN and Coop (Re and dth). During the instability period, network gradually becomes sparse causing load on high residual-energy nodes, whereas the number of neighbors is managed by variations in depth threshold. After the expiry of initial nodes, the network destabilizes due to shortage

TABLE 6.2: Alive nodes available after equal intervals

Protocol	**First node dies at**	**Efficiency in percentage**	**2000 rounds**	**4000 rounds**	**6000 rounds**	**8000 rounds**	**10000 rounds**
EEDBR	1185	100	212	178	146	105	82
iAMCTD	3185	268	225	220	177	120	86
Coop (Re and dth)	3275	276	221	225	203	154	132
Co-UWSN	1850	525	224	224	224	212	189

of eligible neighbors. The stability period of iAMCTD is greater than EEDBR, as there is gradual increase in network energy consumption. When the network becomes sparse, number of neighbors decreases quickly in EEDBR causing network instability. In iAMCTD, the consideration of two forwarding attributes; depth and residual energy, causes a trade-off between the network lifetime and transmission loss which is not suitable for reactive applications. Lifetime of iAMCTD is increased compared to EEDBR, due to lower throughput by responsive network. Moreover, it provides minimum transmission loss and delay which is specifically suitable for time-decisive applications. During the instability period of iAMCTD, network gradually becomes sparse causing load on high residual energy nodes, whereas the number of neighbors is managed by variations in depth threshold. Lifetime of Co-UWSN is increased due to lower throughput by responsive network. In our suggested scheme, employment of Thorps energy model specifies the detailed channel losses, useful for selective data forwarding in responsive networks. Increase in stability period also confirms reduction in redundant transmissions. Table 6.2 indicates a numerical comparison of all the four compared protocols in terms of alive nodes after equal intervals of rounds. The table shows that as the stability period of EEDBR is the least, hence if we keep it as a reference, then the percentage improvements in other schemes are shown numerically with regard to EEDBR.

The plots in 6.6 show the PDR comparison of Co-UWSN with that of the other afore-mentioned techniques. Performance of the EEDBR is reduced in comparison to other three schemes. Although the drop in PDR in Co-UWSN is more than iAMCTD in early rounds but we see a remarkable change in the two ratios after 4500 rounds. There is a big shift in the plots because when the packet inter-arrival time is small in iAMCTD, the higher traffic is sent from source nodes. This increases packet collision leading a lower packet delivery ratio. Co-UWSN scheme improves the possibility of receiving packets successfully by forwarding packets on multiple paths and combining at receiver node. A larger number of cooperating nodes are available for data forwarding, higher reliability can be achieved as can

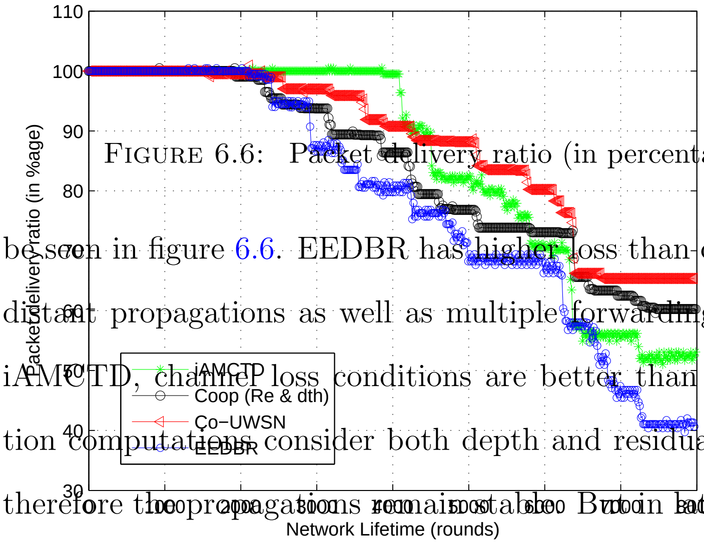

FIGURE 6.6: Packet delivery ratio (in percentage) vs Network lifetime

be seen in figure 6.6. EEDBR has higher loss than other techniques as it employs distant propagations as well as multiple forwarding and hence a lower PDR. In iAMCTD, channel loss conditions are better than EEDBR, as the weight function computations consider both depth and residual energy of forwarding nodes, therefore the propagations remain stable. But in later rounds, the performance of iAMCTD gradually decreases with the decrement in qualified forwarders, therefore both the packet loss and delay increase and there is a drop in its PDR. Coop (Re and dth) scheme shows a similar type of rise-fall behavior in case of PDR because the scheme does not consider the channel conditions as well as the SNR of the link and the throughput decreases due to quick fall in network density It improves itself after 6000 rounds. 6.3 shows a numerical comparison of all the four compared protocols in terms of PDR after equal number of rounds. The table also highlights the average efficiency of all the compared schemes in terms of PDR and Co-UWSN shows an average efficiency of 84%.

Figure 6.7 describes the comparison between the average energy consumption of Co-UWSN and the other three schemes. In our scheme, energy utilization of sensor nodes is much efficient because the use of co-operation makes the data forwarding is better with the help of neighbor nodes and load balancing is achieved. Also

Table 6.3: Packet delivery ratio after equal intervals

Protocol	**Average efficiency (%)**	**2000 rounds**	**4000 rounds**	**5000 rounds**	**6000 rounds**	**8000 rounds**
EEDBR	72	1	0.8	0.7	0.7	0.65
iAMCTD	80.5	1	1	0.8	0.7	0.51
Coop (Re and dth)	79.75	1	0.87	0.75	0.62	0.60
Co-UWSN	83.75	1	0.9	0.88	0.8	0.75

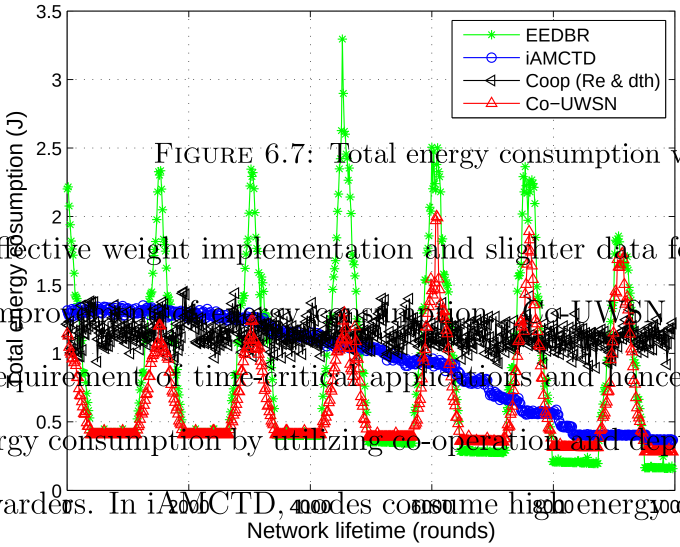

Figure 6.7: Total energy consumption vs Network lifetime

effective weight implementation and slighter data forwarding further helps in the improvement of energy consumption. Co-UWSN is mainly concerned with the requirement of time-critical applications and hence addresses the problem of energy consumption by utilizing co-operation and depth difference between data forwarders. In iAMCTD, nodes consume high energy due to larger distance between nodes, however in EEDBR, energy consumption is higher than other techniques due to frequent selection of high energy nodes. In Coop (Re and dth), there is a sudden increase in network energy consumption during the initial rounds as all nodes become active and perform the routing process. Later on, energy consumption decreases because nodes fail to find relay nodes due to reduction in network density. Hence, chances of cooperative routing being performed by any source node are reduced which in turn reduces energy consumption. Table 6.4 highlights

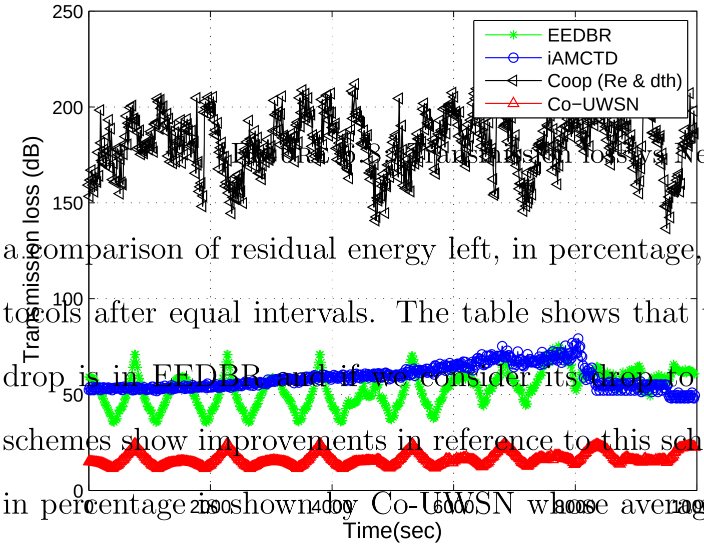

Figure 6.8: Transmission loss vs Network lifetime

a comparison of residual energy left, in percentage, of all the four compared protocols after equal intervals. The table shows that the maximum residual energy drop is in EEDBR and if we consider its drop to be maximum, then the other schemes show improvements in reference to this scheme. The maximum efficiency in percentage is shown by Co-UWSN whose average drop is 72 % in comparison to EEDBR which is assumed to be 100%.

Table 6.4: Residual energy drop in percent after equal intervals

Protocol	**Average efficiency (%)**	**2000 rounds**	**4000 rounds**	**6000 rounds**	**8000 rounds**	**10000 rounds**
EEDBR	100	5.10	13.4	25.5	36.7	37.87
iAMCTD	90	3.65	15.8	22.7	29.12	36.5
Coop (Re and dth)	74	3.2	11.5	17.4	23	33.6
Co-UWSN	72	7.6	9.2	14.4	21.8	32.37

Figure 6.8 shows that transmission loss of the network in Co-UWSN is much less than the previous techniques due to prioritization of relay strategy, cooperation role and SNR in the model design of our protocol. Higher throughput in iAMCTD is achieved in compromise of transmission loss as number of redundant transmissions between sender nodes and sink is increased. In EEDBR multiple transmissions increase transmission loss between sender node and the sink. Our

scheme utilizes Thorps attenuation model for UWA to calculate the transmission loss in packet forwarding between a source node and sink. It considers transmission frequency, noise density and bandwidth efficiency which scrutinize the signal quality during data transmission. Coop (Re and dth) has higher loss than other techniques as it employs distant propagations as well as multiple forwarding. In EEDBR, the initial rounds show low losses due to high network density; but as the network becomes sparse, there is a sharp decrease in network performance causing high packet loss. In iAMCTD, channel loss conditions are better than EEDBR and Coop (Re and dth), as the weight function computations consider both depth and residual energy of forwarding nodes; therefore, the propagations remain stable. In later rounds, the performance of iAMCTD gradually goes down with the decrement in qualified forwarders; therefore, both the packet loss and delay increase. Table 6.5 indicates a numerical comparison of all the four compared protocols in terms of transmission loss after equal rounds traversed. The table shows that the efficiency of our scheme Co-UWSN is maximum in comparison to other schemes in terms of transmission loss and the scheme Coop(Re and dth) shows the minimum efficiency i.e approx 11%.

Table 6.5: Transmission loss after equal intervals

Protocol	**Average efficiency (%)**	**2000 rounds**	**4000 rounds**	**6000 rounds**	**8000 rounds**	**10000 rounds**
EEDBR	43.56	32	47	52	57	53
iAMCTD	35.2	51	58	65	75	50
Coop (Re and dth)	10.8	200	175	222	180	195
Co-UWSN	100	20	19	21	20	25

6.4.3 Performance with trade-offs

In our scheme of Co-UWSN, improvement in end-to-end delay is achieved at the cost of time lag. The end-to-end delay of the network in Co-UWSN is improved compared to iAMCTD, EEDBR and Coop (Re and dth); but at the cost of possible time lag due to consideration of SNR and cooperation mechanism. In EEDBR, delay is improved at the cost of repeated transmissions. The delay in EEDBR is much higher in initial rounds due to distant data forwarding but at the cost of redundant transmissions because the low-quality underwater channel can increase packet loss at the destination. In iAMCTD, end-to-end delay is improved on the cost of energy depletion. End-to-end delay in iAMCTD is better than EEDBR as both threshold variations and weight functions perform load balancing but at the cost of sharp energy depletion of the nodes. End-to-end delay in Coop (Re and dth) is improved but at the cost of energy consumption and transmission loss.

In Co-UWSN, the stability period is improved on the cost of more forwarding nodes and energy consumption. Our scheme improves the stability period of network by avoiding the forwarding of unnecessary data along with maintaining lower transmission loss but at the cost of utilization of relay nodes and proper selection of relay forwarding nodes. In Co-UWSN, the instability period starts from almost 6220th round, after which the packet delivery ratio remains even, however total energy consumption increases slowly. In iAMCTD, the stability period is achieved at the cost of transmission loss. In this protocol, there are only two forwarding selection attributes; depth and residual energy. This consideration causes a trade-off between the network lifetime and transmission loss which is not suitable for reactive applications. During the instability period of iAMCTD, network gradually becomes sparse causing load on high residual energy nodes. In EEDBR, the stability period is improved at the cost of greater energy consumption. In Coop (Re and dth), the stability period is improved at the cost of end-to-end delay and transmission loss.

In Co-UWSN, PDR is improved at the cost of time-lag. The drop in PDR in Co-UWSN is much less than that of other schemes. When the packet inter-arrival time is small, higher traffic is sent from source nodes. This increases packet collision leading a lower packet delivery ratio. Co-UWSN scheme improves the possibility of receiving packets successfully by forwarding packets on multiple paths and combining at receiver node. This reduction in packet delivery ratio is achieved at the cost of higher energy consumption of the network as more nodes are involved in the data forwarding mechanism. In EEDBR, transmission loss improved at the cost of low PDR. In this protocol, higher transmission loss is achieved than the other two techniques as it employs distant propagations as well as multiple forwarding. iAMCTD achieves improvement in PDR at the cost of packet loss and delay. In iAMCTD, channel loss conditions are better than EEDBR, as the weight function computations consider both depth and residual energy of forwarding nodes, therefore the propagations remain stable. But in later rounds, the performance of iAMCTD gradually decreases with the decrement in qualified forwarders, therefore both the packet loss and delay increase but at the cost of drop in its PDR. Table 6.6 indicates the various performance parameters which are enhanced on the price which they have to pay, for the four compared protocols.

TABLE 6.6: Performance parameters with their trade-offs

Protocol	**Advances achieved**	**Reference**	**Price to Pay**	**Reference**
Co-UWSN	End-to-end delay improves	Fig. 6.4	Time lag and energy consumption	Fig. 6.7
	Stability period extends	Fig. 6.5	More forwarding nodes and end-to-end delay	Figs. 6.4,6.5
	Packet delivery ratio improves	Fig. 6.6	Time lag and energy consumption	Fig. 6.7
EEDBR	End-to-end delay improves	Fig. 6.4	Packet delivery ratio	Fig. 6.6
	Stability period extends	Fig. 6.5	Greater energy consumption due to only depth consideration	Fig. 6.7
	Packet delivery ratio improves	Fig. 6.6	Transmission loss and delay	Figs. 6.4,6.8
iAMCTD	End-to-end delay improves	Fig. 6.4	Transmission loss due to selection attributes of couriers	Fig. 6.8
	Stability period extends	Fig. 6.5	Redundant transmissions due to packet loss at the destination	Figs. 6.4,6.5
	Packet delivery ratio improves	Fig. 6.6	Transmission loss due to distant propagations	Fig. 6.8
Coop (Re and dth)	End-to-end delay improves	Fig. 6.4	Transmission loss due to lag of SNR	Fig. 6.8
	Stability period extends	Fig. 6.5	Redundant transmissions and packet delivery ratio	Fig. 6.6
	Packet delivery ratio improves	Fig. 6.6	Transmission loss and greater energy consumption	Figs. 6.7,6.8

6.5 Conclusion of the chapter

In this chapter, we have proposed Co-UWSN routing protocol which promises to maximize the network lifetime and reduce the energy consumption of UWSNs. Utilization of cooperation strategy and SNR enhances the network lifetime, improves the PDR and reduces the overall network energy consumption. This is especially beneficial for delay-sensitive and time-critical applications. Relay selection mechanism considers the instantaneous link conditions and distance among neighbouring nodes to successfully relay packets to destination in the constrained UWA environment. Variations in depth-threshold increase the number of eligible neighbors, thus minimizing critical data loss in delay-sensitive applications. Optimal weight computation and role of cooperation not only provides the load balancing in the network, but also gives proficient improvement in the network stability period.

Reliability is a key factor for application-oriented UWSNs which are planned to achieve certain objectives for efficient data routing schemes. Hence, our next chapter presents a reliability aware routing protocol RACE for UWSNs. Multiple nodes coordinate their broadcasts to take advantage of spatial diversity in conserving energy. Cooperative diversity at physical layer and multi-hop routing at network layer aids in designing minimum energy routing as a combined optimization of the broadcast power at physical layer and path selection at the network layer.

Chapter 7

RACE

7.1 Summary of the chapter

Physical layer cooperative communication is explored in this research to design network layer routing algorithm for UWSNs that guarantees to be energy-efficient. Reliability is a key factor for application-oriented UWSNs which are planned to achieve certain objectives for efficient data routing schemes. Each node in the network is equipped with a single omnidirectional antenna and multiple nodes coordinate their transmissions in order to take advantage of spatial diversity in saving energy. Cooperative diversity at physical layer and multi-hop routing at network layer helps formulate minimum energy routing as a joint optimization of the transmission power at physical layer and link selection at the network layer. Results show that RACE routing protocol performs better in terms of stability period, packet delivery ratio, end-to-end delay, and energy consumption comparative to routing protocols ACE and AMCTD.

7.2 Motivation

As it does not require multiple antennas per terminal, cooperation among distributed single-antenna nodes offers resilience to path-losses in UW environment. In most applications the network consists of battery-powered nodes. Due to low transmit power, these nodes have limited communication range. Thus, cooperative communication, in which nodes share their resources, is essential for these networks. Replacing long and weaker links with short and stronger links can reduce the burden on the link. The presented scheme leads to enhance the reliability of the UWA channel through cooperative transmission scheme. Cooperative diversity is a kind of spatial diversity that can be obtained without use of multiple antennas. It is especially useful when time, frequency and spatial diversity through multiple antennas are not feasible. This motivated us to introduce the cooperation in UWA environment, and study its impact on system performance.

7.3 RACE: The proposed protocol

Consider a sensor network environment consisting of a set of N_i sensor nodes distributed randomly in an area A of an ocean. Let L be the number of edges or links forming a route between these nodes. Each node has a single omni-directional antenna. Let the neighbouring relay and sensor nodes for any i-th node belong to the sets R_i and S_i respectively. It is assumed that each node of the network in the set $N_i = R_i \bigcup S_i$ can adjust its transmission power and all of them have the same maximum transmission power P_{max}. The communication range of each node N_i is proportional to the P_{max}; and two nodes will be called neighbours and belong to the set R_i if their Euclidean distance is less than the communication range.

7.3.1 Network model

A k-hop cooperative path l is a sequence of k cooperative links $\{l_1, ..., l_i\}$ where link l_i is formed between a set of transmitters $t_i \epsilon T_k$ and receivers $r_i \epsilon R_k$ using cooperative transmission at the physical layer. The sequence of link l_i connects a source t to a destination r in a loop-free path as shown in figure 7.1.

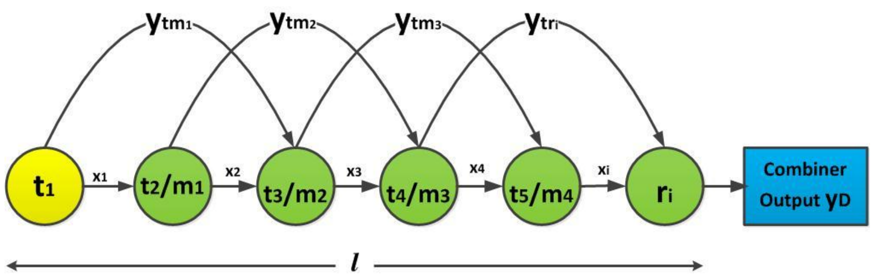

FIGURE 7.1: Linear cooperative path model

Our objective is to find a path that minimizes end-to-end transmission power to reach the sink at surface of the ocean subject to a constraint on throughput of the path. Let $\mathcal{C}(T_k, R_k) = P_{l_i}$ be the cost of the link l_i which is the minimum transmission power to form cooperative link in a single-loop cooperative routing.

Given any source-destination pair (t,r), the goal is to find the source-destination route the minimizes the total transmission power satisfying a specific throughput η and maintaining a minimum signal-to-noise ratio γ. For a link $l_i \epsilon L$, the problem can be formulated as

$$\text{minimize} \sum_{l_i \epsilon L} P_{l_i} \tag{7.1}$$

subject to

$$\begin{cases} min(\eta_{l_i}, \eta_{l_{i+1}}, ..., \eta_{l_L}) \geq \eta_0, \\ \text{and} \\ \sum_{i=1}^{L} \gamma_{l_i} \geq \gamma_0 \end{cases}$$

where $min(\eta_{l_i}, \eta_{l_{i+1}}, ..., \eta_{l_L})$ is the minimum required throughput of the link defined as the number of successfully transmitted bits/sec/Hz. η_o is the desired value of the end-to-end throughput. γ_{l_i} is the SNR for the particular i^{th} link and γ_0 is the prescribed threshold SNR and must be maintained for the overall link.

In different one-hop transmissions, some relays from the set R_i must be employed by different source nodes at different times and may have different cooperative transmission powers P_{R_k} for any $k \epsilon R_i$ or $k \epsilon \{0, 1, ..., R_i\}$. Hence equation (7.1) can be modified as

$$\text{minimize} \sum_{l_i \epsilon L} P_{co-l_i} = \text{minimize} \sum_{l_i \epsilon L} [P_{b,i} + \sum_{k=0}^{R_i} P_{R_k}] \tag{7.2}$$

subject to

$$\begin{cases} min(\eta_{l_i}, \eta_{l_{i+1}}, ..., \eta_{l_L}) \geq \eta_0, \\ \text{and} \\ \sum_{i=1}^{L} \gamma_{l_i} \geq \gamma_0 \end{cases}$$

where P_{co-l_i} is the cooperative transmission power for any node i for any link l_i in the cooperation phase.

7.3.2 Channel model

Consider a transmitting node t_i which transmits a signal x_i towards a receiving node r_j which receives a signal y_j in broadcasting phase or direct phase. x_i has unit power and transmitter t_i is able to control its power $P_{b,i}$ up to some limit P_{max}. N_j denotes the noise and other interferences of UW channel received at r_j. The received signal at r_j can be expressed as

$$y_j^d = \sqrt{\frac{P_{b,i}^d}{d_{ij}^\alpha}} \quad h_{ij}.x_i + N_j(f) \tag{7.3}$$

where the superscript d indicates the direct communication phase. d_{ij} is the distance between nodes t_i and r_j, α is the path-loss exponent having the value between 1 and 3. h_{ij} is the complex channel gain between these nodes modeled as

$$h_{ij} = |h_{ij}|e^{j\theta_{ij}} \tag{7.4}$$

where $|h_{ij}|$ is the channel gain magnitude and θ_{ij} is the phase. $|h_{ij}|$ has a Rayleigh distribution with unit power i.e $\mathbb{E}[|h_{ij}|^2] = 1$ modeled as $h_{ij} \sim \mathcal{CN}(0, \sigma_{ij}^2)$ with $\sigma_{ij}^2 = E[|h_{ij}^2|] = 1$.

The received power P_{x_j} at node r_j is given as

$$P_{x_j} = \sum_{i,j\epsilon T} (\frac{|h_{ij}|^2}{d_{ij}^\alpha}) P_{b,i}^d \tag{7.5}$$

where T is the set of all transmitting nodes in the network.

We consider here a channel with additive noise effects which follows Gaussian distribution of zero mean and a variance that is a function of distance and frequency. Let γ_{ij}^d be the SNR at the receiver r_j, then

$$\gamma_{ij}^d = \overline{\gamma}|h_{ij}^2| = \frac{1}{d_{ij}^\alpha} \frac{P_{b,i}^d}{P_{n_j}} .|h_{ij}|^2 \tag{7.6}$$

where P_{n_j} is the noise power at receiver r_j. As $|h_{ij}|^2 = 1$, hence equation (7.6) becomes

$$\gamma_{ij}^d = \overline{\gamma}|h_{ij}^2| = \frac{1}{d_{ij}^{\alpha}} \frac{P_{b,i}^d}{P_{n_j}} \tag{7.7}$$

where

$$\overline{\gamma} = \text{average} \quad SNR(d,f) = \frac{P_{x_j}/A(d,f)}{N_j(f)B} \tag{7.8}$$

where B is the bandwidth of the transmitted signal x_j with a power P_{x_j}.

7.3.3 Propagation in UW channel

For to compute the attenuation and propagation delay for an underwater, we will follow the same model as given in section (3.1), and hence following the equations (3.1) till (3.7).

7.3.4 SNR in UW acoustic channel

The SNR of an emitted UW signal with unit transmit power $\hat{p}(t)(watts)$ at the receiver is given by section (3.1.3).

7.3.5 Outage formulation

Channel capacity of a Gaussian channel with infinite bandwidth presents an upper limit for on the amount of information being transmitted successfully over a communication path. This can be expressed by the equations (3.12) and (3.13) and this condition is used to assess the quality of incoming signal at the receiver side. In contrast to equation (3.13), outage occurs when the transmission rate R exceeds C, i.e.

An error occurs if the channel is in outage or there is a decoding error. It is assumed here that the probability of error is almost zero when channel is not in outage. Hence, the outage probability P_{outage} is given by:

$$P_{outage} = P\{C(d, \rho) < R\} \tag{7.9}$$

$$P_{outage} = P\{Blog_2(1 + \rho(d, f)) < R\} \tag{7.10}$$

$$P_{outage} = P\{\rho(d, f) < 2^{(R/B)} - 1\} \tag{7.11}$$

$$P_{outage} = P\{20log(\frac{\hat{p}(t)}{2\pi H}) - A(d, f) - N(f) < 2^{(R/B)} - 1\} \tag{7.12}$$

$$P_{outage} = P\{log(\frac{\hat{p}(t)}{2\pi H}) < \frac{2^{(R/B)} + A(d, f) + N(f) - 1}{20}\} \tag{7.13}$$

$$P_{outage} = P\{\hat{p}(t) < 2\pi H \times exp(\frac{2^{(R/B)} + A(d, f) + N(f) - 1}{20})\} \tag{7.14}$$

Equation (7.14) clearly indicates that the outage probability at any instant is totally dependent on the depth of the ocean and the attenuation and noise factors occurring in ocean currents. In terms of SNR and ignoring the (-1) term, equation (7.14) can be expressed as

$$P_{outage} = P\{\hat{p}(t) < 2\pi H \times exp(\frac{2^{(R/B)} + SL + \rho(d, f)}{20})\} \tag{7.15}$$

7.3.6 Reliability in UWA channel

With the passage of time and advancement in technology there are lots of methods that are used to avoid the loss of data when the channel is in outages [67]. However, this research concentrates and focuses on the reliability of the link to be obtained through the use of routing by isolating the diversity obtaining issue, and the results can be applied in combination with other forms of diversity techniques. Different links combine to form hops and then these multiple-hop paths make a sequential combination of nodes which pass the information to one another and ultimately lead to the destination D from a source S. That event will be deemed as a successful end-to-end transmission in which all the packets or transmissions are successful and the probability of occurrence of an event is defined as End-to-End Reliability denoted by $\mathfrak{R}$ [75]. Hence, $\mathfrak{R}$ can be written as:

$$\mathfrak{R} = 1 - P_{outage} \tag{7.16}$$

$$\mathfrak{R} = 1 - \{2\pi H \times exp(\frac{2^{(R/B)} + SL + \rho(d,f)}{20})\} \tag{7.17}$$

According to this expression, $\mathfrak{R}$ is a monotonically decreasing function and establishes the result for a point-to-point link. It is dependent on the depth of the water, channel state and the distance between two nodes. The net reliability for the entire end-to-end path can be computed from equation (7.17) as given below:

$$\mathfrak{R} = 1 - \{\sum_{i=1}^{n}(2\pi H_i \times exp(\frac{2^{(R/B)} + SL + \rho(d,f)_i}{20}))\} \tag{7.18}$$

The maximum reliability route is the route that minimizes this sum and the maximum amount of power that can be spent in relaying the information from S to D is limited to the summation of SNR for individual nodes as given in equation (7.2).

7.4 Performance evaluation

To evaluate the performance of RACE, it is compared with the existing schemes ACE and AMCTD. By following multiple-sink model of conventional methods with 5 sinks deployed on the surface of the water, 225 nodes are randomly deployed in the network field of 500m x 500m. Transmission range of sensor node is assumed to be 100 meters. Each node shares the vital physical metrics, especially depth threshold and weight with its neighbors to keep informed with the varying circumstances of the network.

7.4.1 Energy consumption

The plots in figure 7.2 show that the net energy consumption in case of cooperative scheme RACE is considerably better than of ACE and AMCTD.

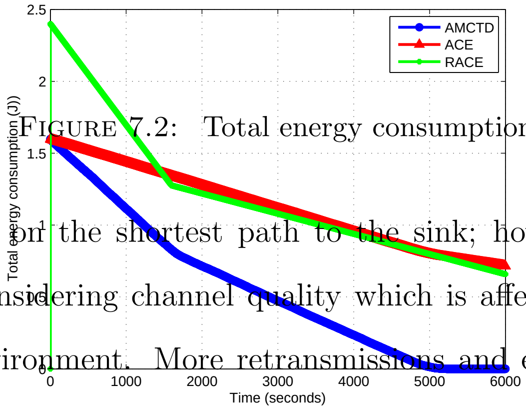

FIGURE 7.2: Total energy consumption vs network lifetime

ACE relies on the shortest path to the sink; however, the packet is forwarded without considering channel quality which is affected by various types of noises in UW environment. More retransmissions and energy consumption is required for sending a packet to reach the sink. On the other hand, the transmission scheme with cooperation utilizing relay nodes is based on channel estimation that improves the received packet quality at receiver node, however, transmission with one-path can be affected when the channel quality changes. RACE consumes almost constant energy throughout the network lifetime by proper relay selection and introduction of cooperation as compared to the ACE and AMCTD protocols.

7.4.2 Packet delivery ratio

Figure 7.3 shows the packet delivery ratio comparison of RACE with ACE and AMCTD. In a non-cooperative environment, when the packet inter-arrival time is small, higher traffic is sent from source nodes. This increases packet collision leading to a lower packet delivery ratio. The cooperative RACE protocol achieves

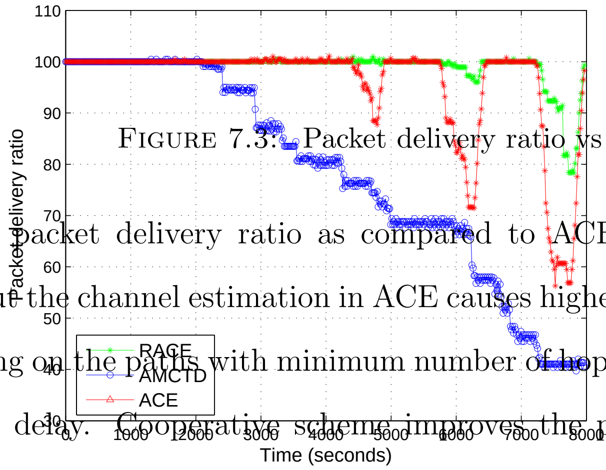

FIGURE 7.3: Packet delivery ratio vs network lifetime

higher packet delivery ratio as compared to ACE and AMCTD. Transmission without the channel estimation in ACE causes higher packet loss. Moreover, traffic focusing on the paths with minimum number of hops can cause more collisions and packet delay. Cooperative scheme improves the possibility of receiving packets successfully by forwarding packets on multiple paths and combining at receiver node.

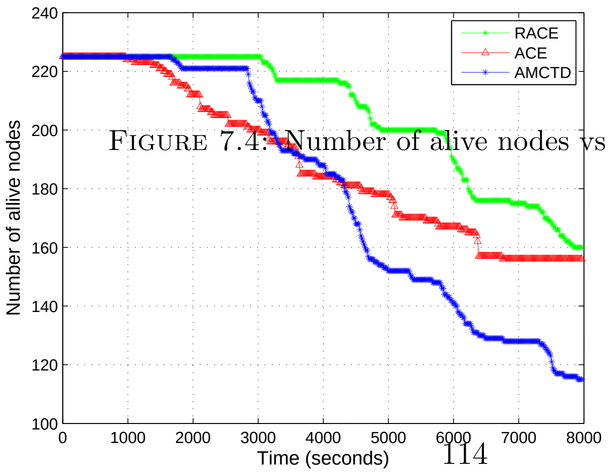

FIGURE 7.4: Number of alive nodes vs network lifetime

7.4.3 Network lifetime

Figure 7.4 represents the comparison between the network lifetime of RACE, ACE and AMCTD. In RACE, first node dies after about 3200 seconds in comparison to ACE in which the first node dies after 1150 seconds and in AMCTD after 1780 seconds. After the death of initial nodes, adaptive variations in SNR provide longer lifetime to the network. The modifications in relay selection techniques and consideration of channel losses in the medium also encourages the efficient instability period. In the non-cooperative technique of ACE, the stability period ends quickly due to prioritization of residual energy or depth solely in the selection of optimal neighbors, which causes inefficient instability period. The instability period of ACE is much better than AMCTD as there is gradual increase in network energy consumption. When the network becomes sparse, number of neighbors decreases quickly causing network instability.

7.4.4 End-to-end delay

The propagation delay in UW channel causes high latency for packets. Average end-to-end delay with respect to three schemes, is shown in figure 7.5. Their comparisons show that end-to-end delay of network in RACE is less than the previous techniques due to minimum forwarding distances between the nodes in both dense and sparse conditions. AMCTD has the highest delay compared to other two schemes because it does not consider any losses present in the UW medium. But in RACE, there is a minimum possible time lag because of the consideration of SNR, depth differences between sender and receiver nodes and introduction of cooperation.

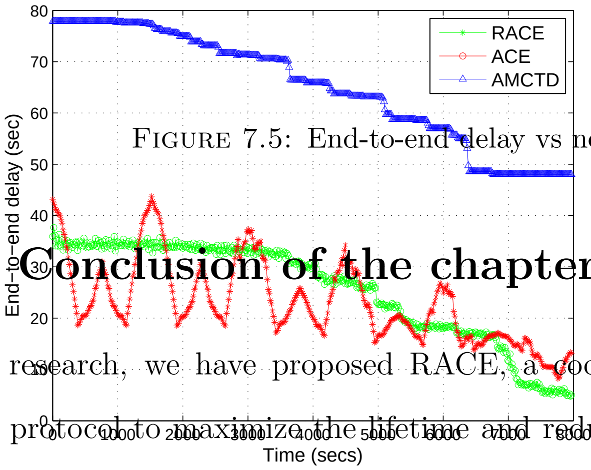

FIGURE 7.5: End-to-end delay vs network lifetime

7.5 Conclusion of the chapter

In this research, we have proposed RACE, a coopertion based energy-efficient routing protocol to maximize the lifetime and reduce the energy consumption of UWSNs. Introduction of cooperation and SNR enhances the network lifetime, improves the packet delivery ratio and reduces the overall network energy consumption; especially for delay-sensitive applications and even in sparse conditions. The relay selection process considers the instantaneous link conditions and distance cost among surrounding nodes to successfully relay packets to the destination in a constrained environment as UWSN. Characteristics of single-hop and multi-hop communication schemes have been utilized to reduce path-loss effects and increase network lifetime in comparison to non-cooperation based ACE and AMCTD protocols.

Co-EEUWSN scheme is proposed in the next chapter, in which a scheme to route information via UW networks with minimum path-loss over the channel; and the attributes of single-hop and multi-hop are taken into account. The presented protocol considers UW noises that follow Gaussian distribution and the channel is stable for some time period. The probability of error is also computed for a specific modulation at a particular value of SNR. The chapter considers a distributed UWA environment in the ocean, where the channel is heavily affected by multi-path fading.

Chapter 8

Co-EEUWSN

8.1 Summary of the chapter

In this chapter, we discover physical layer cooperative communication in order to plan network layer routing algorithm for UWSNs that proves to be energy-efficient. It is supposed that each sensor in the network is furnished with a solo omnidirectional antenna and various nodes synchronize their broadcasts in order to take benefit of spatial diversity in conserving energy. The emphasis in this work is limited to the AF scheme at the relay node and FRC strategy at the receiver. Cooperative diversity at physical layer and multi-hop routing at network layer aids frame least energy routing as a combined optimization of the broadcast power at physical layer and link choice at the network layer. Simulations are conducted to validate the extensive mathematical modeling done for energy-efficient proposed protocol. Results show that Co-EEUWSN routing protocol performs better in terms of end-to-end delay, packet delivery ratio and energy consumption comparative to non-cooperative routing protocols DBR and EEDBR and a cooperative routing protocol (Co-DBR).

8.2 Motivation

There has been a growing attention in the progress of UWSNs in recent ages. Former efforts to investigate UWSN performance were grounded on the technology established for land-dwelling WSNs. In spite of alike functionalities, UWSNs unveil various architectural variances in comparison to terrestrial ones, chiefly due to the sea water as broadcast medium and signal utilized to spread data. Likewise, the proposal of applicable network design for UWSNs is convoluted by the circumstances of communication system and, as a result, the whole network architecture is desired to stream a suitable network facility for the challenging claims in such an unfavorable oceanic communication situation.

UWSNs exhibit many unique features like slow propagation speed, variable link quality, low available bandwidth, high end-to-end delay and energy constraint. These constraints present a big challenge in devising transmission efficient, energy-saving, and low delay routing protocols for UWSNs. Cooperative routing in wireless networks has attracted much attention recently of researchers. It uses the broadcast behaviour of the wireless medium for the design of energy-efficient routing algorithms. Cooperative communication systems using different relay techniques prove to achieve spatial diversity gain, enhanced coverage, and increased capacity potentially. As it does not require multiple antennas per terminal, co-operation among distributed single-antenna nodes offers resilience to path-losses in UW environment. Most applications of sensor networks visualize applications which have limited battery-powered sensors; and limited communication range due to low transmit powers. Thus, cooperative communication is beneficial for such networks, in which nodes share their resources. Replacing weaker and longer links with short but stronger links can minimize the load on the link. Substitute routes between the users and the base-station offer strength in contradiction of shadowing and multi-path fading, and lead to new design possibilities for scheduling and routing.

Local depth information of sensor nodes is only required in DBR to forward data towards sink present at the water surface and uses the greedy approach. DBR follows a receiver based approach in which the sensors deployed with smaller depth contribute in data forwarding. In this technique, repeated useless transmissions become a major source of energy consumption. DBR is a non-cooperative routing protocol. Data is forwarded from source to sink along the only lossy path in a multihop manner. Due to the presence of noise and multipath fading in environment of oceans, signals in underwater generally suffer from high BER. The performance of DBR is enhanced in EEDBR, in which both the parameters of local depth information of nodes and their residual energy are used to select the best forwarder for achievement of load balancing. Frequent useless data forwarding is restricted by introduction of holding time for forwarding nodes based on these two parameters. Co-DBR aims to solve the issues of DBR and EEDBR by the use of cooperative diversity. Co-DBR selects two relays based on minimum depth that route the data to sink using cooperation. It upsurges the rate of effective data transfer to the end point because in case of link miscarriage, at least one link is proficient of carrying the data fruitfully to the sink. However, Co-DBR expends source node along with two relays to transfer data to the next hop and hence consumes three times more transmission energy than DBR. This shows the tradeoff between energy conservation and reliability. In order to address the issues of all these three protocols, we have tried to propose a new protocol by the name of Co-EEUWSN.

In Co-EEUWSN scheme, we have suggested a technique to forward the data through UW networks with minimum path-loss; and the features of both single-hop and multi-hop are utilized. The suggested scheme considers UW noises that are Gaussian in nature and the link is stable for some time interval. The channel for acoustic link is described by path loss model in terms of frequency and distance. The probability of error is also computed for a random modulation at some particular value of SNR. Simulation results show that Co-EEUWSN protocol has considerably enhanced the network stability time with reduced effects of path-loss. This research takes into account a distributed UW environment, where the communication path is largely attenuated due to multi-path fading. Sensor nodes forward the data towards the sink which is then transferred to the base station onshore using long range radio frequency. Each sensor monitors and detects events from local environment and the generated signal is modeled by a Rayleigh random variable. The presented scheme leads to enhance the reliability of the UW links using cooperation. In this research we shall be considering FRC for signal combining. Cooperative diversity is a kind of spatial diversity obtained without use of multiple antennas. It is beneficial when frequency, time and spatial diversity by the use of multiple antennas are not appropriate. This makes our motivation in introduction of cooperation in UW environment, and study its impact on system working. Special measures need to be considered for any present weakness in the cooperation technique.

8.3 Co-EEUWSN: The proposed protocol

Consider a sensor network environment consisting of a set of N_i sensor nodes distributed randomly in an area A of an ocean. Let L be the number of edges or links forming a route between these nodes. Every sensor in the network has only one omni-directional antenna. Let the neighbouring relay and sensor nodes for any i-th node belong to the sets R_i and S_i respectively. It is assumed that each node of the network in the set $N_i = R_i \bigcup S_i$ can adjust its transmission power and all of them have the same maximum transmission power P_{max}. The communication range ($C.R$) of each node N_i is proportional to the P_{max}; and two nodes will be called neighbours and belong to the set R_i if their Euclidean distance is less than the range $C.R$.

8.3.1 Cooperation model

In a co-operation based network, each node has the dual responsibility of not only acting as a source of information, but also as a relay which helps routing the information of other nodes as well. Here, a two-phase communication technique is taken into account which follows a non-overlapping data forwarding for the source and relay nodes as given in section (3.1.4).

8.3.2 Network model

A k-hop cooperation based link l is a continuity of k cooperative paths $\{l_1, ..., l_i\}$ where link l_i is made between a group of transmitters $t_i \epsilon T_k$ and a group of receivers $r_i \epsilon R_k$ using cooperation at the physical layer. The order of link l_i connects a source

t to a destination r in a loop-free path as in figure 8.1.

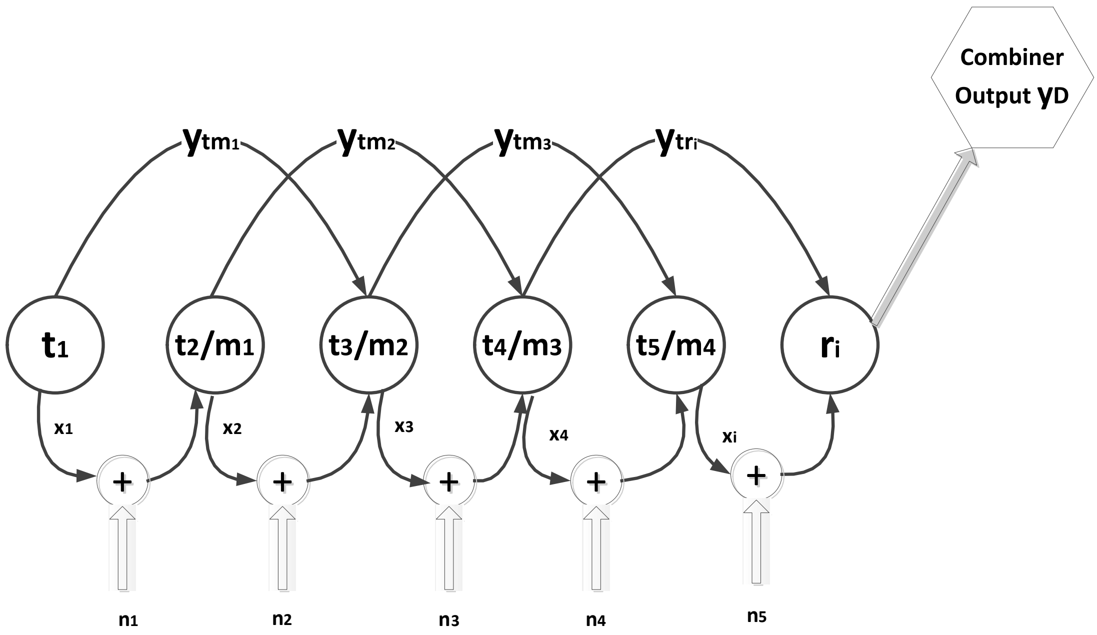

FIGURE 8.1: Linear cooperative path model

The goal is to determine a path that minimizes the net transmission power to reach the sink at surface of the ocean subject to a limitation on throughput of the path. Let $\mathcal{C}(T_k, R_k) = P_{l_i}$ be the cost of the link l_i which is the least communication power desired in forming a cooperative link. Given any source-destination pair (t, r), the objective is to determine the (t-r) path that minimizes the net transfer power satisfying a particular throughput η and keeping a minimum SNR γ. For a link $l_i \epsilon L$, the problem can be formulated as

$$\text{minimize} \sum_{l_i \epsilon L} P_{l_i} \tag{8.1}$$

subject to

$$\begin{cases} \quad min(\eta_{l_i}, \eta_{l_{i+1}}, ..., \eta_{l_L}) \geq \eta_0, \\ \text{and} \\ \quad \sum\limits_{i=1}^{L} \gamma_{l_i} \geq \gamma_0 \end{cases}$$

where $min(\eta_{l_i}, \eta_{l_{i+1}}, ..., \eta_{l_n})$ is the minimum required throughput of the link defined as the number of successfully transmitted bits/sec/Hz. η_o is the desired throughput. γ_{l_i} is the SNR for the particular i^{th} link and γ_0 is the prescribed threshold SNR and must be maintained for the overall link.

As the optimal link is a combination of both cooperative and point-to-point transmissions, hence two sorts of building blocks will be considered here: direct transmission and cooperative transmission. The overall route will be reflected as a series of these building chunks and the over-all power of the path will be the aggregation of the transmission powers along this route. The minimization problem in equation (8.1) is solved by applying Bellman-Ford algorithm which is a a shortest-path routing algorithm.

In different one-hop transmissions, some relays from the set R_i must be employed by different source nodes at different times and may have different cooperative transmission powers P_{R_k} for any $k \epsilon R_i$ or $k \epsilon \{0, 1, ..., R_i\}$. Hence equation (8.1) can be modified as

$$\text{minimize} \sum_{l_i \epsilon L} P_{co-l_i} = \text{minimize} \sum_{l_i \epsilon L} [P_{b,i} + \sum_{k=0}^{R_i} P_{R_k}] \tag{8.2}$$

subject to

$$\begin{cases} \quad min(\eta_{l_i}, \eta_{l_{i+1}}, ..., \eta_{l_L}) \geq \eta_0, \\ \text{and} \\ \quad \sum_{i=1}^{L} \gamma_{l_i} \geq \gamma_0 \end{cases}$$

where P_{co-l_i} is the cooperative transmission power for any node i for any link l_i in the cooperation phase.

8.3.3 Channel model

Here we take into account a broadcasting node t_i which transmits a signal x_i towards a receiving node r_j which receives a signal y_j in broadcasting phase or direct phase. x_i constitutes a unity power and transmitter t_i can control its power $P_{b,i}$ up to some limit P_{max}. N_j denotes the noise and other interferences of UW channel received at r_j. The received signal at r_j can be expressed as

$$y_j^d = \sqrt{\frac{P_{b,i}^d}{d_{ij}^\alpha}} \quad h_{ij}.x_i + N_j(f) \tag{8.3}$$

where the superscript d indicates the direct communication phase. d_{ij} is the separation between sensors t_i and r_j, α denotes the path-loss exponent having its range between 1 and 3. h_{ij} expresses the channel gain between these sensors formulated as

$$h_{ij} = |h_{ij}|e^{j\theta_{ij}} \tag{8.4}$$

where $|h_{ij}|$ is the magnitude of channel gain and θ_{ij} denotes its phase. $|h_{ij}|$ has a Rayleigh distribution having power of unity i.e $\mathbb{E}[|h_{ij}|^2] = 1$ modeled as $h_{ij} \sim \mathcal{CN}(0, \sigma_{ij}^2)$ with $\sigma_{ij}^2 = E[|h_{ij}^2|] = 1$.
The received power at node r_j is given as

$$P_j^d = \sum_{t_i \epsilon T} (\frac{|h_{ij}|^2}{d_{ij}^\alpha}) P_{b,i}^d \tag{8.5}$$

where T is the group of all transmitting sensors of the network.
Let γ_{ij}^d be the SNR at the receiver r_j, then

$$\gamma_{ij}^d = \overline{\gamma}|h_{ij}^2| = \frac{1}{d_{ij}^\alpha} \frac{P_{b,i}^d}{P_{n_j}}.|h_{ij}|^2 \tag{8.6}$$

where P_{n_j} represents the noise in terms of power at receiving node r_j. As $|h_{ij}|^2 = 1$, hence equation (8.9) becomes

$$\gamma_{ij}^d = \overline{\gamma}|h_{ij}^2| = \frac{1}{d_{ij}^\alpha} \frac{P_{b,i}^d}{P_{n_j}} \tag{8.7}$$

where

$$\overline{\gamma} = \text{average} \quad SNR(d, f) = \frac{P_{x_j}/A(d, f)}{N_j(f)B} \tag{8.8}$$

where B is the bandwidth of the transmitted signal x_j with a power P_{x_j}.

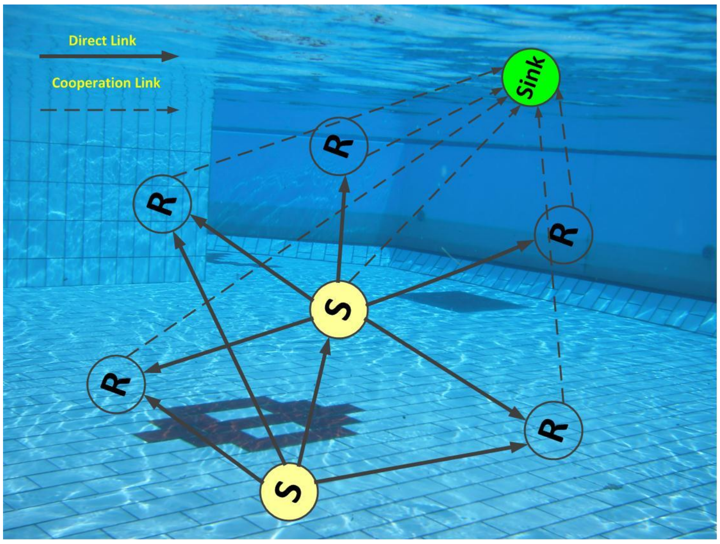

FIGURE 8.2: Multi-hop relay communication

8.3.4 Noise model in UW channel

Figure 8.2 shows an underwater environment comprising of various types of sensor nodes having multi-hop relay communication among them. Supposing the lack of site-specific noise, the receiver is affected by colored ambient noise only as given in sections (3.1.1) and (3.1.2).

8.3.5 Capacity limitation

When the noise effects follow Gaussian distribution and the UW link remains stable for some time period known as the coherence time; then the capacity of a Gaussian channel having maximum or infinite bandwidth denotes the upper limit on the information broadcasted fruitfully over the channel. Hence accordingly we will the follow the model in section (3.1.5).

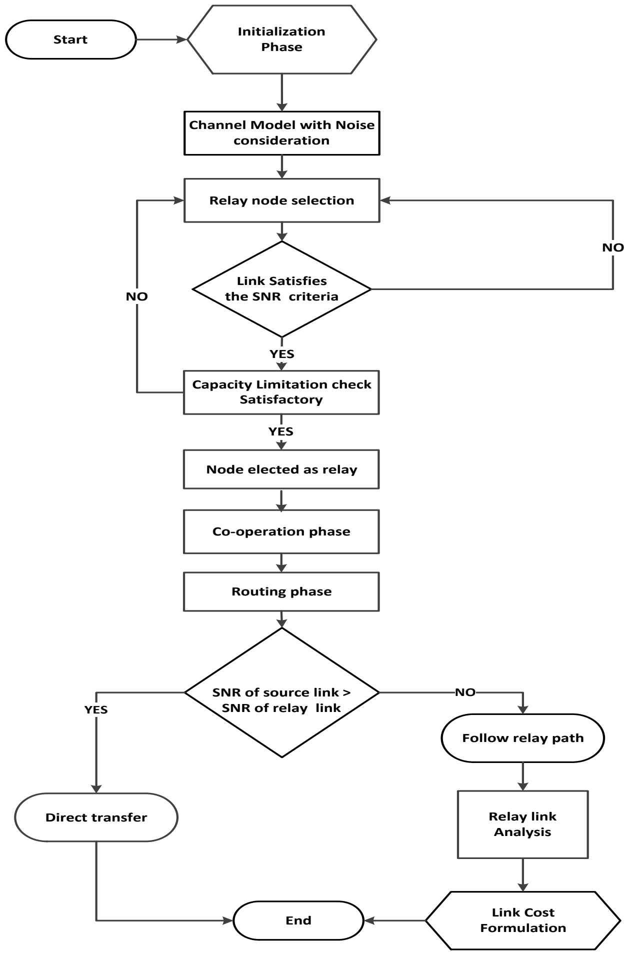

FIGURE 8.3: Flow-chart for Co-EEUWSN

The research features a distributed UW sensor network where the path is largely attenuated by various fading effects. Packets of data from sensors arrive at the sink floating on the surface of the ocean which can communicate with the onshore base station through radio frequency. This research investigates on the applications in the water region where the signal is modeled as Rayleigh random variable. The suggested technique leads to a solution which enhances the reliability of the UW link by the use of cooperation. Hence due to Rayleigh fading or small scale fading, its SNR follows the probability distribution expressed as

$$p_d(X) = \frac{1}{\overline{\gamma}}.e^{-\frac{X}{\overline{\gamma}}} \tag{8.9}$$

The probability of error can be calculated as

$$p_e(d) = \int_0^{\infty} p_e(X) p_d(X).dX \tag{8.10}$$

where $p_e(X)$ is the probability of error for an arbitrary modulation at a specific value of SNR X over distance d is given as

$$p_e(d) = \frac{1}{2}.(1 - \sqrt{\frac{\overline{\gamma}}{1+\overline{\gamma}}}) \tag{8.11}$$

Thus, for any pair of sensors with separation d, the probability of a packet with size b bits to reach its destination is given by

$$p(d, b) = (1 - p_e(d))^b \tag{8.12}$$

The broadcasting power of a node determines the SNR at each neighbouring node. Assume that the $k-th$ relay node can retrieve data correctly if its SNR in the broadcasting phase, γ_k is above a prescribed threshold $\overline{\gamma}_0$. If the above condition is not met, this node will not be engaged in cooperative transmission. Hence γ_k^d for non-cooperative point-to-point wireless transmission is given as

$$\gamma_k^d = \frac{1}{d_{ik}^{\alpha}} \quad \frac{P_{b,i}^d}{P_{nk}} \quad |h_{ik}|^2 \tag{8.13}$$

The minimum SNR requirement is a necessary condition for cooperative transmission, formulated as $\gamma_k \geq \gamma_0$

or

$$\frac{1}{d_{ik}^{\alpha}} . \frac{P_{b,i}^d}{P_{nk}} \quad |h_{ik}|^2 \geq \gamma_0, \quad \text{for} \quad \text{any} \quad k \epsilon \{1....n\} \tag{8.14}$$

or

$$P_{b,i}^{d} \quad |h_{ik}|^2 d_{ik}^{-\alpha} \geq \gamma_0 P_{nk} \tag{8.15}$$

8.3.6 Relay link analysis

Assuming that a single relay m_i helps the source t_i to communicate with the sink r_i. Source node t_i broadcasts the symbols to r_i, also intercepted by m_i, which forwards the amplified symbols to r_i. As the signals from t_i and m_i reach via two separate paths, if fading is present, we consider Time-Division Duplex (TDD) mode. Data communication here is comprised of two slots. As we have seen that in slot 1, broadcasting phase occurs or direct transmission; whereas in slot 2, co-operative transmission occurs. In slot 1, t_i broadcasts modulated symbol x_i with average power $P_{b,i}$ as seen in equation (8.5). The detected symbol x_i is remodulated by the relay node m_i and ultimately broadcasted during slot 2 with the same power $P_{b,i}$. Detected symbol at D is now accordingly,

$$y_j^c = \sqrt{\frac{P_{b,m}^c}{d_{mj}^{\alpha}}} \quad h_{mj}\hat{x}_m + N_j(f) \tag{8.16}$$

where $\hat{x}_m$ is the re-modulated symbol at R. The superscript c indicates the co-operation phase, h_{mj} denotes the channel coefficient from relay m to destination j such that $h_{mj} \sim \mathcal{CN}\ (0, \sigma_{mj}^2)$ with $\sigma_{mj}^2 = E\{|h_{mj}|^2\} = 1$. $N_j(f)$ denotes the cumulative noise effects at D as described in the previous subsection. i.e.
$h_{mj} = |h_{mj}|e^{j\theta mj}$

$|h_{mj}|$ follows Rayleigh Distribution with power of unity as before i.e $\mathbb{E}[|h_{ij}|^2] = 1$. The received power at node x_j due to relay m is given by

$$P_j^c = \sum_{\substack{m\epsilon R \\ t_i \epsilon T}} (\frac{|h_{mj}|^2}{d_{mj}^{\alpha}}) P_{b,i}^c \tag{8.17}$$

where R is the group of all relay sensors of the network.

$P_j^c = P_{b,i}$ if the relay correctly decodes the symbol and

$P_j^c = 0$ otherwise.

Let γ_{im}^c be the SNR at relay m_i, then

$$\gamma_{im}^c = \overline{\gamma}|h_{ij}|^2 = \frac{1}{d_{im}^{\alpha}}.\frac{P_{b,i}^c}{P_{n_m}}.|h_{im}|^2 \tag{8.18}$$

where P_{n_m} is the noise power at relay m_i. As $|h_{im}|^2 = 1$, hence equation (8.18) becomes

$$\gamma_{im}^c = |h_{im}|^2 = \frac{1}{d_{im}^{\alpha}}.\frac{P_{b,i}}{P_{n_m}} \tag{8.19}$$

such that

$$\overline{\gamma} = \text{average}SNR(d,f) = \frac{P_{x_m}/A(d,f)}{N_m(f)B} \tag{8.20}$$

where $N_m(f)$ has the same value as in equation (3.3).

The destination node (r_j in this case) combines the directly received signal from the source (t_i) in phase 1 and that from the relay (m_i) in phase 2 by the sue of the MRC. An instantaneous SNR at the MRC output of r_j is

$$\gamma_{r_j} = \frac{\gamma_{ij}^d + \gamma_{im}^c}{var(N_j(f)) + var(N_m(f))} \tag{8.21}$$

and similar to equation (8.2), we must have $\gamma_{r_j} \geq \gamma_0$.

Errors at the sink take place either when the $t_j - m_i$ broadcast is intercepted correctly and the $m_i - r_i$ is received in error, or when the $t_j - m_i$ is received in error and the $m_i - r_i$ is intercepted correctly. Therefore for any modulation, the two-hop $t_j - m_i - r_i$ link has end-to-end BEP given by

$$BEP_{eq}(\gamma_{i_m}, \gamma_{m_j}) = [1 - BEP(\gamma_{im})]BEP(\gamma_{mj}) \\ +[1 - BEP(\gamma_{mj})]BEP(\gamma_{im})$$

This BEP_{eq} is the error probability at the destination of an equivalent one-hop Additive-White-Gaussian-Noise (AWGN) link whose output SNR γ_{eq} is

$$\gamma_{eq} = \frac{1}{\beta}\{Q^{-1}[BEP_{eq}(\gamma_{im}, \gamma_{mj})]\}^2 \tag{8.22}$$

$$\text{where} \quad Q(x) = \frac{1}{\sqrt{2}\pi}.\int_x^\infty \exp(-t^2/2).dt \tag{8.23}$$

β is a constant whose value is 2 for BPSK. According to [57], if $\gamma_{min} = min\{\gamma_{im}, \gamma_{mj}\}$ it follows that γ_{eq} in equation (8.22) is limited by

$$\gamma_{min} - \frac{3.24}{\beta} < \gamma_{eq} \leq \gamma_{min} \tag{8.24}$$

8.3.7 Link cost formulation

The cost of the link l_i between a transmitter t_i and receiver r_i represented by $C(t_i, r_i)$ is the least expected broadcasting power to send a message from t_i to r_i utilizing two-phase cooperation transmission scheme subject to rate R' and outage probability $\overline{p_o}$. The objective is to formulate $C(t_i, r_i)$ subject to an desirous throughput η_o over the communicating link $l_{ti}r_i$.

If $\eta_{l_i}(P_{b,i}, R')$ denotes the throughput of a link l_i subject to power allocation $P_{b,i}$ and transmission rate R', then

$$\eta_{l_i}(P_{b,i}, R') = \eta_{l_i}(1 - \bar{p}_o(P_{b,i}, R')) \tag{8.25}$$

As the throughput of the link l_i is the number of fruitfully transferred bits/sec/Hz,thus it can also be calculated as

$$\eta_{li} = P_{b,i} \times R' \quad (8.26)$$

As outage probability is the probability of mutual information sharing between t_i and r_i over a path l_i is less than the desired broadcasting rate R', hence

$$\overline{p_0} = \text{Prob}(I_{ij} \leq R') \quad (8.27)$$

where

$$I_{ij} = log(1 + \gamma_{ij}^d) \quad (8.28)$$

$i.e.\overline{p}_0 = \text{Prob}[log(1 + \gamma_{ij}^d) \leq R']$
$= \text{Prob}[1 + \gamma_{ij}^d \leq 2^{R'}]$
$= \text{Prob}[\gamma_{ij}^d \leq 2^{R'} - 1]$
$= \text{Prob}[\overline{\gamma}|h_{ij}|^2 \leq 2^{R'} - 1]$
$= \text{Prob}[|h_{ij}|^2 \leq \frac{(2^{R'}-1)}{\overline{\gamma}}]$

In terms of Probability Density Function (pdf), the outage probability is expressed as

$$\overline{p}_0 = 1 - exp(-\frac{(2^{R'} - 1)}{\overline{\gamma}}) \quad (8.29)$$

Data is considered lost if an outage occurs; hence probability of success is computed as

$$\overline{p}_0^s = 1 - \overline{p}_0 = exp(-\frac{(2^{R'} - 1)}{\overline{\gamma}}) \quad (8.30)$$

$log(\overline{p}_0^s) = (-\frac{(2^{R'}-1)}{\overline{\gamma}})$

$$\overline{\gamma} = \frac{(2^{R'}-1)}{-log(\overline{p}_0^s)}$$
$$= \frac{1-2^{R'}}{log(\overline{p}_0^s)}$$

$$\text{implies} \quad \frac{P_{x_j}/A(d,f)}{N_j(f)B} = \frac{1-2^{R'}}{log(\overline{p}_0^s)} \tag{8.31}$$

$$\text{i.e} \quad P_{x_j}^d = \frac{(1-2^{R'}).A(d,f).N_j(f).B}{log(\overline{p}_0^s).d_{ij}^{-\alpha}} \tag{8.32}$$

This equation helps us to find the required transmission power in direct mode, implies

$$P_{x_j}^d = \mathcal{J}.d_{ij}^{\alpha} \tag{8.33}$$

$$\text{where} \quad \mathcal{J} = \frac{(1-2^{R'}).A(d,f).N_j(f).B}{log(\overline{p}_0^s)} \tag{8.34}$$

For the cooperative transmission mode, let the probability that the source is transmitting is given by $p(t)$ i.e.

$$p(t) = [p(I_{t,r} \leq R')][p(I_{t,m} \leq R')] + [1 - p(I_{t,r} \leq R')] \tag{8.35}$$

where the first term indicates that both the source-destination and the source-relay links are in outage; whereas the second term indicates that the source-destination channel is not in outage. In other words, the probability that the relay is in cooperation with the transmitter is given by

$$\overline{p}(t) = 1 - p(t) \tag{8.36}$$

In terms of $\mathcal{J}$, equation (8.35) can be expressed as

$$p(t) = [\mathcal{J}.d_{tr}^{\alpha}].[\mathcal{J}.d_{tm}^{\alpha}] + [1 - \mathcal{J}.d_{tm}^{\alpha}] \tag{8.37}$$

and hence

$$\overline{p}(t) = 1 - (\mathcal{J}.d_{tr}^{\alpha}).(\mathcal{J}.d_{tm}^{\alpha}) + (\mathcal{J}.d_{tm}^{\alpha}) \tag{8.38}$$

8.4 Performance evaluation

To evaluate the performance of Co-EEUWSN, it is compared with the existing schemes DBR and EEDBR. In the simulation environment where the network lifetime has been expressed in seconds, nodes have been deployed randomly in every simulated technique. The following metrics have been considered for evaluation.

8.4.1 Performance metrics

Key performance metrics evaluated for the suggested protocol are defined in section 5.6.

8.4.2 Basic assumptions

By following multiple-sink model of conventional methods with 5 sinks deployed on the surface of the water, 225 nodes are randomly deployed in the network field of 500m x 500m. Transmission range of sensor node is assumed to be 100 meters, which follows the physical characteristics of UWA modem. Data packet size is assumed to be of 50 bytes and that of control packet be 8 bytes. Each node shares the vital physical metrics, especially depth threshold and weight with its neighbors to keep informed with the varying circumstances of the network. After some suitable network lifetime, nodes compute their distance from the neighbor nodes. The nodes transfer their data to the upper layer using cooperation of neighbor nodes till data reaches the sink. Sink supervises the depth thresholds and the adaptive mobility of cooperating nodes. The introduction of cooperation and variations in depth threshold make Co-EEUWSN scheme as a feasible contender for data-critical applications.

8.4.3 Stability period

Figure 8.4 illustrates the comparison between stability period of Co-EEUWSN, Co-DBR, EEDBR and DBR. After equal intervals of time, every alive sensor sends a packet, which is transferred until that reaches the relay or sink node. In Co-EEUWSN, first sensor dies after about 5500 seconds in comparison to Co-DBR in which the first node dies after 2800 seconds, after 2600 seconds in the case of EEDBR and after 2050 seconds in DBR. Modifications in relay link analysis and consideration of channel losses as well as SNR in the medium are the causes in the improvement of stability period. This does not allow rapid consumption of energy of nodes due to the presence of relay nodes supporting cooperation. The stability period of Co-DBR is better than DBR and EEDBR; however, the network energy consumption is greater in Co-DBR. In DBR and EEDBR, the source nodes forward data to next-hop neighbor nodes only, whereas Co-DBR utilizes source node along-with two relay nodes to transmit data to the next-hop. The stability period in case of DBR ends quickly due to consideration of depth or residual energy only in selecting best neighbors. This results in inefficient instability period. Instability period of DBR is improved in EEDBR as there is a slow rise in network energy consumption. As the network becomes light, neighbor nodes decrease rapidly leading to network instability.

Figure 8.4 illustrates that Co-EEUWSN and Co-DBR schemes improve the stability periods of DBR and EEDBR by avoiding the forwarding of unnecessary data along with maintaining lower transmission loss. The load on medium-depth nodes is shared due to adaptive movement of relay nodes. After the expiry of initial nodes, the network destabilizes due to diminution of eligible neighbors. In DBR, the stability period is lesser than that of Co-EEUWSN as it considers only depth of forwarding nodes as the ultimate determining factor. When the network becomes sparse, number of neighbors decreases quickly causing network instability. In Co-EEUWSN, there are two selection attributes for forwarding; depth and residual

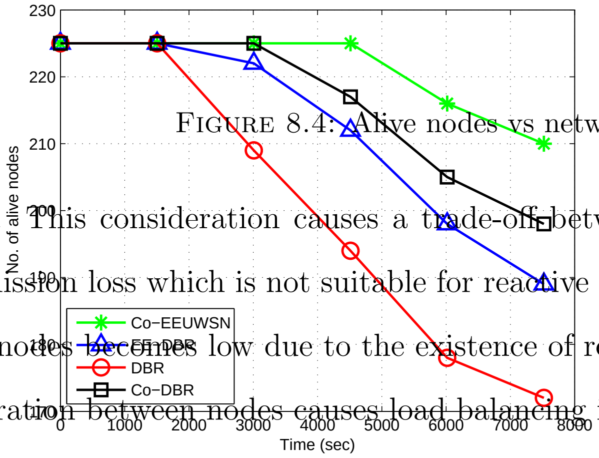

FIGURE 8.4: Alive nodes vs network lifetime

energy. This consideration causes a trade-off between the network lifetime and transmission loss which is not suitable for reactive applications. The load on high depth nodes becomes low due to the existence of relay nodes.

Cooperation between nodes causes load balancing in Co-EEUWSN and Co-DBR. During instability period, network gradually becomes sparse causing load on high residual-energy nodes, whereas, the number of neighbors is managed by variations in depth threshold. In our suggested scheme, employment of Thorps energy model specifies the detailed channel losses, which are useful for selective data forwarding in responsive networks. The consideration of channel losses is absent in the Co-DBR scheme. Thus, Co-EEUWSN outperforms not only the selected non-cooperative DBR and EEDBR but also the Co-DBR. Increase in stability period in Co-EEUWSN also confirms reduction in redundant transmissions.

8.4.4 End-to-end delay

Figure 8.5 shows a comparison of end-to-end delay of the proposed scheme Co-EEUWSN with those of Co-DBR, EEDBR and DBR. The figure shows that the end-to-end delay in Co-EEUWSN is reduced compared to DBR because of least possible forwarding distances between the sensors in both dense and sparse conditions. The transmission delay in underwater conduit roots great latency for

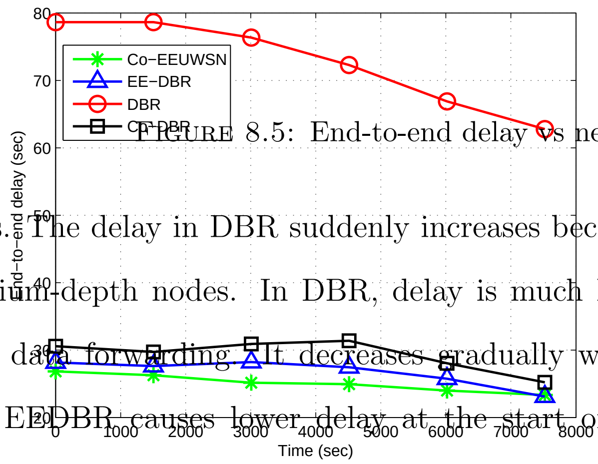

FIGURE 8.5: End-to-end delay vs network lifetime

packets. The delay in DBR suddenly increases because of quick energy depletion of medium-depth nodes. In DBR, delay is much higher in initial stages due to distant data forwarding. It decreases gradually with the sparseness of the network. EEDBR causes lower delay at the start of the network comparative to Co-EEUWSN and Co-DBR due to prioritization of residual energy; and the delay increases whenever the network becomes scattered causing data forwarding at increased distance.

In our technique, there is a minimum possible time lag due to consideration of signal quality and depth differences between sender and receiver nodes with introduction of cooperative relay nodes. Co-EEUWSN is well suited to delay-sensitive applications specifically in on-demand routing. Co-DBR and EEDBR schemes forward data with least hops however the degraded quality UW channel increases packet loss at the receiver. Hence, the packets are required to be retransmitted. This raises the end-to-end delay of the packets. Co-EEUWSN protocol is based on channel estimation and considers SNR as well as underwater losses. Data is forwarded with profound reliability, resulting in reduced retransmissions, and reaches sink with much lower delay. Adaptive movement of relay nodes and utilization of weight function reduces the percentage of lost data packets along-with a decline in end-to-end delay of data at the sink. Co-EEUWSN reduces end-to-end delay by utilizing SNR in extreme low-depth and high-depth regions, thus providing flexibility for delay-sensitive applications in UWSN.

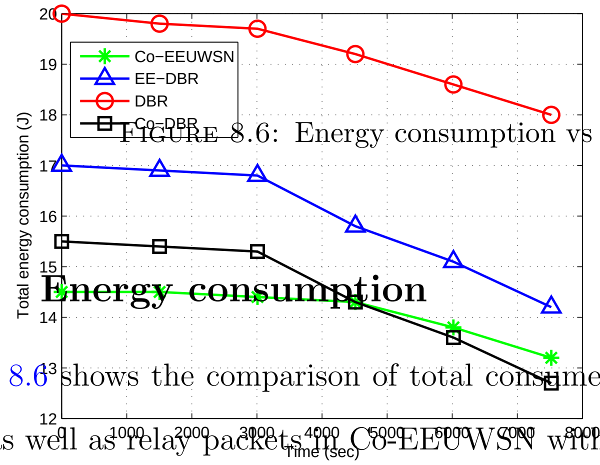

FIGURE 8.6: Energy consumption vs network lifetime

8.4.5 Energy consumption

Figure 8.6 shows the comparison of total consumed energy of all sensors to generate as well as relay packets in Co-EEUWSN with that of underwater protocols, Co-DBR, EEDBR and DBR. It is evident from the plots that the net energy consumption in case of Co-EEUWSN is quite less than of its counterparts. DBR and EEDBR protocols focus on the minimum path to sink; although, data is routed without taking into account channel quality and noise types in UW environment. DBR consumes higher energy because of unnecessary data forwarding and nodes die out quickly. In this protocol, energy consumption increases continuously as percentage of optimal forwarding nodes drops off with rising density of the network and regular selection of high energy nodes i.e. unequal distribution of load. Energy consumption in EEDBR is greater due to regular selection of high energy nodes.

The cooperative transmission scheme Co-DBR consumes approximately three times more energy than DBR and EEDBR in stable region. As, the nodes start to die after 2000 seconds, the total energy consumption tends to decrease. In Co-DBR, nodes transmit most of the time without relays when few nodes are left alive and there is no unnecessary data forwarding, so energy consumption is less than both the schemes DBR and EEDBR. Besides, the cooperation scheme using relay nodes Co-EEUWSN is focused on channel estimation that improves the received packet quality. Transmissions on a single path are generally affected when the channel quality changes. Co-EEUWSN offers load balancing like Co-DBR as these schemes consume less energy throughout the network lifetime by relay cooperation in comparison to DBR and EEDBR protocols.

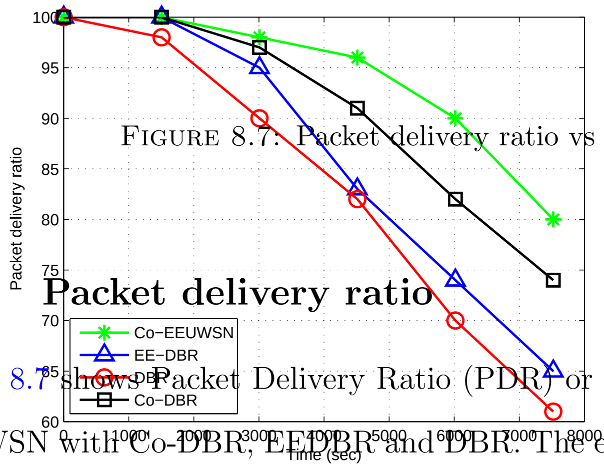

FIGURE 8.7: Packet delivery ratio vs network lifetime

8.4.6 Packet delivery ratio

Figure 8.7 shows Packet Delivery Ratio (PDR) or throughput comparison of Co-EEUWSN with Co-DBR, EEDBR and DBR. The effects of the cooperative transmission model on UW link are evaluated to minimize the packet loss which is due to signal fading. In a non-cooperative environment, when inter-arrival time of data packets is less, much profound traffic is forwarded from source sensors. It raises the chances of packet collision causing a lower delivery ratio. CO-EEUWSN, and Co-DBR protocols achieve greater delivery ratio in comparison to DBR and EEDBR. Higher packet loss results due to transmissions in DBR without consideration of channel estimation. Also, data transmissions following paths with minimum hops cause more collisions and introduce packet delays. Cooperative schemes improve the chances of successful packet reception by routing data on multiple paths and aggregating at receiver end. DBR as well as EEDBR schemes send unnecessary data with high propagation losses and throughput fall rapidly due to sudden decrease in network density after 3000 seconds. In Co-DBR, throughput remains constant up to 4200 seconds whereas in Co-EEUWSN, throughput remains constant up to 5500 seconds and then steadily decreases due to constant network density and reduced energy consumption. The throughput of both DBR and EEDBR schemes decline rapidly, not acceptable for delay-tolerant as well as delay-sensitive applications. But our protocol Co-EEUWSN outperforms Co-DBR, DBR and EEDBR due to less delay in data delivery, thus validating its better performance in flooding-based protocols.

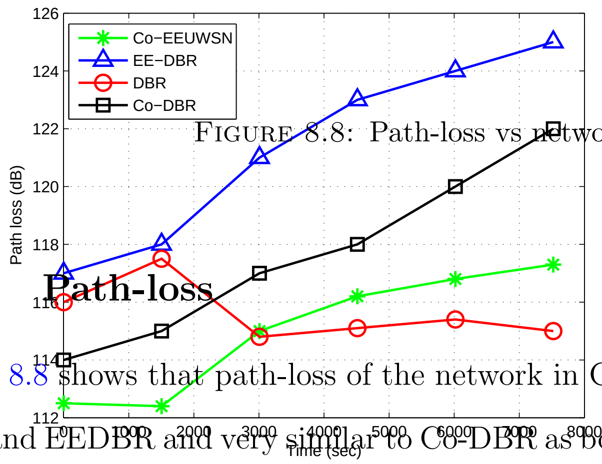

FIGURE 8.8: Path-loss vs network lifetime

8.4.7 Path-loss

Figure 8.8 shows that path-loss of the network in Co-EEUWSN is much less than DBR and EEDBR and very similar to Co-DBR as both Co-EEUWSN and Co-DBR involve the use of cooperation. The plots very clearly indicate that the effective use of cooperation outperforms the schemes which are not utilizing the relay nodes performance. In DBR, there are preferences of distant transmissions; similarly, in

EEDBR multiple transmissions increase transmission loss between sender node and sink. However in Co-EEUWSN, we have utilized Uricks model and Thorps attenuation model for underwater environment to calculate the transmission loss in packet forwarding. These models determine the effect of path-loss on transmission frequency, bandwidth efficiency, and noise density during data transmission. In DBR, the initial times of the network show low losses due to high network density. As network becomes sparse there is a sharp decrease in network performance causing high packet loss. This is because of non-availability of neighbor nodes to forward packets. In Co-EEUWSN, channel loss conditions are better than DBR and EEDBR as the SNR computations consider both depth and residual energy of relay nodes as well as the utilization of cooperation scheme. In later stages, the performance of Co-EEUWSN gradually decreases with decrement in relay nodes; therefore, both the packet loss and delay increase. In our proposed scheme, transmission loss is one of the key factors for data-sensitive responsive networks.

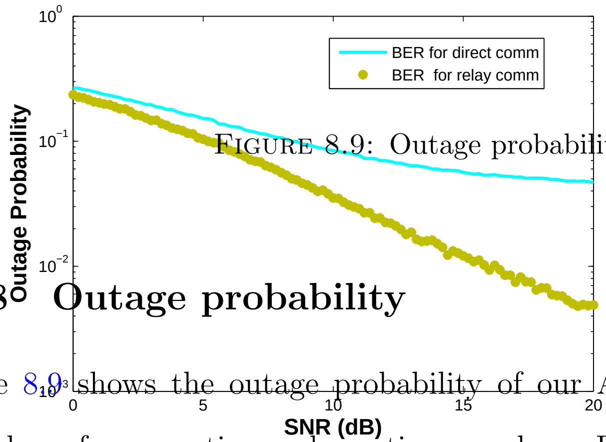

FIGURE 8.9: Outage probability vs SNR

8.4.8 Outage probability

Figure 8.9 shows the outage probability of our AF Co-EEUWSN scheme with a number of cooperative nodes acting as relays. Plots like in the figure assist in system plan not only because outage probability is a significant QoS factor in itself, but also since they permit us to govern the optimum number of cooperative nodes. For this simulation we have set the transmission rate R' = 1 as outage probability is dependent on the transmission rate as shown in equation (8.27). The blue plot in the figure shows the variation in outage probability for direct communication between a broadcasting node and sink node and no relay is utilized.

On the other hand, the green plot shows the variation of outage probability with that of SNR for a fully cooperative environment. The plots clearly indicate that for lower values of SNR till 6 dB, there is no major difference in the two plots. But beyond this value, we find a remarkable improvement in outage probability for cooperative or relay communication in contrast to direct communication. This is due to the fact that with the increase in SNR value, more relay nodes take part in data transfers rather than direct communication in order to combat the varying underwater channel losses. Hence, we deduce that AF scheme provides "full diversity" such that the diversity order (with outage probability as performance metric) is the net figure of cooperating sensors in the network. This shows that the best figure of cooperating sensors is truly a complex function of the SNR and cooperative diversity scheme.

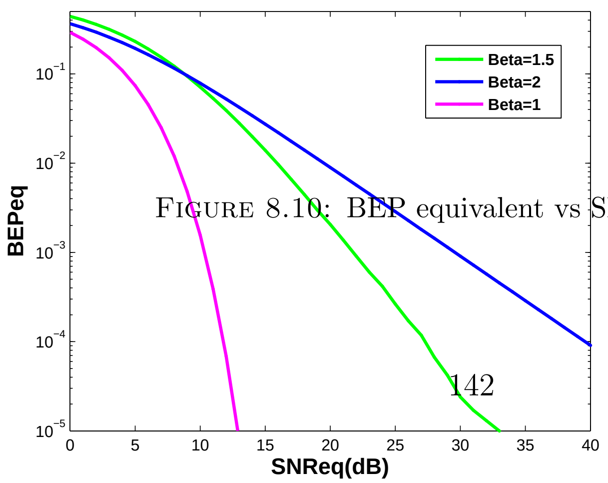

Figure 8.10: BEP equivalent vs SNR equivalent

8.4.9 BEP vs SNR

Figure 8.10 indicates the different plots of Bit Error Probability BEP versus equivalent SNR. By definition, we know that the more is SNR, better is the reception and signals can be more reliably converted to bits at sink. Energy per bit considers data rate, i.e. the number of bits/symbol. Total bit error probability depends on SNR and modulation utilized. The plots are plotted for different values of β i.e. for $\beta = 1$, $\beta = 1.5$ and $\beta = 2$ as indicated by equation (8.24); and it is very much clear from the graph that near to optimum results are found for β=2 and this accounts due to the fact that we are considering the BPSK technique which corresponds exactly to the theoretical concept. In the modeling we had already considered the value of $\beta = 2$ for equivalent one hop AWGN link.

8.4.10 Performance with trade-offs

Table 8.1 shows a comparison performance of the compared schemes on the prices they have to pay. In Co-EEUWSN, the stability period is improved on the cost of more forwarding nodes and energy consumption. The scheme improves the stability period of the network by avoiding the forwarding of unnecessary data along with maintaining lower transmission loss but at the cost of utilization of relay nodes and computation of relay link analysis. In Co-EEUWSN, the instability period starts after 5500th second, after which the packet delivery ratio remains even, however total energy consumption increases slowly. In DBR, the stability period is achieved at the cost of transmission loss. In this protocol, there are only two forwarding selection attributes; depth and residual energy. This consideration causes a trade-off between the network lifetime and transmission loss which is not suitable for reactive applications. During the instability period of DBR, network gradually becomes sparse causing load on high residual energy nodes. In EEDBR, the stability period is improved at the cost of greater energy usage. In Co-DBR, the stability period improves but at the cost of energy usage as it utilizes two relay nodes in the data forwarding and also the end-to-end delay increases as the data has to flow through the relay nodes till the sink is the next hop.

In our scheme of Co-EEUWSN, improvement in end-to-end delay is gained at the cost of time lag. End-to-end delay in Co-EEUWSN is improved compared to Co-DBR, DBR and EEDBR; but at the cost of possible time lag due to consideration of SNR and cooperation mechanism. In EEDBR, delay is improved at the cost of repeated transmissions. The delay in EEDBR is much higher in initial rounds due to distant data forwarding but at the cost of redundant transmissions because the noisy UW channel leads to more data loss at the reception. In DBR, end-to-end delay is improved on the cost of energy depletion. End-to-end delay in Co-DBR is better than DBR and EEDBR as both depth variations and involvement of relay nodes and cooperation scheme perform load balancing but at the cost of sharp energy depletion of the nodes.

TABLE 8.1: Performance parameters with their trade-offs

Protocol	Advances achieved	Reference	Price to Pay	Reference
Co-EEUWSN	Stability period extends	Fig. 8.5	More forwarding nodes and delay	Fig. 8.6
	End-to-end delay improves	Fig. 8.6	Time lag due to SNR and cooperation	Fig. 8.5
	Packet delivery ratio improves	Fig. 8.8	Time lag and energy consumption	Fig. 8.7
	Path loss declines	Fig. 8.9	Shorten stability period and energy consumption	Figs. 8.5,8.7
Co-DBR	Stability period extends	Fig. 8.5	Energy consumption due to two nodes relaying and delay	Figs. 8.6,8.7
	End-to-end delay improves	Fig. 8.6	Throughput decreases due to packets loss in the midway	Figs. 8.5,8.8
	Packet delivery ratio improves	Fig. 8.8	Transmission loss due to distant propagations	Fig. 8.9
	Path loss declines	Fig. 8.9	Redundant transmission and lower stability period	Fig. 8.5
EEDBR	Stability period extends	Fig. 8.5	Sharp energy depletion	Fig. 8.7
	End-to-end delay improves	Fig. 8.6	Greater energy consumption	Fig. 8.7
	Packet delivery ratio improves	Fig. 8.8	Transmission loss and delay	Figs. 8.6,8.9
	Path loss declines	Fig. 8.9	Redundant transmission and lower stability period	Fig. 8.5
DBR	Stability period extends	Fig. 8.5	Sharp energy depletion	Fig. 8.7
	End-to-end delay improves	Fig. 8.6	Greater energy consumption due to only depth consideration	Fig. 8.7
	Packet delivery ratio improves	Fig. 8.8	Transmission loss due to distant propagations	Figs. 8.6,8.9
	Path loss declines	Fig. 8.9	Packet Delivery ratio and delay	Fig. 8.8

In Co-EEUWSN, packet delivery ratio (PDR) is improved at the cost of time-lag. The drop in PDR in Co-EEUWSN is much less than that of other schemes. This scheme enhances the chances of data reception by transmitting data on various paths and then aggregating them at the reception. This reduction in packet delivery ratio is gained at the cost of higher energy usage as more sensors participate in data forwarding mechanism. In Co-DBR, transmission loss improved at the cost of low PDR. In this protocol, higher transmission loss is achieved than the other two techniques DBR and EEDBR as it employs distant propagations as well as multiple forwarding through relay node mechanism. DBR achieves improvement in PDR at the cost of packet loss and delay. In EEDBR, channel loss conditions are better than DBR, as the weight function computations consider both depth and residual energy of forwarding nodes, therefore the propagations remain stable. But in later stages, performance of EEDBR gradually goes down with the decrement in qualified forwarding nodes, therefore both the packet loss and delay increase but at the cost of drop in its PDR.

In CO-EEUWSN, the transmission loss reduces at the cost of stability period and the energy consumption. With the increase in total numbers of relay nodes with the passage of time and redundant transmissions between the sink and the sender nodes causes energy depreciation. CO-EEUWSN performs better than Co-DBR, EEDBR and DBR in terms of net transmission loss because of giving preference to SNR in its computations. With the help of Thorps attenuation model for underwater environment, the total transmission loss in packet is calculated between the source node and the receiver or the sink through relay. Due to the consideration of bandwidth efficiency, transmission frequency and the different noise presence in water channels, which are used to judge and analyze the signal quality during the transmission of data; this model is preferred and hence used. As in Co-DBR there are redundant transmissions between the source nodes and the sink they lead to higher throughput with the expense of transmission loss in the network. But still comparing it to other techniques like DBR and EEDBR channel loss conditions are far better in Co-DBR. The advantage of considering both residual energy and depth of forwarding nodes in EEDBR, the propagations and data transmission remain stable comparatively than DBR. With the passage of time in later stages the qualified forward nodes decrease in number due to which the network experiences the delay in the transmission as far as the packet loss in Co-DBR.

Table 8.2 indicates a numerical comparison of all the four compared protocols in terms of their efficiency for all the parameters in terms of which their comparison is done.

TABLE 8.2: Efficiency of protocols in percentage in terms of their parameters

Protocol	**Stability period**	**End-to-end delay**	**PDR**	**Energy consumed**	**TL**
DBR	100	149	100	100	170
EEDBR	122	100	140	175	165
Co-DBR	135	175	180	144	100
Co-EEUWSN	168	153	161	120	185

8.5 Conclusion of the chapter

In this chapter, we have proposed Co-EEUWSN, a coopertion based energy-efficient routing protocol to maximize the lifetime and reduce the energy consumption of UWSNs. Introduction of cooperation and SNR enhances the network lifetime, improves the packet delivery ratio and reduces the overall network energy consumption; especially for delay-sensitive applications and even in sparse conditions. The transmission schemes without cooperation utilize channel estimation that enhance the data quality at reception, however, broadcasting with a single-path can be attenuated as the channel quality varies. The relay selection process takes into account the instantaneous path situations and separation parameter among neighbouring sensors to reliably relay packets to the destination in UW constrained environment. Features of both single-hop and multi-hop communication have been considered to lesson down the path-loss effects and improve network lifetime in comparison to non-cooperation based DBR and EEDBR protocols and cooperation based Co-DBR protocol. While this research provides useful insights for the design of energy-efficient cooperative routing schemes, several issues remain to be addressed towards a comprehensive cooperative routing algorithm.

In the next chapter, we present a cooperation-based routing protocol for UWSNs to enhance their performance called SPARCO. Cooperative communication is explored in order to design an energy-efficient routing scheme for UWSNs. Both multi-hop and single-hop schemes are exploited which contribute to lowering of path-losses present in the channels connecting nodes and forwarding of data. The performance is also compared with three cooperation-based routing protocols for UWSN, Cog-Coop, CoDBR and Coop Re and dth. The protocol uses a cost function, computed using node distances from the destination and their residual energies.

Chapter 9

SPARCO

9.1 Summary of the chapter

Reliability is a key factor for application-oriented UWSNs which are utilized for gaining certain objectives and a demand always exists for efficient data routing mechanisms. Cooperative routing is a promising technique which utilizes the broadcast feature of wireless medium and forwards data with cooperation using sensor nodes as relays. Here, we present a cooperation-based routing protocol for underwater networks to enhance their performance called SPARCO. Cooperative communication is explored in order to design an energy-efficient routing scheme for UWSNs. Each node of the network is assumed to be consisting of a single omnidirectional antenna and multiple nodes cooperatively forward their transmissions taking advantage of spatial diversity to reduce energy consumption. Both multi-hop and single-hop schemes are exploited which contribute to lowering of path-losses present in the channels connecting nodes and forwarding of data. Simulations demonstrate that SPARCO protocol functions better regarding end-to-end delay, network life-time, and energy consumption comparative to non-cooperative routing protocol iAMCTD. The performance is also compared with three cooperation-based routing protocols for UWSN, Cognitive Cooperation (Cog-Coop), CoDBR and Coop (Re and dth).

9.2 Motivation

Majority of network applications consist of battery-powered nodes having limited transmission-reception range. Thus, cooperative communication or alternately cooperative routing is particularly needed for such networks, in which sensor nodes share their resources among each other. Migrating from lengthy but weak links to shorter as well as strengthened links can minimize the load on the path connecting sensors. Different available paths present between sensors and sinks provide means for the new design options regarding scheduling and routing.

Cog-Coop uses both spectrum sensing information and residual energy of sensors to select the optimal forwarder nodes. It improves the spectrum sensing performance along with having better energy consumption of the sensors. Optimal conditions are attained centered on the typical optimization approaches to find the priority of sensors for spectrum sensing. They showed that cooperation among cognitive nodes is necessary for lowering the fading as well as shadowing effects, and hence, correct sensing. Also, the forwarding node selection criteria is suggested to save energy and deal with the issue of direct communications with the fusion center. It is a cooperative routing protocol and redundant transmissions consume a lot of energy. Therefore, packets are forwarded over a single lossy channel in a multihop order. Due to noise and multipath fading in UW environment, signal suffers high bit error rate. In iAMCTD, a routing scheme is proposed to maximize the lifetime of reactive UWSNs. iAMCTD considers signal quality as well as residual energy for routing metrics. It is a prototype scheme in localization-free and flooding centered data forwarding for UW scenarios. It improves the network throughput and minimizes PDR to a larger extent by using formulated forwarding functions. iAMCTD faces redundant transmissions resulting in major energy consumption.
Coop (Re and dth) aims to solve the issues of EEDBR and iAMCTD via cooperative diversity. This protocol involves data transmission through the use of partner nodes/relays that use cooperation to route the data to the sink. This improves the rate of fruitful packets delivery to the sink as in the chances of link disaster, at least one link is present for forwarding of packets reliably to the final end. The scheme considers a node link state information along with its residual energy and depth as selection criterias. So, Coop (Re and dth) is consuming more broadcasting energy than iAMCTD and EEDBR. This presents us with the tradeoff between reliability and energy conservation. Also, the protocol does not consider any transmission impairments present in the underwater environment. CoDBR aims to solve the issues of EEDBR via cooperative diversity. The protocol chooses the forwarder sensor using two relays selected on the basis of least depth that route their packets

to sink, cooperatively. This enhances the successful data delivery rate because if a link fails, then at least another path is present for forwarding packets successfully to the sink. As CoDBR considers one source node and two relay sensors to forward packets to next hop, hence CoDBR consumes three times greater broadcasting energy than EEDBR. It is also a tradeoff between link availability and energy conservation. In order to address the issues of all these four protocols, we have tried to propose a new protocol by the name of SPARCO.

In SPARCO scheme, we suggest an approach to forward information through UWSNs with much lower path-loss over a link using the features of single-hop and multi-hop. The protocol uses a cost function to find the most suitable path to sink. This function is computed using node distances from the destination and their residual energies. Simulations depict that SPARCO scheme enhances the network stability period with much reduced path-loss, to a large extent.

The research takes into account an underwater acoustic environment, where the channel is largely attenuated by fading and other noise effects. The sensed signal by the sensors is modeled by a Rayleigh random variable. The proposed mechanism leads to enhance the reliability of the underwater channel by the use of cooperative routing. In this work, we consider the technique of FRC for signal combining. Cooperative diversity is obtained without using various antennas. This is particularly useful when frequency, time and diversity by the use of several antennas are not appropriate. This not only motivated us to the utility of cooperation in underwater environment, but also to evaluate its impact on system performance.

9.3 SPARCO: The system model

Figure 9.1 shows a 5-node UWSN model, where S and D are the source and destination nodes, respectively. Data transferred by S is received by nodes $R1$, $R2$ and $R3$. Having done with the initial transmission, nodes S, $R1$, and $R2$ have the data and cooperatively transmit the data to $R3$ and then D. Let the least possible energy link from S to D is determined via $R2$ i.e. S→ R2→ D. Sensor $R1$, present within the broadcast range of S to $R2$, captures the data forwarded from S. The dark lines in the figure 9.1 show the direct communication paths whereas the dotted lines indicate the cooperative routes in case the direct transfer path is not available or not feasible to use.

It is assumed that each sensor dynamically adjusts its transmission power to manage its range. Further that various sensors in cooperation help forwarding data to only one receiving sensor can delay their transmission for perfect phase synchronization at D.

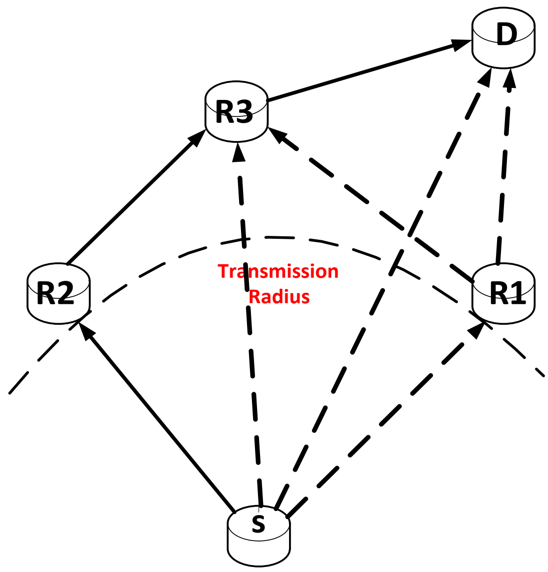

Figure 9.1: Multi-hop routing

It is also assumed that the information is routed from S to D in transmission slots one after another. For each slot, a sensor is chosen for transmitting the data to a set of sensors that received the information. This will help the nodes to cooperate for transmitting the data to another group of sensors.

The routing problem is tackled as a multi-stage decision problem. The decision is made at each stage to select the receiving as well as forwarding group of sensors and the transmission power level among all sensors of that stage as well. The purpose is to get the data reach the final point with least energy consumption.

Let the transmitting group at any stage k be denoted by S_n and the receiving group of nodes by R_m. Cost in terms of link between S_n and R_m, denoted by C(S_n,R_m) is the least power required for data transmission from S_n to R_m. Here, $S_n = \{s_1, s_2, ..., s_n\}$ and $R_m = \{r_1, r_2, ..., r_m\}$.

To derive the equations for the costs on the link connecting nodes, we consider 4 different possibilities [90]:

(i) {Point-to-point link} i.e. (n=1, m=1):

A single source node transmitting to a single receiving node within a time-slot.

(ii) {Point-to-multipoint/ broadcast link} i.e. (n=1, $m > 1$):

One node transmitting to various receiving nodes.

(iii) {Multipoint-to-point/ cooperative link} i.e. ($n > 1$, m=1):

Various nodes cooperating in forwarding the same data to one receiver. The signal is aggregated at the destination and full decoding only takes place if the achieved SNR is more than the threshold SNR_{min}.

(iv) {Multipoint-to-multipoint link} i.e. ($n > 1$, $m > 1$):

Several nodes transmitting data to various other nodes makes redundant transmission at various receivers which is not feasible. Hence it is dealt as a MIMO case.

The preceding four cases are discussed individually with their link-cost formulations.

9.3.1 Case I:

{Point-to-point link} i.e. (n=1, m=1):

Here S_n={s_1} and R_m={r_1}. Let the wireless channel in underwater between these nodes is described by 2 factors: magnitude or attenuation factor α_{nm} and phase delay ϕ_{nm} as shown in figure 9.2. The generated signal is managed by a scaling factor f. In UW applications, f is a complex factor adopting both phase and power adjustment by the sender. As there is a single receiver in this case, hence the phase can be ignored.

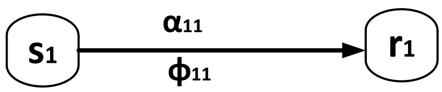

FIGURE 9.2: Single-Input-Single-Output linkage

The signal received is computed as follows [90]:

$$x(t) = \alpha e^{j\phi} f \times \hat{p}(t) + N(t) \tag{9.1}$$

where $\hat{p}(t)$ is the unit-power generated signal and $N(t)$ is the cumulative receiver noise in UW having power P_N. Net generated power is $P_T = f^2$ and SNR at the receiving node is $\frac{\alpha^2|f^2|}{P_N}$. SNR needs to be more than the threshold value SNR_{min}. Minimum power needed is $\bar{P}_T$ and therefore the point-to-point $C_{p-p}(s_1, r_1)$ is expressed by [90]:

$$C_{p-p}(s_1, r_1) = \bar{P}_T = \frac{SNR_{min} \times P_N}{\alpha^2} \tag{9.2}$$

$$\bar{P}_T \propto \frac{1}{\alpha^2} = \frac{1}{d^2} \tag{9.3}$$

i.e. C_{p-p} is inversely proportional to square of the separation d between s_1 and r_1.

9.3.2 Case II:

{Point-to-multipoint link} i.e. (n=1, $m > 1$):

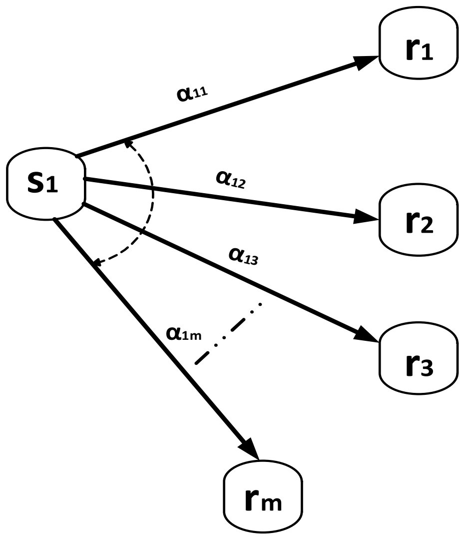

FIGURE 9.3: Broadcast linkage

In this case, $S_n = \{s_1\}$, and $R_m = \{r_1, r_2, ..., r_m\}$ as shown in figure 9.3, thus m similar SNR limitations should be satisfied at receiver nodes. The signal broadcasted by s_1 is received by all those sensors that are within the broadcast radius and proportional to the broadcast power P_T. Minimum power needed for this broadcast is represented by $C_{p-m}(s_1, R_m)$, expressed as:

$$C_{p-m}(s_1, R_m) = maximize\{C_{11}(s_1, r_1), C_{12}(s_1, r_2), ..., C_{1m}(s_1, r_m)\} \qquad (9.4)$$

As the receiver nodes can be in various dimensions in terms of placement, so we use Principal Component Analysis (PCA) technique for this maximization problem. PCA is a reknowned technique for dimension reduction and exploratory data analysis [94].

For a group of sensed v-dimensional data vectors $\{v_t\}$, $t\epsilon\{1, 2, ..., T\}$, the q principal axes w_j, $j\epsilon\{1, 2, ..., q\}$, are those orthonormal axes onto which the reserved variance under projection is utmost. The vectors w_j are expressed by the

q foremost eigenvectors (i.e. ones having maximum related eigen-values λ_j) of the sample covariance matrix, $M = E[(v-\mu)(v-\mu)^T]$, so that $M_{w_j} = \lambda_j.w_j$. The q major components of the noticeable vector v_t are expressed in terms of the vector $x_t = W^T(v_t - \mu)$, where $W^T = (w_1, w_2, ..., w_q)^T$. The variables x_j are such decorellated that the covariance matrix $E[x.x^T]$ is diagonal with elements λ_j.

9.3.3 Case III:

{Multipoint-to-point link} i.e. ($n > 1$, $m = 1$):

In this case, $S_n = \{s_1, s_2, ..., s_n\}$, and $R_m = \{r_1\}$ as shown in figure 9.4. Here n transmitting nodes amend their phases so that that the signal is received at the destination in phase.

As we are considering PCA in this modeling, so a latent variable model is required to relate the group of v-dimensional noticeable data vectors $\{v_t\}$ to a matching group of q-dimensional latent variables $\{x_m\}$ such that [90]:

$$l = y(x; \theta) + \epsilon \tag{9.5}$$

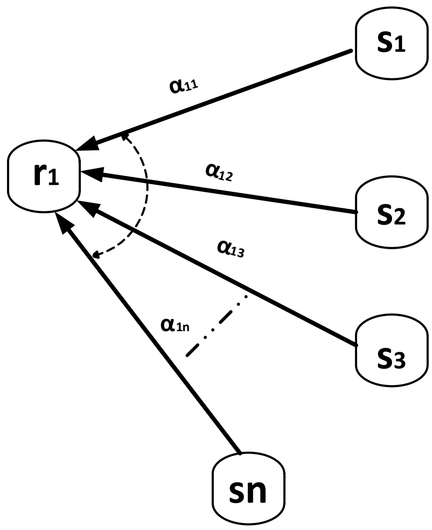

FIGURE 9.4: Cooperative linkage

where $y(x;\theta)$ is a function of the latent variable x with parameter θ, and ϵ is an x-independent noise process. Equation (9.5) is quite similar to equation (9.1) which is utilized for a single point-to-point node data transfer.

Generally $q < v$ in the way that latent variable offers a better promising explanation of the data and in case III, $q = 1$, thus only a single receiving node is being used here. In standard form, the mapping $(x;\theta)$ is linear, so

$$l = Wx + \mu + \epsilon \tag{9.6}$$

for which the latent variables $x \sim \mathcal{N}(0, I)$ follow a unit Gaussian distribution. Noise model is also Gaussian in nature and $\epsilon \sim \mathcal{N}(0, \psi)$ having ψ diagonal, the $(v \times q)$ parameter matrix in our case i.e. $(v \times 1)$. Hence, the model for l is also normal i.e. $\mathcal{N}(\mu, C)$, such that the covariance $C = \psi + WW^T$.

The prototype is selected due to diagonality of ψ and the sensed variables l do not depend on the latent variables, x. In this case, the latent variables are the parameters α_{n1} and ϕ_{n1}. Analytic solution for W and ψ does not exist in literature and their values are to be computed by iterative methods.

For the model of equation (9.6), with an isotropic noise, so that $\psi = \sigma^2$. The noise model $\epsilon \sim \mathcal{N}(0, \sigma^2)$ in equation (9.6) implies that a probability distribution over l-space for a given x expressed by [90]:

$$p(l|x) = (2\pi\sigma^2)^{-t/2} exp\{\frac{-1}{2\sigma^2}||l - Wx - \mu||^2\} \tag{9.7}$$

having a Gaussian on latent variables given by

$$p(x) = (2\pi)^{-q/2} exp\{\frac{-1}{2}.x^T.x\} \tag{9.8}$$

Here in case III, $q = 1$, so

$$p(x) = (2\pi)^{-1/2} exp\{\frac{-1}{2}.x^T.x\} \tag{9.9}$$

and marginal distribution of l in the form

$$p(l) = \int p(l|x).p(x).dx \tag{9.10}$$

$$p(x) = (2\pi)^{-q/2}|C|^{-1/2}exp\{\frac{-1}{2}.(l-\mu)^T.C^{-1}(l-\mu)\} \tag{9.11}$$

where $q = 1$; and the model covariance is

$$C = \sigma^2 I + WW^T \tag{9.12}$$

Net transmitted power is $\sum_{i=1}^{n} |f_i|^2$ and the received signal power is $|\sum_{i=1}^{n} f_i\alpha_{i1}|^2$. Hence for this case, the power allocation problem can be stated as

$$\text{minimize} \sum_{i=1}^{n} |f_i|^2 \tag{9.13}$$

subject to

$$\frac{|\sum_{i=1}^{n} f_i\alpha_{i1}|^2}{P_N} \geq SNR_{min} \tag{9.14}$$

$$|\sum_{i=1}^{n} f_i\alpha_{i1}|^2 \geq SNR_{min} \times P_N \tag{9.15}$$

$$|f_i|^2|\sum_{i=1}^{n} \alpha_{i1}|^2 \geq SNR_{min} \times P_N \tag{9.16}$$

Applying Lagrangian multiplier technique for each node

$$|f_i| = \frac{\alpha_{i1}}{|\sum_{i=1}^{n} \alpha_{i1}|^2} \times \sqrt{SNR_{min} \times P_N} \tag{9.17}$$

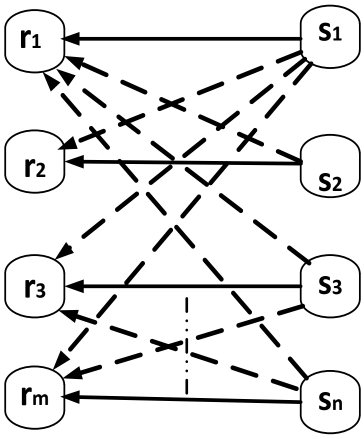

FIGURE 9.5: MIMO linkages

Resulting link cost by the use of cooperation $C_{m-p}(S, r_1)$ defined as the optimal net power is therefore expressed as

$$C_{m-p}(S, r_1) = \bar{P_T} = \frac{1}{\sum\limits_{i=1}^{n} \frac{\alpha_{i1}^2}{SNR_{min} \times P_N}} \tag{9.18}$$

9.3.4 Case IV:

{Multipoint-to-multipoint link} i.e. ($n > 1$, $m > 1$):

In this case, $S_n = \{s_1, s_2, ..., s_n\}$, and $R_m = \{r_1, r_2, ..., r_m\}$ as shown in figure 9.5. This is the MIMO case which helps implement in cooperative reception and transmission of data among group sensors. Here we suppose that all sensors are working in half-duplex mode. This case is a combination of working formulations of cases II and III. In case II, multiple nodes are transmitting thus the link cost in equation (9.4) applies for n transmitters and m receivers. Moreover, the technique of PCA is applicable for a group of v-dimensional data vectors $\{v_t\}$, $t\epsilon\{1, 2, ..., T\}$. Similarly in case III, we considered a single receiver node with $q = 1$, however here the receiving nodes are more than one in distinct dimensions, thus $q < t$ and the equations (9.8) and (9.11) apply for any value of q, and the formulation of factor analysis applies.

9.4 Attenuation, propagation delay and noise in UW channel

Simulation of UWSN communication links requires modeling the acoustic wave propagation in the scenario that a sensor node in UW struggles to forward data to another one. As a signal travels towards a sensor, its energy gets lessened and is distorted by noise. For UWA links, both link separation d and signal frequency f depend on attenuation denoted by $A(d, f)$. Hence, for a generated signal with low bandwidth, focused around frequency f with unit power, the recovered signal has an SNR expressed as $\rho(d, f)$ [15].

For to compute the attenuation and propagation delay for an underwater, we will follow the same model as given in section (3.1), and hence following the equations (3.1) till (3.7).

9.5 SNR in UW acoustic channel

The SNR of an emitted UW signal with unit transmit power $\hat{p}(t)(watts)$ at the receiver is given by section (3.1.3).

Figure 9.6 shows the schematic flow-chart for the SPARCO protocol.

9.6 Outage formulation in UWA channel

When the noise effects follow Gaussian distribution and the UW link remains stable for some time period known as the coherence time; then the capacity of a Gaussian channel having maximum or infinite bandwidth denotes the upper limit on the information broadcasted fruitfully over the channel. Hence according to Shannon-Hartley theorem [65] expresses this by stating that "A communication system has a maximum information transfer rate C known as the channel capacity.

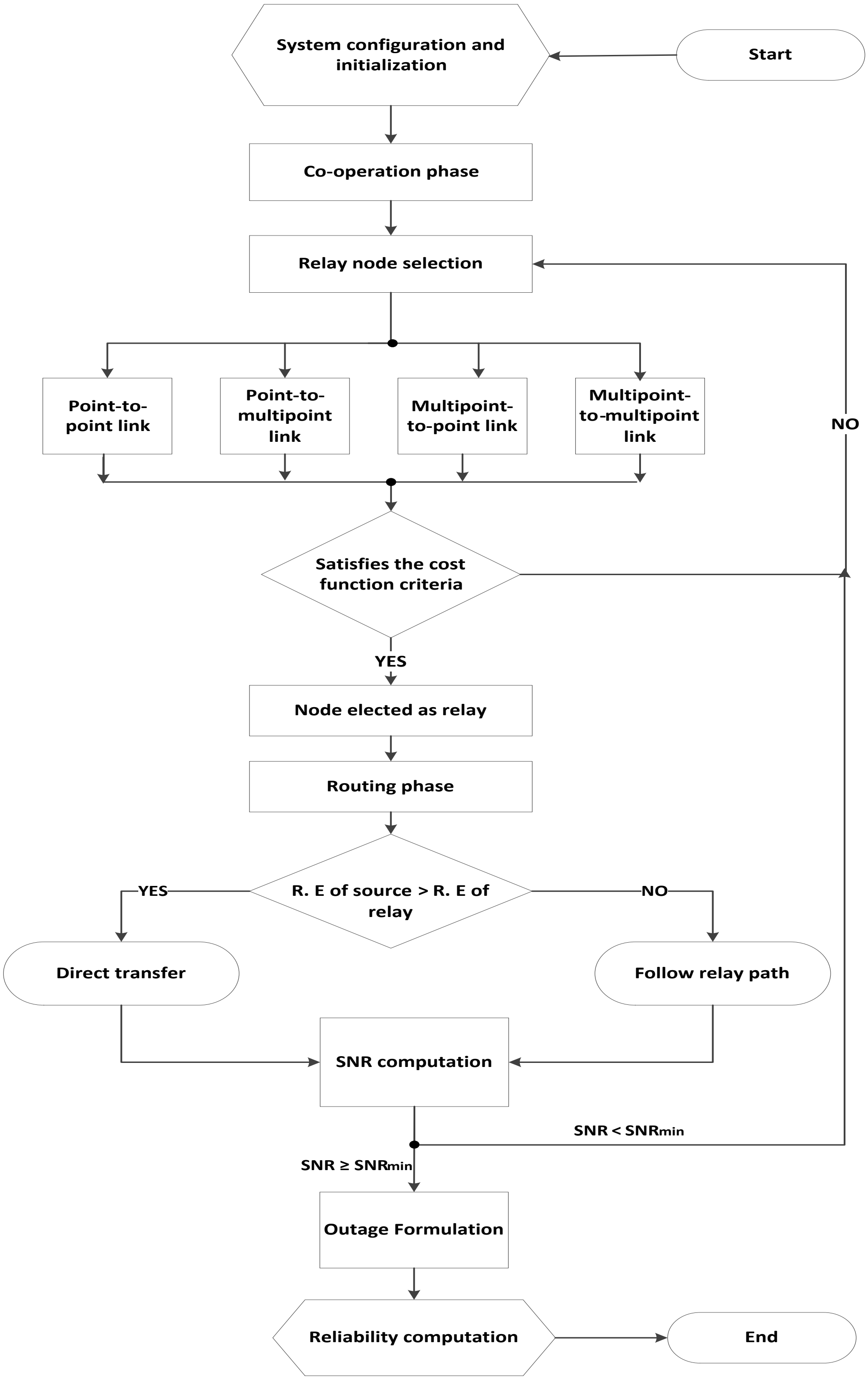

Figure 9.6: Flow-chart of SPARCO protocol

If the information rate R is less than C, then we can expect arbitrarily small error probabilities using intelligent coding techniques. To get minimum error probabilities, the encoder has to work on longer blocks of signal data. This entails longer delays and higher computational requirements." Thus:

$$C(d, \rho) = Blog_2(1 + \rho(d, f)) \tag{9.19}$$

where $C(d, \rho)[bits/sec]$ is the link capacity depending on both distance and frequency, whose expression makes intuitive sense:

1. When the bandwidth of a channel rises, then we can make rapid variations in the information signal, which increases the information rate.

2. When the value of S/N rises, we can raise the rate of information and still avoiding errors due to noise.

3. If noise is absent; S/N approaches ∞ and a maximum information transfer occurs independent of bandwidth.

Hence there is a trade off bandwidth for SNR. However, as $B \to \infty$, channel capacity does not tend to infinity because, with a rise in bandwidth, the power of noise also goes high.

Channel capacity of a Gaussian channel with infinite bandwidth presents an upper limit for on the amount of information being transmitted successfully over a communication path. This can be expressed by the equations (3.12) and (3.13) and this condition is used to assess the quality of incoming signal at the receiver side. In contrast to equation (3.13), outage occurs when the transmission rate R exceeds C, i.e.

An error is said to take place when the channel goes in outage or a decoding error occurs. The probability of error is approximately zero if the channel is not in outage. Therefore, the outage probability P_{outage} is expressed as:

$$P_{outage} = P\{C(d, \rho) < R\} \tag{9.20}$$

$$P_{outage} = P\{Blog_2(1 + \rho(d, f)) < R\} \tag{9.21}$$

$$P_{outage} = P\{\rho(d, f) < 2^{(R/B)} - 1\} \tag{9.22}$$

$$P_{outage} = P\{20log(\frac{\hat{p}(t)}{2\pi H}) - A(d, f) - N(f) < 2^{(R/B)} - 1\} \tag{9.23}$$

$$P_{outage} = P\{log(\frac{\hat{p}(t)}{2\pi H}) < \frac{2^{(R/B)} + A(d, f) + N(f) - 1}{20}\} \tag{9.24}$$

$$P_{outage} = P\{\hat{p}(t) < 2\pi H \times anti - log(\frac{2^{(R/B)} + A(d, f) + N(f) - 1}{20})\} \tag{9.25}$$

Equation (9.25) clearly indicates that the outage probability at any instant is totally dependent on the depth of the ocean and the attenuation and noise factors occurring in ocean currents. In terms of SNR and ignoring the (-1) term, equation (9.25) can be expressed as

$$P_{outage} = P\{\hat{p}(t) < 2\pi H \times exp(\frac{2^{(R/B)} + SL + \rho(d, f)}{20})\} \tag{9.26}$$

9.7 Reliability in UWA channel

With the passage of time and advancement in technology there are lots of methods that are used to avoid the loss of data when the channel is in outages like employing ARQ protocols, obtaining information from the transmitter side channel or coding for a longer period [91]. However, this study concentrates and focuses on the reliability of the link to be obtained through the use of routing by isolating the diversity obtaining issue, and the results can be associated with other diversity techniques. Different links combine to form hops and then these multiple-hop paths make a sequential combination of nodes which pass the information to one another and ultimately lead to the destination D from a source S. That event will be deemed as a successful end-to-end transmission in which all the packets or transmissions are successful and the probability of occurrence of an event is defined as End-to-End Reliability denoted by $\mathfrak{R}$ [75]. Hence, $\mathfrak{R}$ can be written as:

$$\mathfrak{R} = 1 - P_{outage} \tag{9.27}$$

$$\mathfrak{R} = 1 - \{2\pi H \times exp(\frac{2^{(R/B)} + SL + \rho(d,f)}{20})\} \tag{9.28}$$

According to this expression, $\mathfrak{R}$ is a monotonically decreasing function and establishes the result for a point-to-point link. It is dependent on the depth of the water, channel state and the distance between two nodes. The net reliability for the entire end-to-end path can be computed from equation (9.28) as given below:

$$\mathfrak{R} = 1 - \{\sum_{i=1}^{n}(2\pi H_i \times exp(\frac{2^{(R/B)} + SL + \rho(d,f)_i}{20}))\} \tag{9.29}$$

The maximum reliability route is the route that minimizes this sum and the maximum amount of power that can be spent in relaying the information from S to D is limited to the summation of SNR for individual nodes as given in equation (9.18).

9.8 Performance evaluation of SPARCO

Major metrics of performance for all compared protocols are the same as defined in earlier chapters.

9.8.1 Results and discussions

Existing schemes CoDBR, Cog-Coop, iAMCTD and Coop (Re and dth) are used as benchmark to evaluate and analyze SPARCO performance. Nodes are randomly deployed for every simulated technique. Utilizing multiple-sink model of conventional methods having 10 sinks deployed on the water surface, 225 nodes

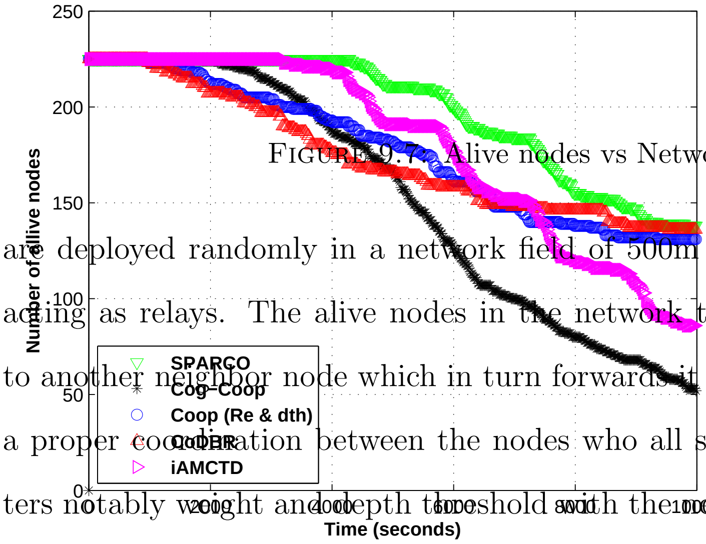

FIGURE 9.7: Alive nodes vs Network lifetime

are deployed randomly in a network field of 500m x 500m with 4 courier nodes acting as relays. The alive nodes in the network transmit threshold-based data to another neighbor node which in turn forwards it to another neighbor. There is a proper coordination between the nodes who all share proper physical parameters notably weight and depth threshold with the neighbor node to keep informed with the fluctuating circumstances of the network. Nodes calculate their distances from their neighbors after fixed intervals. Sensors forward their information to the upper layer using cooperation of neighboring sensors till that information reaches at the sink. The sink supervises the depth thresholds and adaptive mobility of cooperating sensors. The introduction of depth thresholds and cooperation makes SPARCO scheme a feasible application for data-critical situations.

Figure 9.7 shows a comparison of the stability period of SPARCO, CoDBR, iAMCTD, Coop (Re and dth) and Cog-Coop with respect to network lifetime. It is obvious from the figure that due to the reason of maintaining lower path loss and neglecting the unnecessary data forwarding results in higher stability than the other four schemes. The time interval after which the nodes start dying, in the simulations of 10,000 seconds, the initial or first node in case of SPARCO dies at 4290th second which is extended than the other four. This increases the stability duration such that, in CoDBR first nodes dies after 961st second, in iAMCTD it dies after 3185th second, in Cog-Coop after 1857th second, and in Coop (Re and dth) after 961st second. In other words we can say that the instability period starts after around 4300 seconds, after which the end-to-end delay decreases very slowly. Cooperative nodes play an important role in SPARCO, Coop (Re and dth), CoDBR and Cog-Coop by the introduction of cooperation scheme, because these nodes distribute and share the load of data forwarding which results in achievement of load balancing, hence increasing the stability period. Network lifetime of iAMCTD gets increased than CoDBR, having a slow raise in energy utilization. As the network gets light slowly, figure of neighbor nodes falls suddenly in CoDBR which causes the instability in the network. iAMCTD considers two forwarding attributes; depth and residual energy which causes a trade-off between network stability and path-loss. This does not make it suitable for reactive applications. Network stability of iAMCTD is raised in comparison to CoDBR, due to lower throughput by responsive network.

Cooperation between nodes causes load balancing both in SAPRCO and Coop (Re and dth). In our proposed protocol, utility of Thorps energy model identifies the net channel losses, which are quite needful for selection of appropriate data forwarding. The consideration of channel losses is absent in the Co-DBR scheme. Raise in stability period of SPARCO also confirms lowering of redundant transmissions. The stability period of iAMCTD is better than CoDBR and Coop(Re and dth); however, the network energy consumption is greater in CoDBR. In iAMCTD and Coop (Re and dth), the source nodes are transmitting the date to next-hop neighbor nodes only, whereas CoDBR is utilizing source sensor and two relay sensors for broadcasting its packets to the next-hop. In CoDBR, the stability period finishes too suddenly due to prioritization of residual energy in selection of reasonable neighbor nodes, which causes inefficient instability period. Table 9.1 indicates a numerical comparison of all the four compared protocols in terms of alive nodes after equal intervals. The table shows that as the stability periods of

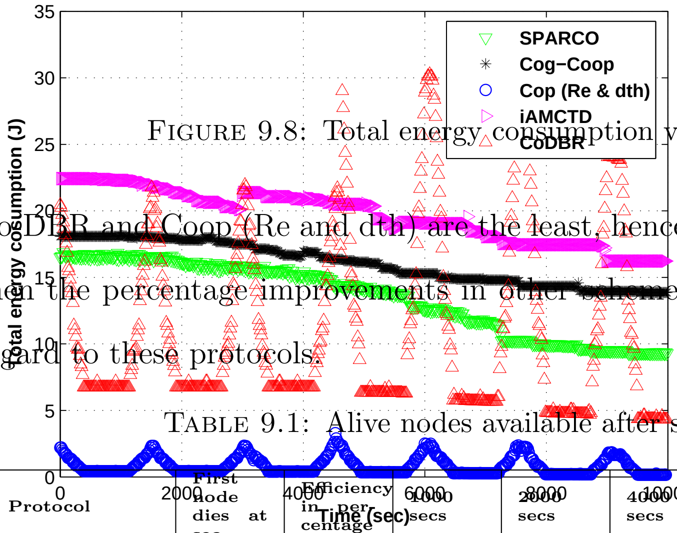

FIGURE 9.8: Total energy consumption vs Network lifetime

CoDBR and Coop (Re and dth) are the least, hence if we keep them as reference, then the percentage improvements in other schemes are shown numerically with regard to these protocols.

TABLE 9.1: Alive nodes available after specified intervals

Protocol	First node dies at sec	Efficiency in percentage	1000 secs	2000 secs	4000 secs	6000 secs	8000 secs	10000 secs
CoDBR	961	100	225	207	176	158	146	136
iAMCTD	3185	331.4	225	225	220	177	120	86
Cog-Coop	1857	193.2	225	225	187	126	80	52
Coop (Re and dth)	961	100	225	213	193	162	138	131
SPARCO	4290	446.4	225	225	225	200	155	138

The figure 9.8 shows the graphical representation of the difference between the energy consumption of iAMCTD (existing non-cooperative schemes), CoDBR and Cog-Coop (existing cooperative schemes) and SPARCO. As the graph shows the energy is much efficiently utilized in SPARCO than the existing schemes due to efficient forwading of data with the help of neighbor nodes and load balancing is ultimately achieved. Other reason for the efficiency is due to the reason that energy consumption is improved with the help of effective weight implementation. As SPARCO‘s main concern is with those application which are time bound, therefore it has to has to be efficient, and for the purpose of which it utilizes cooperation and depth difference between data forwarders in the network to solve the issue of energy consumption.

In iAMCTD, the larger distance between the neighboring nodes makes them consume high energy, while in other existing scheme i.e. CoDBR, the frequent switching to select high energy nodes make them consume higher energy that other existing techniques which make it least efficient. The stability period of Cog-Coop is extended than CoDBR and iAMCTD; however, the network energy consumption is greater in Cog-Coop. The cooperative transmission scheme Cog-Coop is expensing about thrice more energy than CoDBR and iAMCTD. After the nodes start to diminish after 3000 seconds, the net energy utilization gets increasing more sharply. In Cog-Coop and iAMCTD, the source nodes are transmitting the date to next-hop neighbor nodes only, whereas CoDBR is utilizing source sensor and two relay sensors to forward data to the next-hop. In Coop (Re and dth), a sudden raise in network energy consumption is observed during the initial rounds as all sensors get active and perform the routing mechanism. Later on, energy consumption decreases because sensors cannot search for relay sensors due to a major cut in network density. Hence, the possibility of cooperative routing performed by any source sensor gets lowered which in turn suppresses energy consumption. Table 9.2 illustrates a comparison of residual energy left, in percentage, of all the five compared protocols after equal intervals which clearly shows that in SPARCO the value of residual energy drop is the least among the four. The table shows that the maximum residual energy drop is in Cog-Coop and if we consider its drop to be maximum, then the other schemes show improvements in reference to this scheme. The maximum efficiency in percentage is shown by SPARCO whose average drop is 65.2 % in comparison to Cog-Coop which is assumed to be 100%.

PDR is the ratio of data packets received at receiver end to those generated by the source which is the throughput in other words. The comparative analysis of all the four schemes under study based on PDR comparison is illustrated in figure 9.9. As we can see the drop in the PDR in SPARCO is much less as compared

Table 9.2: Residual energy drop in percent after equal intervals

Protocol	**Average efficiency (%)**	**2000 secs**	**4000 secs**	**6000 secs**	**8000 secs**	**10000 secs**
CoDBR	95.6	5.06	11.4	24	36.7	39.87
iAMCTD	88.1	3.65	15.8	22.7	29.12	36.5
Cog-Coop	100	2.65	17.8	25.52	36.35	40
Coop (Re and dth)	72.5	3.2	11.5	17.4	23	33.6
SPARCO	65.2	8	9.2	14.4	19.8	28.37

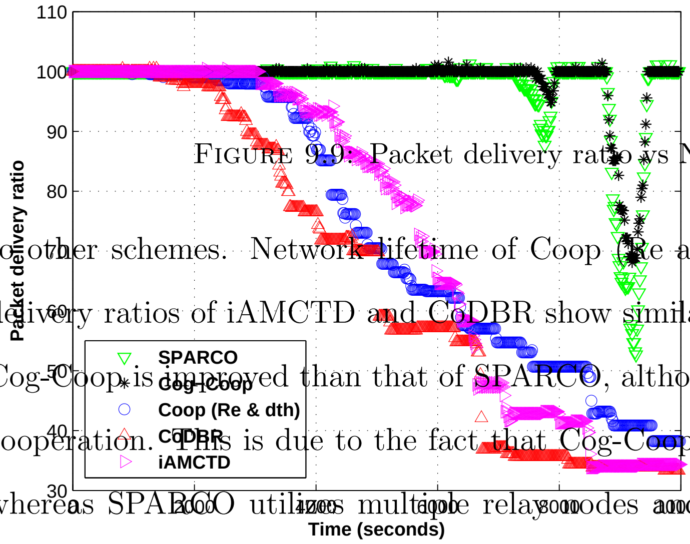

Figure 9.9: Packet delivery ratio vs Network lifetime

to other schemes. Network lifetime of Coop (Re and dth) gets lowered but the delivery ratios of iAMCTD and CoDBR show similar plots. The delivery ratio in Cog-Coop is improved than that of SPARCO, although both schemes are utlizing cooperation. This is due to the fact that Cog-Coop utilizes only two relay nodes whereas SPARCO utilizes multiple relay nodes and considers SNR in the links. Traffic is flooded from the source nodes in case of iAMCTD and CoDBR, when the total time between the source and destination in nodes is small, which ultimately results in lower PDR due to the increase in packet collision.

In SPACRO scheme instead of single path, a number of different multiple paths are used to forward the data and then they are combined at the receiver node. Due to this the data which is sent in packets has higher chance of being successfully transmitted. A larger number of cooperating nodes are available for data forwarding whereas higher reliability can be achieved. On the other hand, other two schemes are lagging behind in the reliability of forwarding packets because in CoDBR, the distant propagation as well as multiple forwarding used results in lower PDR. In iAMCTD, the propagations remain stable due to the fact that both residual energy and depth is considered in the weight function computation which makes it better than CoDBR in term of transmission loss. Coop (Re and dth) scheme shows a similar type of rise-fall behaviour in case of PDR because the scheme does not consider the channel conditions as well as the SNR of the link and the throughput decreases due to quick fall in network density. Table 9.3 shows a numerical comparison of all the five compared protocols in terms of PDR after equal number of intervals. The table also highlights the average efficiency of all the compared schemes in terms of PDR and SPARCO shows an average efficiency of 94%.

TABLE 9.3: Packet delivery ratio after equal intervals

Protocol	**Average efficiency (%)**	**2000 secs**	**4000 secs**	**6000 secs**	**8000 secs**	**10000 secs**
CoDBR	60	0.97	0.76	0.57	0.36	0.34
iAMCTD	66.6	1	0.93	0.65	0.41	0.34
Cog-Coop	92.6	1	1	1	0.95	0.68
Coop (Re and dth)	68.8	1	0.93	0.63	0.5	0.38
SPARCO	94	1	1	1	0.95	0.75

Figure 9.10 further illustrates that the path-loss of the network in CoDBR, Coop (Re and dth), Cog-Coop and iAMCTD is much higher than SPARCO because of prioritizing SNR in its modeling. The plots very clearly indicate that the effective use of relay nodes in SPARCO and iAMCTD outperforms the other three schemes. Distant transmissions are preferred in both Cog-Coop and CoDBR, while on the contrary to the existing schemes, Uricks model and Thorps attenuation model for UWA are utilized in SPARCO and iAMCTD to trace out and measure the total loss in transmission during data transfer between the source and the destination. It takes into account transmission frequency, bandwidth efficiency, and noise

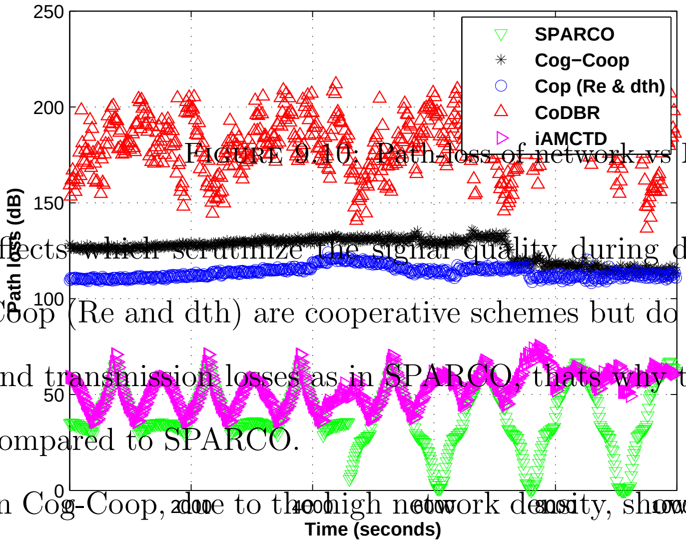

Figure 9.10: Path-loss of network vs Network lifetime

effects which scrutinize the signal quality during data forwarding. CoDBR and Coop (Re and dth) are cooperative schemes but do not consider any noise factors and transmission losses as in SPARCO, thats why their performance is much less compared to SPARCO.

In Cog-Coop, due to the high network density, shows less losses in starting phases of node deployment. As the network scatters, its losses increase which haunts the network performance ultimately resulting in high packet loss during its transmission. In iAMCTD, channel loss conditions are better than CoDBR and Coop (Re and dth), as its cost computation considers both residual energy and depth of forwarding sensors; hence, the propagations remain stable. SPARCO again gives good results than the other schemes as its SNR calculation takes into account both residual energy and depth of the relay sensors as well as the utilization of cooperation scheme; which ultimately results in more stable propagations. In SPARCO, we have utilized Uricks model and Thorps attenuation model for UW environment to calculate the transmission loss in packet forwarding. These models determine the effect of path-loss on transmission frequency, bandwidth efficiency, and noise density during data transmission. Table 9.4 indicates a numerical comparison of

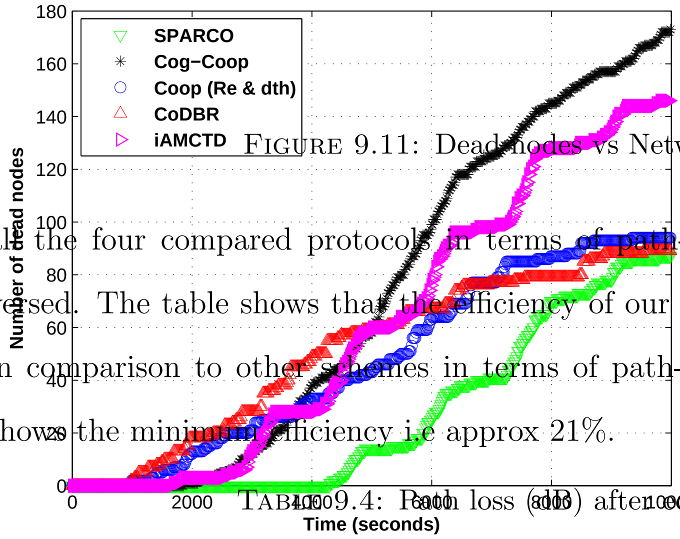

FIGURE 9.11: Dead nodes vs Network lifetime

all the four compared protocols in terms of path-loss after equal intervals traversed. The table shows that the efficiency of our scheme SPARCO is maximum in comparison to other schemes in terms of path-loss and the scheme Co-DBR shows the minimum efficiency i.e approx 21%.

TABLE 9.4: Path loss (dB) after equal intervals

Protocol	**Average efficiency (%)**	**2000 secs**	**4000 secs**	**6000 secs**	**8000 secs**	**10000 secs**
CoDBR	21.4	197	196	196	193	186
iAMCTD	81.4	40	43	58	53	60
Cog-Coop	33.3	129	130	128	119	116
Coop (Re and dth)	36.5	112	119	115	111	110
SPARCO	100	39	43	26	38	61

Figure 9.11 shows a comparison of dead nodes in case of SPARCO with those of CoDBR, Coop (Re and dth), Cog-Coop and iAMCTD. The figure shows the time interval after which the nodes start dying. In the simulations of 10,000 seconds, the initial or first node in SPARCO dies being in operation after 4300th second which is greater than the other four schemes. This increased the stability duration such that, in CoDBR nodes start dying after 970th second, in iAMCTD they start

dying after 1700th second, in Coop (Re and dth) after 1000 seconds and in Cog-Coop the nodes start dying after around 1900 seconds. Cooperative nodes play an important role by the introduction of cooperation scheme in both SPARCO and Coop (Re and dth), because relay nodes distribute and share the load of data forwarding which results in achievement of load balancing, hence increasing the stability period.

TABLE 9.5: Dead nodes available after specified intervals

Protocol	**First node death (sec)**	**Average Effi-ciency (%)**	**1000 secs**	**2000 sec**	**4000 sec**	**6000 sec**	**8000 sec**	**10000 sec**
CoDBR	961	100	2	18	42	55	68	85
iAMCTD	3185	331.4	zero	3	28	78	127	147
Cog-Coop	1857	193.2	zero	1	38	99	145	173
Coop (Re and dth)	961	100	2	13	32	63	87	94
SPARCO	4290	446.4	zero	zero	zero	25	70	87

Due to the fact that in iAMCTD there is a gradual increase in network energy consumption is that its stability period is greater than CoDBR and Coop (Re and dth). The primary reason which causes network instability in CoDBR is that as the network becomes sparse, the number of neighbor nodes decreases quickly. As discussed, there are two forwarding attributes in iAMCTD which are depth and residual energy. This results in the trade-off between path-loss of packets and network lifetime which is not appropriate for reactive applications. During the instability period of iAMCTD and Coop (Re and dth), network slowly gets sparse creating load on high energy nodes, while the number of neighbors is handled by variations in depth threshold. The stability period of Cog-Coop is less than SPARCO because the nodes are consuming three times more energy than SPARCO. Lifetime of SPARCO is increased due to lower throughput by reactive network. In the proposed schemes, Thorps energy models helps to analyze specifically and in detail the channel losses, which is very useful in reactive networks for data forwarding. The redundant transmissions are also reduced due to the increase in stability period. Table 9.5 illustrates the comparative analysis of all the five schemes under study in terms of the total dead nodes after equal intervals

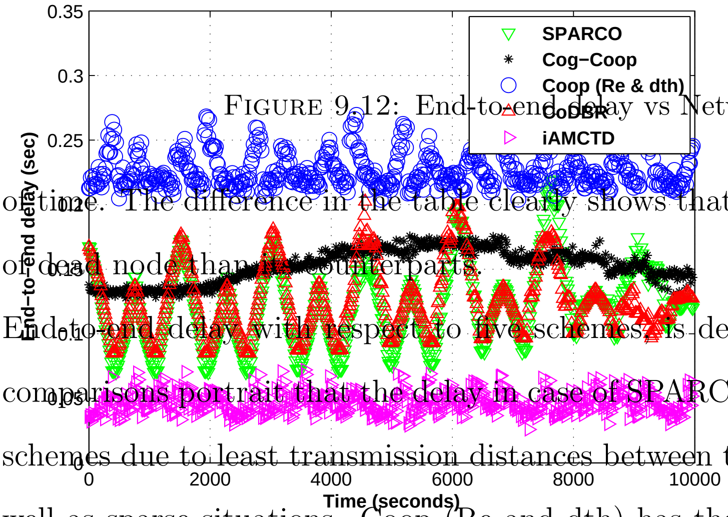

Figure 9.12: End-to-end delay vs Network lifetime

of time. The difference in the table clearly shows that SPARCO has least number of dead node than its counterparts.

End-to-end delay with respect to five schemes, is depicted in figure 9.12. Their comparisons portrait that the delay in case of SPARCO is lower than the previous schemes due to least transmission distances between the sensors in both sparse as well as sparse situations. Coop (Re and dth) has the highest delay compared to other four schemes because it is utilizing relay nodes in every data transfer and also does not consider any losses present in the UW medium. In CoDBR, delay is much higher in the beginning due to distant data transmission. It slowly gets lowered with the sparseness of the network and the network causes data transferring at least distance. In iAMCTD the end-to-end delay is best than the previous schemes due to the load balancing of both threshold variations and weight functions. But in SPARCO, there is a minimum time lag because of the consideration of SNR, difference in depths of sender and receiver sensors and introduction of cooperation. iAMCTD and CoDBR transfer data with least hops, however the attenuated path raises the data loss at receiver, and packets need to be re-forwarded. This intensifies the packet delay. While all the four protocols are focusing on channel estimation, data packets are forwarded with better reliability, resulting in lower redundancy, especially in cooperative schemes Coop (Re and dth), CoDBR and Cog-Coop. The packets, hence, reach the destination with much reduced delay. Table 9.6 indicates a numerical comparison of all the five compared schemes in terms of delay. It also highlights the percentage efficiency of all the compared schemes with the maximum delay achieved by Coop (Re and dth) which is assumed to be 100 % and all other improvements or drops in delays are expressed with reference to it.

Table 9.6: End-to-end delay after equal intervals

Protocol	**Average efficiency (%)**	**2000 secs**	**4000 secs**	**6000 secs**	**8000 secs**	**10000 secs**
CoDBR	50.8	0.08	0.10	0.19	0.10	0.13
iAMCTD	22.9	0.05	0.06	0.05	0.05	0.06
Cog-Coop	63.55	0.13	0.16	0.17	0.15	0.14
Coop (Re and dth)	100	0.24	0.24	0.21	0.24	0.25
SPARCO	45.7	0.07	0.09	0.16	0.1	0.12

Figure 9.13 shows the outage probability of proposed SPARCO scheme with a number of cooperative nodes acting as relays. These plots aid in the design of the system as outage probability is a distinguished QoS factor, and they permit us to find the best figure of cooperating sensors. For this simulation, we set the transmission rate equal to 1 as outage probability is dependent on the transmission rate. The blue line in the figure 9.13 shows the variation in outage probability for direct communication between a source sensor and sink sensor and no relay is utilized. On the other hand, variation of outage probability with that of SNR for a fully cooperative environment is shown by the green line.

The plots in figure 9.13 clearly indicate that for lower values of SNR till 6 dB, there is no major difference in the two plots. However beyond this value, we find a remarkable improvement in outage probability for cooperative or relay communication in contrast to direct communication. This is due to the fact that with the increase in SNR value, more relay nodes take part in data transfers rather than direct communication in order to combat the varying underwater channel losses.

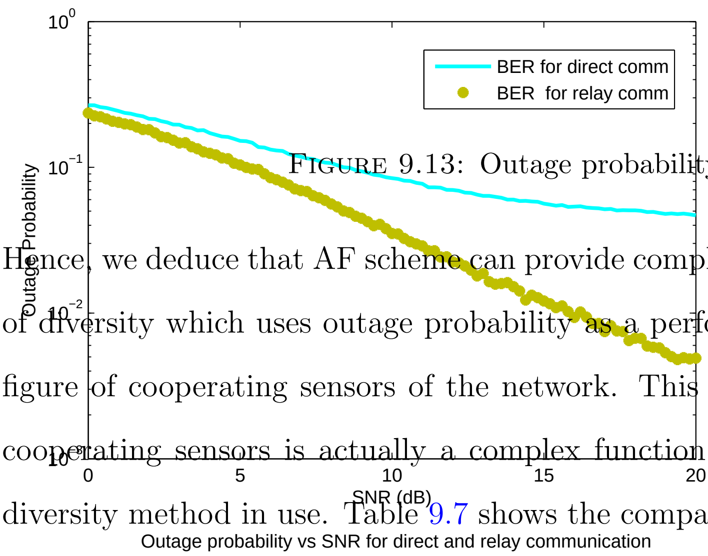

Figure 9.13: Outage probability vs SNR

Hence, we deduce that AF scheme can provide complete diversity so that the order of diversity which uses outage probability as a performance metric, gives the net figure of cooperating sensors of the network. This shows that the best figure of cooperating sensors is actually a complex function of SNR and the cooperative diversity method in use. Table 9.7 shows the comparison of the direct data transfer versus the relay utilized data transfer after equal intervals of SNR. The table clearly shows that probability reduces significantly with SNR raise in case of relay transfer comparative to direct transfer.

Table 9.7: Outage probability for direct versus relay communication after equal intervals of SNR

Type of data transfer	**BER at SNR 0 dB**	**BER at SNR 5 dB**	**BER at SNR 10 dB**	**BER at SNR 15 dB**	**BER at SNR 20 dB**
Direct	0.125	0.067	0.05	0.03	0.28
Relay	0.125	0.05	0.02	0.01	0.004

9.8.2 Performance with trade-offs

In SPARCO, improvement in delay is targeted at the cost of time lag. This end-to-end delay in SPARCO is improved as compared to iAMCTD and CoDBR; but at the cost of possible time lag due to consideration of SNR and cooperation mechanism. In CoDBR, delay is improved at the cost of repeated transmissions. The delay in CoDBR is much higher in initial stages due to distant data forwarding but at the cost of redundant transmissions because the attenuated underwater channel increases packet loss at the receiving end. In AMCTD, delay is improved at the cost of energy depletion. The delay in iAMCTD is better than CoDBR as variations in depth threshold as well as weight functions perform load balancing however at the cost of abrupt energy depletion of the nodes. End-to-end delay in Coop (Re and dth) is improved but at the cost of energy utilization and transmission loss.

In SPARCO, the stability period is improved at the cost of more forwarding nodes and energy consumption. The protocol enhances the network lifetime by avoiding the transmission of useless data and maintaining lower transmission loss however at the cost of utilization of relay nodes and proper selection of relay forwarding nodes. In SPARCO, the instability period starts after 4300 seconds, after which the PDR remains even, however total energy consumption increases slowly. In iAMCTD, the stability period is achieved at the cost of transmission loss. In this protocol, depth and residual energy are the only two forwarding selecting variables used in the scheme. This consideration compromises between the transmission loss of packets and the network lifetime or is a kind of trade-off between them which is not appropriate for reactive application at all. During the instability period of iAMCTD, network slowly becomes sparse creating load on high energy nodes. In CoDBR, the stability period is improved at the cost of greater energy consumption. In Cog-Coop, the stability period improves but at the cost of energy consumption as it utilizes two relay nodes in the data forwarding and also the delay increases as the data has to flow through the relay nodes till the sink is the next hop. In Coop (Re and dth), the stability period is improved at the cost of delay and transmission loss.

In SPARCO, the path-loss reduces at the cost of stability period and the energy consumption as redundant transmissions between sender sensors and sink is raised due to the use of relay nodes. Figure 9.9 illustrates how SPARCO is better than other techniques in terms of medium path-loss because of giving preference to SNR in its computations. In CoDBR, multiple transmissions increase path-loss between sender node and the sink. We utilize Thorps attenuation model for UWA to formulate the transmission loss in packet transferring between a source and destination node through relay. It considers transmission frequency, bandwidth, and noise factors which scrutinize the signal quality during data transmission. Higher throughput in iAMCTD is achieved at the cost of redundant transmissions between nodes and sink. In iAMCTD, channel-losses are better than CoDBR and Cog-Coop, as the cost-function considers both residual energy and depth of transferring sensors; hence, the propagations remain stable. With the passage of time in later stages the qualified forward nodes decrease in number due to which the network experiences the delay in the transmission as far as the packet loss in iAMCTD. In Coop (Re and dth), the path-loss is improved at cost of high delay.

TABLE 9.8: Performance parameters with their trade-offs

Protocol	Advances achieved	Reference	Price to Pay	Reference
SPARCO	Stability period extends	Figs. 9.7, 9.11	More forwarding nodes and energy consumption	Fig. 9.8
	Transmission loss declines	Fig. 9.10	Shorten stability period and energy consumption	Figs. 9.8, 9.11
	Throughput increases	Fig. 9.9	Time lag and energy consumption	Fig. 9.8
	End-to-end delay improves	Fig. 9.12	Transmission loss	Fig. 9.10
CoDBR	Stability period extends	Figs. 9.7, 9.11	Packet delivery ratio	Fig. 9.9
	Transmission loss declines	Fig. 9.10	Redundant transmissions and lesser stability period	Fig. 9.7, 9.11
	Throughput increases	Fig. 9.9	Transmission loss and delay	Figs. 9.10, 9.12
	End-to-end delay improves	Fig. 9.12	Sharp energy depletion	Fig. 9.8
iAMCTD	Stability period extends	Figs. 9.7, 9.11	Extra forwarding nodes and energy consumption	Fig. 9.8
	Transmission loss declines	Fig. 9.10	Packet delivery ratio and delay	Figs. 9.9, 9.12
	Throughput increases	Fig. 9.9	Transmission loss due to distant propagations	Fig. 9.10
	End-to-end delay improves	Fig. 9.12	Transmission loss due to courier nodes	Fig. 9.10
Cog-Coop	Stability period extends	Figs. 9.7, 9.11	Energy consumption due to two nodes relaying and delay	Fig. 9.8
	Transmission loss declines	Fig. 9.10	Redundant transmissions and lesser stability period	Figs. 9.7, 9.11
	Throughput increases	Fig. 9.9	Transmission loss and delay	Figs. 9.9, 9.11
	End-to-end delay improves	Fig. 9.12	Sharp energy depletion	Fig. 9.8
Coop (Re and dth)	Stability period extends	Figs. 9.7, 9.11	Redundant transmissions and packet delivery ratio	Fig. 9.9
	Transmission loss declines	Fig. 9.10	End-to-end delay	Fig. 9.12
	Throughput increases	Fig. 9.9	Transmission loss and greater energy consumption	Fig. 9.8, 9.10
	End-to-end delay improves	Fig. 9.12	Transmission loss due to lag of SNR	Fig. 9.10

In SPARCO, throughput is improved at the cost of time-lag. The drop in PDR in SPARCO is lower than that of other schemes. Higher traffic is sent from a source as the inter-arrival time of data packets gets lowered. This raises the chances of packet collision resulting in a less PDR. SPARCO protocol enhances the probability of successful packet reception by forwarding data on various links and then aggregating at the receiver node. This improvement is achieved at the cost of higher energy consumption of the network as more nodes are involved in the data forwarding mechanism. In CoDBR, transmission loss improved at the cost of low PDR. In this protocol, higher transmission loss is achieved than the other two schemes as it utilizes distant propagations as well as multiple forwarding. iAMCTD achieves improvement in throughput at the cost of packet loss and delay. In iAMCTD, channel loss conditions are better than CoDBR, as the weight function considers depth and residual energy of active nodes, therefore the propagations remain stable. However in later stages, the performance of iAMCTD slowly gets lowered with the decrement in qualified forwarders, therefore both the packet loss and delay increase but at the cost of drop in its throughput. Table 9.8 indicates the various performance parameters which are enhanced on the price which they have to pay, for the five compared protocols.

9.9 Conclusion of the chapter

In this research, we have proposed SPARCO routing scheme to enhance the stability period and reduce the energy consumption of underwater networks. Introduction of cooperation and SNR improves the network lifetime, improves the PDR and reduces the overall network energy consumption; particularly for delay-sensitive applications and also in sparse conditions. The data forwarding protocols without cooperation are focusing on channel conditions that enhance the quality of the received packet at destination, however, transmissions along a single path are influenced as the channel quality varies. The relay selection criteria takes into account instantaneous path conditions and distance among neighbouring nodes to reliably forward packets to a receiver node in a limited environment of UWSN. Features of multi-hop and single-hop communication methods have been considered to lower the path-loss and improve the network stability. Optimal weight calculation and act of cooperation provides load balancing in the network, and gives considerable improvement in the network lifetime.

The next chapter presents a scheme InCo-CEStat for WBANs. This protocol is presented to enhance the performance of existing schemes for WBANs i.e. Co-CEStat and ACo-CEStat. Presented protocol utilizes cooperative transmission to achieve reliable and quick data delivery and greater network stability period. Incremental relay-based cooperation is utilized to improve energy efficiency of the network.

Chapter 10

InCo-CEStat

10.1 Summary of the chapter

This chapter presents InCo-CEStat for WBANs. This protocol is proposed to enhance the performance of Co-CEStat and ACo-CEStat. Proposed protocol utilizes the merits of both direct and cooperative transmission to achieve reliable and quick data delivery and greater network stability period. Incremental relay-based cooperation is utilized to improve energy efficiency of the network. At relays, DF technique is used, whereas, SC technique is utilized at sink. Simulation results are obtained in which proposed protocol is compared with ACo-CEStat and Co-CEStat protocols. Simulations show that InCo-CEStat has 37% and 58 % more stability period than ACo-CEStat and Co-CEStat, respectively. InCo-CEStat also achieved 51% and 79% higher throughput than that of compared protocols.

10.2 Importance of WBANs

Current health care systems: structured and optimized for reacting to crisis and managing illness, are facing new challenges: a rapidly growing population of elderly and rising health care spending. Restructuring health care systems toward proactive managing of wellness rather than illness, and focusing on prevention and early detection of disease emerge as the answers to these problems. Wearable systems for continuous health monitoring are a key technology in helping the transition to more proactive and affordable healthcare.

Wearable health monitoring systems allow an individual to closely monitor changes in her or his vital signs and provide feedback to help maintain an optimal health status. If integrated into a telemedical system, these systems can even alert medical personnel when life-threatening changes occur. In addition, patients can benefit from continuous long-term monitoring as a part of a diagnostic procedure, can achieve optimal maintenance of a chronic condition, or can be supervised during recovery from an acute event or surgical procedure. Long-term health monitoring can capture the diurnal and circadian variations in physiological signals. These variations, for example, are a very good recovery indicator in cardiac patients after myocardial infarction. In addition, long-term monitoring can confirm adherence to treatment guidelines or help monitor effects of drug therapy. Other patients can also benefit from these systems; for example, monitors can be used during physical rehabilitation after hip or knee surgeries, stroke rehabilitation, or brain trauma rehabilitation.

When integrated into a broader telemedical system with patients medical records, WBAN promises a revolution in medical research through data mining of all gathered information. Large amount of collected physiological data will allow quantitative analysis of various conditions and patterns. Researchers will be able to quantify the contribution of each parameter to a given condition and explore synergy between different parameters, if an adequate number of patients is studied in this manner.

10.3 Motivation

Low energy consumption of sensor nodes and reliable and quick delivery of data are of special concerns in WBANs.

Immediate transmission is required in WBANs whenever the sensed information belongs to the emergency class. Direct link between transmitter and receiver is appropriate for such situations. However, in case of normal conditions, energy consumption may be reduced by utilizing multi-hop or cooperative communication. Major objective behind this research is to wisely utilize the merits of both direct and cooperative communication, and to achieve better performance in terms of stability period and throughput of network.

In Co-CEStat, communication links between nodes are considered to be free from noise and fading. However, in reality, transmitted data may be affected by variation of path-loss due to fading and noise present in the communication link. Less

SNR at any particular time, causes more packet drops at sink due to more Bit Error Rate (BER) than maximum allowed BER. Therefore, in ACo-CEStat, fading due to path-loss and AWGN is introduced and BER calculation is done on receiver side. Multiple-relay based cooperation is more reliable than single-relay based cooperation. Therefore, in discussed protocols cooperative nodes are paired as partners and transmit the same data to sink received from respective source node.

Cooperative communication allows the transmitting node to send same data to sink through different links. This strategy decreases the chance of packet drop due to high BER and increases the throughput at the destination.

For a specific relay selection, the relaying strategy can be fixed, selective or incremental. To improve the energy efficiency in ACo-CEStat, incremental relay-based cooperation is implemented in InCo-CEStat which reduces the energy consumption by each cooperative node. System model of InCo-CEStat is explained in sections below.

Furthermore, in many contemporary routing protocol, sensor nodes repeatedly transmit the same data in their respective time slots. This strategy increases the load on network and reduces network lifetime. Therefore, in order to reduce energy consumption of sensor nodes, repeated transmission of same data is avoided unless it is an emergency information.

Links between nodes experience path-loss due to fading or noise in both Line of Sight (LOS) and Non Line of Sight (NLOS) scenarios. Equations, which take into account all these affects, are provided to explain signal propagation. Our derived formulation is mostly dependent on distance between sensor nodes.

10.4 Terminologies used in this chapter

Some major terminologies and performance metrics that are used in this chapter are defined in sections in previous chapters and the rest as below:

- *Dynamic routing:* Type of routing in which route selection is done on the bases of destination and certain changes in condition is called dynamic routing.
- *Heterogeneous network:* A network in which different initial energies are assigned to sensor nodes is called heterogeneous network.
- *Data aggregation:* Intermediate nodes process the raw data received by other nodes and send the aggregated information to the sink.
- *Number of alive nodes:* This measure gives the total number of nodes which still have residual energy to communicate.
- *Advanced nodes:* Sensor nodes which have more initial energy than that of other normal nodes are called advanced nodes.

10.5 InCo-CEStat protocol:

In WBAN protocols, on-body sensor network has great importance in research and this chapter will also concentrate on cooperative communication between sensor nodes and sink attached on the human body.

10.5.1 Preliminaries

Proposed protocol has following properties:

- Every node in the network is fixed and stationary.
- There is only one coordinator (sink) which is fixed at the center of the body and responsible for gathering the data from all sensor nodes. Sink has adequate hardware and software with constant power supply but batteries of sensor nodes are not rechargeable.
- Transmission range and transmission power of each sensor node is fixed.
- Location of all the nodes is initially obtained through some position algorithm.

- The main destination for each sensor node is sink node. Data transmission beyond the sink node is not allowed.
- The size of generated packet by each node is always fixed and each node transmits its generated data in its own time slot.

10.5.2 System model:

Star and star-mesh hybrid topologies are well suited for wearable/on-body sensors. Both schemes exploit the hierarchal nature of WBANs. We implemented mesh topology in our protocol. In this protocol, coordinator limits all nodes to transmit only in their own reserved time slot. Collision avoidance and network coordination is essential to maintain QoS in WBANs. Further, half-duplex communication is assumed, and all the nodes are within the transmission range of each other.

We consider two communication schemes: direct communication and two-relay cooperative communication. Our cooperative transmission is modeled into three orthogonal phases by using Time Division Multiple Access (TDMA).

In this chapter, we consider three phase incremental relay-based cooperation by using two potential relays (R1 and R2) for each source node. In the first phase, the source transmits data to sink, which is overheard by its two potential relays, R1 and R2. If the destination is able to detect the packet correctly in this phase, it sends back an ACK, and relays just remain idle. If NACK is received from sink at source node, it indicates that data packet is dropped due to high BER and data forwarding from R1 is needed.

If R1 successfully detects the data packet in the first phase, it forwards the data packet to the destination (sink) during the second phase. If data packet is received with acceptable BER at the sink, the second phase of cooperation is successfully done. However, if sink fails to detect the packet correctly by R1, R2 is supposed to forward the packet which was correctly received in the first phase, to sink. If the sink again fails to receive the packet from R2 due to high BER, failure of the third phase cooperation occurs as well. It is observed that even if R1 fails to transmit packet correctly in second phase due to more BER, R2 may also forward the packet to sink in third phase such that reducing the energy consumption and also achieving the purpose of cooperation.

Figure 10.1 shows three phase communication between source (S) and sink (D) by using two cooperative relays (R1 and R2).

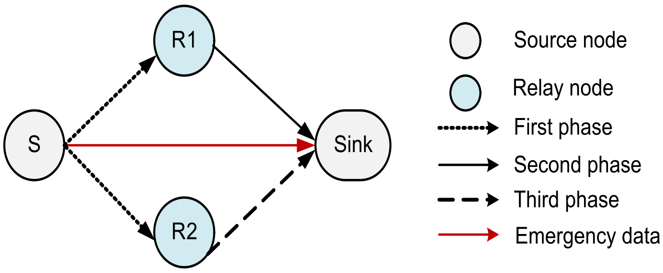

FIGURE 10.1: Cooperative communication model

A heterogeneous network consisting of eight sensor nodes is shown in figure 10.2. There are four normal nodes source nodes (S), four nodes are cooperative nodes (R), and a sink node (D). Cooperative nodes also have their own sensed data to be transmitted along with forwarded data.

All nodes transmit on different links and are independent of each other. TDMA is utilized and channel is accessed by nodes in different time slots.

10.5.2.1 First phase

In the very first phase, S initiates the communication by sending data packet to sink R1, which is also overheard by R2. Direct link between S and D is established in case of emergency or when relay nodes are dead. Distance between relays and source is d_1 and the distance between the relays and destination is d_2.

Generated signal is modulated by BPSK scheme [56]. BPSK is widely used because of its low BER and design simplicity.

For binary 0,

$$S_0(x) = \sqrt{2E_s/T cos(2\pi f_c t)}, \tag{10.1}$$

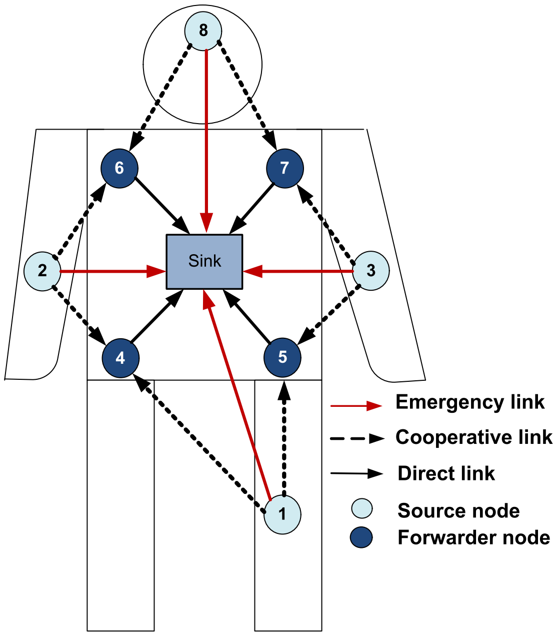

FIGURE 10.2: Deployment of nodes on human body

and for binary 1,

$$S_1(x) = -\sqrt{2E_s/T}cos(2\pi f_c t), \tag{10.2}$$

where fc is the frequency of the carrier-wave and T is symbol period and equals to:

$$T = T_b log_2 M. \tag{10.3}$$

T_b is the bit duration and E_s is average symbol energy and equals to:

$$E_s = 1/M \sum_{i=1}^{M} E_i, \tag{10.4}$$

where, E_i=$E_s = E_b log_2 M$.

E_b is the energy/bit which is the total energy of the signal divided by the total number of bits in signal. M is a number of alternative modulation symbols.

$$E_b = 1/N * d \sum_{n=1}^{N} x^2(n), \tag{10.5}$$

where, n is the index of sample number of a signal and N is the total number of samples.

The information received at sink, R1 and R2 from the source in phase 1 follows the cooperation model of section 3.1.4 and the equations (3.13) and (3.14). Signal in case of WBAN is attenuated mainly by the effects of free-space path loss and fading, and both should be included in h_s. This co-efficient is modeled as a complex Gaussian random variable with zero mean and variance σ^2 expressed as $\mathcal{CN}(0, \sigma^2)$.

$$y_{SR1} = (S_{SR1}.PL_{SR1})x_S + N_{SR1}. \tag{10.6}$$

$$y_{SR2} = (S_{SR2}.PL_{SR2})x_S + N_{SR2}. \tag{10.7}$$

For direct transmission,

$$y_{SD} = (S_{SD}.PL_{SD})x_S + N_{SD}. \tag{10.8}$$

where S_{SR1} and S_{SR2} are fading effects encountered in the transmission from S to R1 and R2, respectively. S_{SD} is the fading effect in the transmission from S to sink. Shadowing or slow fading is a dominant time-varying effect and is mostly related to the body motion.

Similarly, PL_{SR1}, PL_{SR2} and PL_{SD} are the $log - distance$ path losses for transmission from S to R1, R2 and sink, respectively.

Path loss PL is a function of distance d based on the Friis formula in free space[101], and hence these expressions can be formulated as

$$y_{SR1} = [S_{SR1}.PL_{SR1}(d_1)]x_S + N_{SR1} \tag{10.9}$$

$$y_{SR2} = [S_{SR2}.PL_{SR2}(d_1)]x_S + N_{SR2} \tag{10.10}$$

$$y_{SD} = [S_{SD}.PL_{SD}(d_1 + d_2)]x_S + N_{SD} \tag{10.11}$$

In this research, thermal noise, shadowing and path-loss are considered in which path-loss and shadowing (slow fading) are multiplicative while noise is additive by nature. The main sources of noise are interference and electronic components which can be assumed to be additive complex Gaussian noise with mean zero and variance σ^2 i.e. modeled as $\mathcal{CN}$ $(0, \sigma^2)$ [101]. The total noise power is given by $N_0 = 2\sigma^2$. The $log - distance$ path loss model predicts the average path loss for a transmitter-receiver separation based on measured path loss at a reference distance d_0 and path loss exponent n. Path loss in decibel at reference distance d_0 is :

$$PL(d) = PL_{d_0} + 10n.log_{10}\frac{d}{d_0} \tag{10.12}$$

Applying $log - distance$ path loss formula to equations (10.9) to (10.11), we can have,

$$y_{SR1} = [S_{SR1}.(PL_{0SR1} + 10n.log_{10}\frac{d_1}{d_0})]x_S + N_{SR1} \tag{10.13}$$

$$y_{SR2} = [S_{SR2}.(PL_{0SR2} + 10n.log_{10}\frac{d_1}{d_0})]x_S + N_{SR2} \tag{10.14}$$

$$y_{SD} = [S_{SD}.(PL_{0SD} + 10n.log_{10}\frac{d_1 + d_2}{d_0})]x_S + N_{SD} \tag{10.15}$$

n varies from 0.2 to 1.4 for LOS scenarios and from 1.7 to 2.7 for NLOS scenarios; as the distance dependency is stronger in case of NLOS.

10.5.2.2 Second phase and third phase

In second phase, R1 utilizes Detect and Forward method. In this method, relay node detects the data sent by source node and demodulates it. Data with acceptable BER is retransmitted to sink node. In our proposed model, pairing is used in which each two nodes are paired as cooperative partners. This cooperative scheme has an advantage of simplicity and adaptability. Received signal at sink by R1 is,

$$y_{R1D} = [S_{R1D}.(PL_{0R1D} + 10n.log_{10}\frac{d_1}{d_0})]x_S + N_{R1D} \tag{10.16}$$

In case sink fails to receive packet from R1 due to more BER, R2 forwards the data packet in third phase which was correctly received in the first phase.

$$y_{R2D} = [S_{R2D}.(PL_{0R2D} + 10n.log_{10}\frac{d_1}{d_0})]x_S + N_{R2D} \tag{10.17}$$

$$y_{R1D} = h_{R1D}x_S f(y_{SR1}) + N_{R1D}, \tag{10.18}$$

and in terms of shadowing and path loss; similar to those in phase 1 equation can be re-written as:

$$y_{R1D} = [S_{R1D}.PL_{R1D}(d_2)]x_S f(y_{SR1}) + N_{R1D}. \tag{10.19}$$

and in terms of shadowing effects due to environment L_{eRD} and body movements L_{bRD} received signal can be expressed as:

$$y_{R1D} = (L_{eR1D} + L_{bR1D})f(y_{SR1}).[PL_{0R1D} + 10n.log_{10}\frac{d_2}{d_0}]x_S + N_{R1D}. \tag{10.20}$$

where, $f(y_{SR})$ is the function applied on the received signal by the relay. In case sink fails to receive packet from R1 due to more BER, R2 forwards the data packet in third phase which was correctly received in the first phase.

$$y_{R2D} = h_{R2D} x_S f(y_{SR2}) + N_{R2D}, \tag{10.21}$$

and in terms of shadowing and path loss, equation can be re-written as:

$$y_{R2D} = [S_{R2D}.PL_{R2D}(d_2)] x_S f(y_{SR2}) + N_{R2D}. \tag{10.22}$$

and in terms of shadowing effects due to environment L_{eRD} and body movements L_{bRD} received signal can be expressed as:

$$y_{R2D} = (L_{eR2D} + L_{bR2D}) f(y_{SR2}).[PL_{0R2D} + 10n.log_{10}\frac{d_2}{d_0}] x_S + N_{R2D}. \tag{10.23}$$

In this analysis, the amplitude of the received signal is modeled as a Rayleigh distributed and the links are assumed to be independent and modeled as Rayleigh fading. The mean and variance of the amplitude is given by,

$$\mu(x) = \sigma\sqrt{\frac{\pi}{2}}$$

and

$$var(x) = \frac{4-\pi}{2}\sigma^2$$

10.5.2.3 Receiver side

Due to the arrival of multiple signals, special processing is required at the receiver which may lead to particular design requirements. There are three major processing techniques of antenna diversity at receiver end:

- Switching
- Selecting
- Combining

We utilize the switched combining technique through which the signal with acceptable BER is selected at sink node. Selection procedure results in the selection of only one sensor node's signal at the receiver at any particular time. This ensures that a single node connection is maintained as long as possible. Sink will select signal from other relay, if the current relay is unable to transmit the signal with acceptable BER. Switching can then take place on a packet-by-packet basis if BER of received packet is greater than the maximum BER value.
BER is measured by comparing the received bits with the transmitted bits and by calculating the error counts for total number of bits. In our simulation, we consider the BER performance in terms of SNR per bit and uses BPSK modulation. We evaluate BER performance in terms of SNR per bit by considering AWGN and Rayleigh channels.

10.5.3 Probability of error at receiver side

Due to fading and AWGN present in the channel, there is always an offset between transmitted and received data bits. At receiver end, signal from source or relays is detected, demodulated and correlated with possible transmitted signal. Total number of bits in error are calculated and their sum is taken. Calculated BER at receiver is :

$$BER = E_{bits}/T_{bits},$$

where, E_{bits} is the total number of bits that are erroneous and T_{bits} is the total number of transmitted bits.
Receiver simply selects the the signal with largest SNR or lowest BER. Let ρ is the threshold BER that must not be crossed, then,

if we assume threshold ρ to be 0.5.

$$x_d = \begin{cases} x_{R1D} & if x_{R1D} \leq \rho \\ \\ x_{R2D} & if x_{R2D} \leq \rho,\ x_{R1D} \geq \rho \end{cases} \tag{10.24}$$

where, x_{R1D} and x_{R2D} are decision variables at the first and second diversity links and x_d is the decision variable at the output of the diversity selector.

10.6 Routing and communication flow

To make protocol more quick and reliable in case of emergency situations, threshold approach for data transmission is considered. Whenever the sensed value crosses the threshold value, data is immediately sent to sink without utilizing any cooperation or multi-hoping.

Energy efficiency is another major objective to be achieved by WBAN protocol. For this purpose idea of non-continuous transmission is implemented. In case if information is not critical and currently sensed information by any sensor is same as previously transmitted information, then transmission does not occur. Transmission of information only occurs if variation is observed. This strategy saves the energy consumption of the whole network and reduces the communication load. In our protocol, eight sensor nodes are deployed on the human body, among which four nodes have more initial energy than other three nodes. Data generation rate for each node in each round is 10,000 bits. Source nodes simultaneously transmit data on two different links to avoid information loss. Node 1, 2, 3 and 4 forward their normal sensed data to sink through their corresponding cooperative nodes. Node 4, 5, 6 and 7 are cooperative nodes which collect and forward data of normal source nodes to the sink after aggregation.

Nodes choose less distant node as forwarder which also reduces the energy consumption of network. Energy consumption to transmit data from a node i to another node j is proportional to distance d_{ij}^n between two nodes. n is the path loss exponent and depends on the transmission environment. Transmission energy consumption depends on whether the node directly transmits data to sink or transmit cooperatively using neighbouring nodes as relays.

Coordinates of sensor nodes deployed on human body are shown in table 10.1.

TABLE 10.1: Sensor nodes' deployment on human body

Node no.	x coordinate(m)	y coordinate(m)
1	0.4	1.5
2	0.6	1.2
3	0.2	1.2
4	0.7	0.8
5	0.1	0.8
Sink	0.5	0.5
6	0.7	0.3
7	0.1	0.3
8	0.5	1.6

10.7 Energy model

A first order energy model for WSN is proposed in [57]. Energy required for sensing is much less than the energy required for communication between nodes. This model considers the energy loss due to communication between nodes at distance d. Nodes consume energy during transmission and reception in order to process L number of bits. Energy consumption by transmitter and receiver is given below. Transmission energy of sensor node at distance, d $>d_o$ is ,

$$E_{tx}(L,d) = E_{elec} * L + L * (e_{amp} * d^n), \tag{10.25}$$

whereas, transmission energy for intermediate node is,

$$E_{tx}(L,d) = ((E_{elec} + EDA) * L) + (e_{amp} * L * d^n). \tag{10.26}$$

For d $<d_o$ is,

$$E_{tx}(L,d) = E_{elec} * L + L * (e_{fs} * d^n), \tag{10.27}$$

and for intermediate node,

$$E_{tx}(L,d) = ((E_{elec} + EDA) * L) + (e_{fs} * L * d^n). \tag{10.28}$$

.

Equation for reception energy of all sensor nodes is:

$$E_{rx}(L) = E_{elec} * L. \tag{10.29}$$

In above equations, E_{tx} and E_{rx} are the energies consumed by nodes to transmit and receive L bits over the transmission distance d, respectively.

E_{elec} is the parameter that accounts for per bit energy consumed by circuitry of transmitter and receiver. n is the path loss exponent and d_o is the reference distance. e_{amp} and e_{fs} are characteristics of transmitter amplifier. Whereas, EDA is the energy consumed in data aggregation by intermediate or forwarder nodes. Used values for these parameters are given in table II.

10.8 Simulation results and discussions

In this section, MATLAB simulation results are shown. Our proposed InCo-CEStat protocol is compared with our previously designed routing protocol Co-CEStat. Initial total energy and number of nodes for both protocol is same. Performance parameters that are compared are : throughput, stability period and lifetime of the network. Values used for simulation are presented in table 10.2. Results are averaged over five independent runs and each run performs 5000 rounds of monitoring.

TABLE 10.2: Simulation parameters

Parameter	Value
Number of nodes	8
Number of sink	1
Initial energy	Forwarder node: 0.3 J Source node: 0.1 J
Data generation rate	10,000 bits
E_{elec}	50 nJ/bit
e_{fs}	10 pJ/bit/m^2
e_{amp}	0.0013 pJ/bit/m^4

10.8.1 Stability period

Incremental relaying in InCo-CEStat, reduces the energy consumption of cooperative nodes. Paired cooperative partner only transmit data to sink if the first partner fails to send packet correctly to sink. Also the data aggregation energy of R2 is preserved in case of successful transmission by R1. Reduce energy consumption of nodes causes more residual energy per round, thereby, increasing network lifetime. Figure 10.3 shows the network lifetime comparison of InCo-CEStat with ACo-CEStat and Co-CEStat.

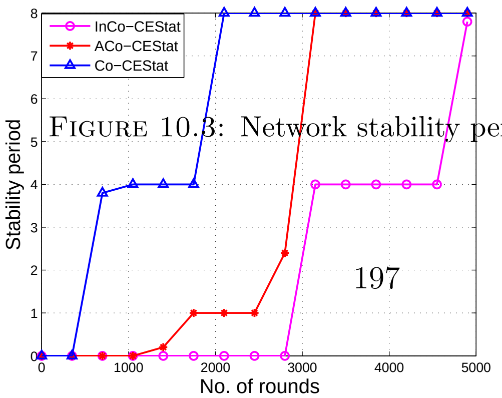

FIGURE 10.3: Network stability period comparison

Balanced load and energy distribution in InCo-CEStat enhance the stability region; whereas, in ACo-CEStat and Co-CEStat, both cooperative partner transmit the same data packet to sink which causes extra energy to be consumed in redundant transmission. Broadcast transmission by normal source node reduces transmission energy, thereby, extending node's lifetime. It is obvious from the figure 10.3 that stability period of ACo-CEStat and Co-CEStat is around 1000 and 400 rounds, whereas, InCo-CEStat proves to be more promising with stability period around 2800 rounds.

10.8.2 Network lifetime

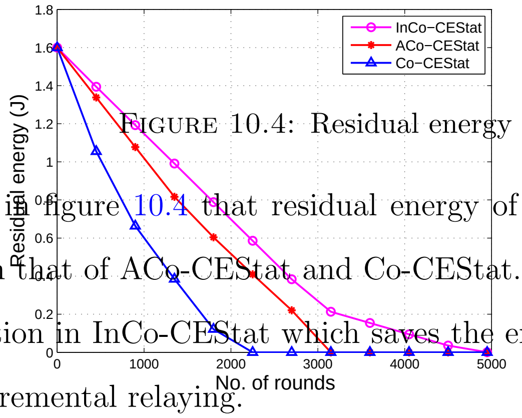

FIGURE 10.4: Residual energy comparison

It is shown in figure 10.4 that residual energy of InCo-CEStat in each round is greater than that of ACo-CEStat and Co-CEStat. This is because of cooperative communication in InCo-CEStat which saves the energy consumption of nodes by utilizing incremental relaying.

10.8.3 Throughput

Greater network lifetime tends to greater end-to-end throughput.It is shown in figure 10.5 that over all network throughput achieved by InCo-CEStat is also more than that of compared protocols. Co-CEStat uses random uniform model of packet drop in which probability of packet drop is fixed to 0.4. Whereas, in

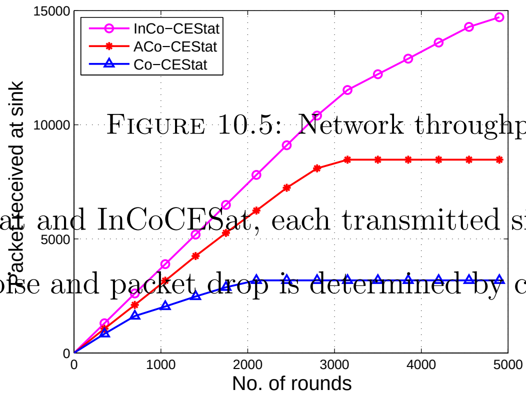

FIGURE 10.5: Network throughput comparison

ACo-CEStat and InCoCESat, each transmitted signal is effected by fading, path-loss and noise and packet drop is determined by certain constraint on BER target level.

10.8.4 End-to-end delay

There is always a trade-off between network throughput and overall propagation delay. Our proposed protocol achieves the higher throughput on the cost of greater propagation delay. Link redundancy enhances successful reception of packets, thereby, increasing the end-to-end delay. Figure 10.6 shows the average delay of all three protocols. Co-CEStat has the lowest average delay per round than ACo-CEStat and InCo-CEStat. This is due to the assumption of noiseless channel and no BER calculation at relays in Co-CEStat. Incremental cooperative relaying in InCo-CEStat increases network reliability by reducing packet error rate. This incremental relaying also introduces more delay in data transmission. Delay reduces gradually for all three protocols due to death of cooperative nodes and increase in direct transmission.

Table 10.3 shows a performance comparison of the InCo-CEStat protocol with those of Co-CEStat and ACo-CEStat schemes.

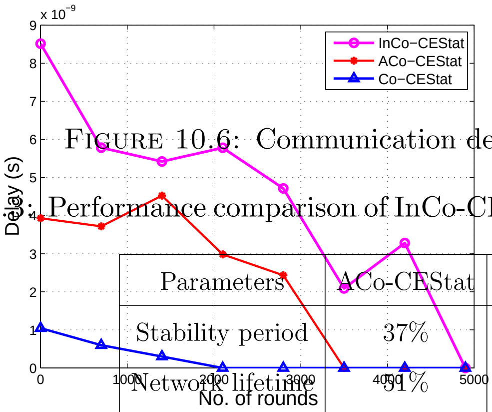

Figure 10.6: Communication delay comparison

Table 10.5: Performance comparison of InCo-CEStat with compared protocols

Parameters	ACo-CEStat	Co-CEStat
Stability period	37%	58%
Network lifetime	91%	79%
Throughput	43%	79%
Delay	-25%	-83%

10.9 Conclusion of the chapter

The main objective of this research is to utilize the cooperative communication to improve the BER in the presence of AWGN and fading channel. Performance of a data link for wireless system is determined by BER and SNR. In simulations, controlled amount of noise and fading is added to the generated signal. At receiver side, signal is recovered and compared with the transmitted signal. Protocol focuses on optimal transmission of a single message from a source node to the destination node through cooperating relay. This cooperative transmission improves the number of successful packets received at the sink and improves the energy efficiency of network.

In the next chapter, we propose a cooperative routing protocol Co-LAEEBA which is a successor of LAEEBA protocol. We compare its working with LAEEBA and other BAN protocols M-ATTEMPT and SIMPLE. The suggested cooperative routing model, promises better throughput with least energy consumption with the introduction of the cooperation at the node level and then implementing the shortest path route algorithm. Certain losses are also considered in this model, the most important being shadowing or slow-fading, path-loss and cumulative noise effects.

Chapter 11

Co-LAEEBA

11.1 Summary of the chapter

WSNs and, particularly WBANs are the key building blocks of upcoming generation networks. Modern health care system is one of the most popular WBAN application and a hot area of research in subject to present work. In recent years, research has focused on channel modeling, energy conservation and design of efficient MAC schemes. Less attention has been paid to the path-loss performance analysis. In this work, we propose two schemes LAEEBA and Co-LAEEBA which are reliable, path-loss efficient and high throughput routing protocols for WBANs. Characteristics of single-hop and multi-hop communication have been utilized to reduce path-loss effects and increase network lifetime. Separate cost functions are proposed in both schemes to select the forwarding node on the basis of high residual energy and minimum distance to sink. Residual energy parameter balances the energy consumption among the sensor nodes while distance parameter ensures successful packet delivery to sink. Results show better performance of LAEEBA comparative to its given variants. Cooperative routing is a promising technique to mitigate the effect of fading. It exploits the broadcast nature of wireless medium and transmits cooperatively using sensor nodes as relays. Co-operative routing is introduced in the functionality of LAEEBA protocol to improve its performance. Simulation results show that LAEEBA and Co-LAEEBA schemes maximize the network stability period and network life-time in comparison to SIMPLE and M-ATTEMPT protocols for WBAN. This contributes to sufficient decrease in path-losses occurring in the links connecting sensors on a human body and hence transferring of data with much lower noise.

11.2 Motivation

As the aging population increases, the number of persons who need medical care or nursing is growing rapidly. Hence, the working load for the medical doctors and nurses becomes heavier and heavier. Applying Medical Information and Communication Technology (MICT)to medical and health-care services is one approach to improve the above situation and provide a high quality medical support [57]. Main roles of MICT include the following aspects [57]:

1. Network formation with high security and reliability for data delivery.

2. Collection and transmission of various medical and health-care from vital sensors.

3. Ranging and positioning of sensors to find location of objectives wireless technology.

WBANs are used to monitor human health with limited energy resources. Different path aware and energy efficient routing protocols have been devised to forward data from body sensors to medical server. It is important that data sensed by nodes on a human body be reliably received to a medical specialist for further analysis. In [72] authors have presented an opportunistic protocol which facilitates mobility at cost of low throughput and additional hardware cost of relay node. They have deployed sink at wrist. In this scheme, as the sink node goes away from transmission range of neighboring nodes, it takes the support of a relay node for the collection of data from other nodes. Whenever the patient moves his hands, the wireless link of sink with sensors disconnects. Link failure consumes more power of sensor plus nodes; also more packets will drop causing the critical data to loss.

In [69] and [70], the authors have tried to devise energy efficient protocols but no attention was paid to the path-loss taking place in the link connecting the sensors among themselves as well as the sink. To enhance the features of such an environment, we have proposed a new scheme, which not only minimizes the path loss of the sink but also contributes to high throughput.

In most applications of WSN, the network consists of battery-powered nodes. Due to low transmit power, these nodes have limited communication range. Thus, cooperative communication, in which nodes share their resources to facilitate each other, is essential for these networks. Replacement of long and weaker links with short and stronger links may lower the burden on the link. Alternative routes between the source nodes and the base-station provide robustness against shadowing and multi-path fading, and introduce new design options for routing. Reliable and quick transmission of data with reduced energy consumption by each sensor node, is of extreme significance. Major applications of WBANs require immediate response whenever the sensed information belongs to emergency data and direct transmission is the appropriate option.

In LAEEBA protocol, we propose a mechanism to route data in WBAN with minimum path-loss over the link. The proposed scheme uses a cost function to select the most appropriate route to sink. In order to increase the achieved throughput by LAEEBA, cooperative routing is introduced in it, utilizing multiple links. Links between nodes experience path-loss, shadowing, fading and noise effects. Considering both Line-of-Sight (LoS) and Non-Line-of-Sight (NLoS) scenarios, we want to have a detailed mathematical model which takes into account all these effects and provide us with an energy efficient protocol for WBAN.

11.3 LAEEBA: The first proposed protocol

In this section, we present a routing protocol for WBANs. The limited number of nodes in a WBAN environment gives us an opportunity to relax constraints in routing protocols. Considering these constrains in mind, we have tried to improve the network life-time of the network; energy of the network as well as the path loss of the link being established between the nodes.

The path selection is done in such a way that a path with minimum number of hops for data transmission is selected; direct communication is chosen for emergency data and multi hop is chosen for normal data delivery. Thus, relay nodes can easily forward the received data to sink due to higher energy levels. For validating the performance of the protocol we have compared LAEEBA protocol with routing schemes SIMPLE and M-ATTEMPT for BAN technology. Next subsections give detail of the system model and detail of LAEEBA protocol.

11.3.1 System model

In our proposed model, sink is placed at center of the human body. Since WBANs are heterogeneous networks, then placement of nodes on human body is an issue. Eight sensor nodes are deployed on a human body; having equal power and computation capabilities. Sink node is placed at waist as shown in figure 11.1. Node 1 is the sensor for detecting ECG while node 2 is the sensor for detecting glucose. These two nodes transmit data directly to sink. Rests of the nodes are transmitting data to the sink through other nodes acting as relay. The following table 11.1 indicates the various parameters set for the purpose of simulation. Figure 11.2 shows the flow-chart for the proposed LAEEBA protocol.

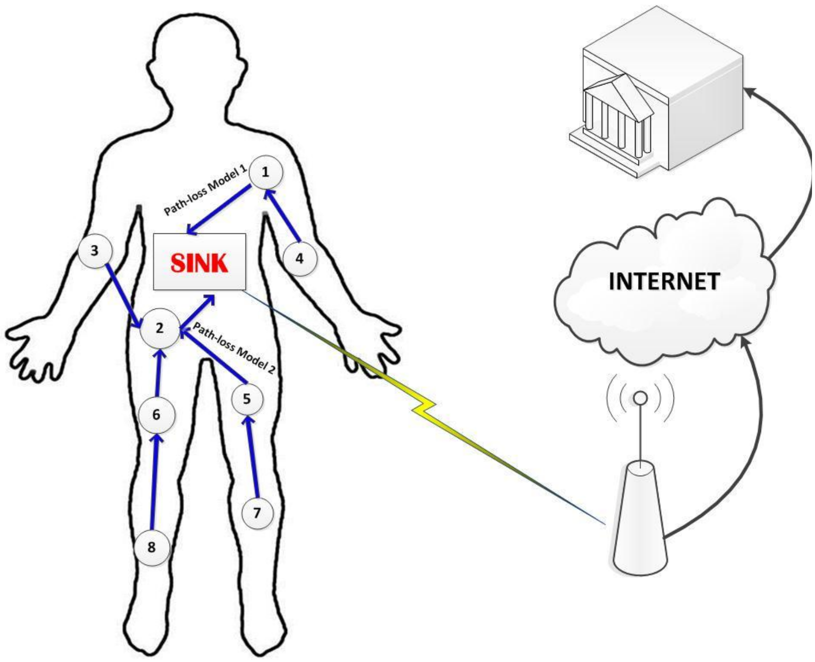

FIGURE 11.1: Schematic for LAEEBA protocol

Table 11.1: Parameters for simulation

Parameters	Values
DC Current (Rx)	18 mA
DC Current (Tx)	10.5 mA
Minimum Supply Voltage	1.9 V
Receiving Energy ($E_{Rx} - elec$)	36.1 nJ/bit
Transmitting Energy ($E_{Tx} - elec$)	16.7 nJ/bit
Transmit Amplifier Energy (E_{amp})	1.97 nJ/bit
Data Aggregation Energy (E_{DA})	5 nJ/bit
Wavelength (λ)	0.125 m
Frequency (f)	2.4 GHz
Initial Energy (E_o)	0.5 J

11.3.2 Initialization phase

Three different types of tasks are performed in this phase; first each node is informed with its neighbors, the location of sink on the body is identified and all the possible routes to sink are also evaluated. The sensors update the location of their neighbors and sink when each node broadcasts an information packet containing its node ID, its own location and its energy status.

11.3.3 Next-hop selection phase

In this section, we present selection criteria for a node to become parent node or forwarder. To balance energy consumption among sensor nodes and to trim down energy consumption of network, LAEEBA protocol elects new forwarder in each round. The sink node knows the ID, distance and residual energy status of all its constituent nodes. It computes the cost function of all nodes and transmits this value to all members. On its basis, each node decides whether to become a forwarder node or not. The cost function c_i of an i^{th} node is computed as follows:

$$c_i = \frac{\sqrt{d(i)}}{E(i)} \tag{11.1}$$

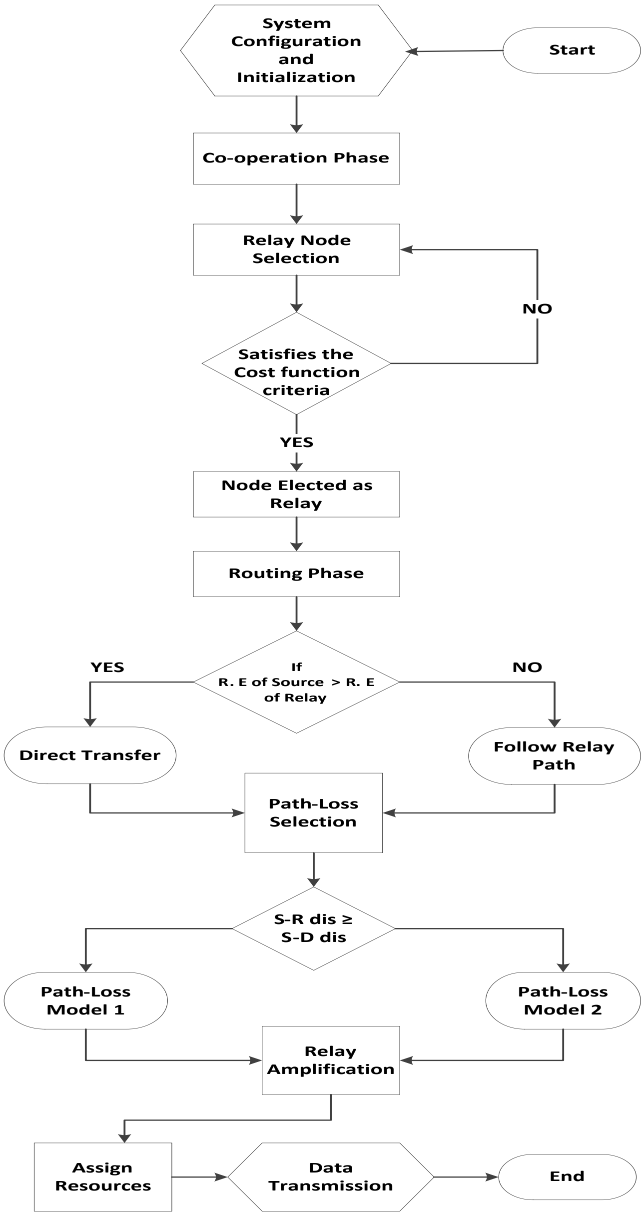

FIGURE 11.2: Flow-chart for LAEEBA protocol

where $d(i)$ is the distance between the node i and sink, $E(i)$ is the residual energy of node i and is calculated by subtracting the current energy of node from its initial energy. A node with minimum cost function is preferred as a forwarder. All the neighbor nodes then stick to the forwarder node and transmit their data to it. Forwarder node aggregates data and transfers to sink. This node has maximum residual energy and minimum distance to sink; therefore, it consumes minimum energy to forward data to sink. Nodes like 1 and 2 used for ECG and Glucose monitoring communicate direct to sink and do not participate in forwarding data.

11.3.4 Routing phase

Next-hop selection phase is followed by the routing phase. In this phase, such routes are selected which are at fewer hops to sink. As the nodes have information of all nodes and sink location, so selected routes are steady fast and consume less energy. In critical scenarios, all processes are lagged until critical data is successfully received by sink node. In case of emergency, all the implanted nodes on the body can communicate directly with the base station. In direct communication, delay is much lower as compared to multi-hop communication, because in multi-hop communication, each intermediate node receives, processes and then sends data to next node. This causes delay and it is considerably increased due to congestion and becomes unacceptable in some critical scenarios. So, single-hop communication is used to minimize this delay.
Energy consumed in single-hop communication is:

$$E_{S-HOP} = E_{tx} \tag{11.2}$$

where E_{tx} is the transmission energy and can be computed as:

$$E_{tx} = b \times (E_{elec} + E_{amp} \times d^2) \tag{11.3}$$

where E_{amp} is the energy needed for transmit amplifier upto a distance of d and packet size b. It is assumed that $E_{rx} = E_{tx}$, E_{rx} being the energy required for reception. The energy consumption due to multi-hop communication is:

$$E_{M-HOP} = n \times b \times E_{tx} + (n-1) \times b \times (E_{rx} + E_{DA}) \tag{11.4}$$

where E_{DA} is the energy consumption for data aggregation and n is the number of hops. There are n transmitters and n receivers in total and the source node does not consume reception energy. Equation (11.5) calculates the energy consumption cost for multi-hop case which depends on the number of transmissions and receptions rather than the number of transmitters and receivers. Thus, we have n transmissions and $n-1$ receptions in equation (11.5).

11.3.5 Path-loss selection phase

Human body is partially conductive by nature, and certain substances having varying thickness, characteristics of impedance and dielectric constants are embodied in it. High losses may occur in response to the communication protocol adopted for nodes, in subject to the operating frequency band. Many standards are in use for communication in WBANs, at present like Bluetooth, ZigBee, MICS etc. When devices communicate, losses between them cause degradation in the performance of monitoring system.

Path loss includes all the consequences linked with distance and interaction of the propagating wave with physical objects in the environment between transmitter and receiver. Hence, it is the reduction in power density of an electromagnetic wave. In case of WBANs, path loss depends on distance and frequency.

In this mode, either of the two path loss models will be followed when the nodes are in the process of transferring their data either to the sink or to the relay nodes. This selection will particularly depend on the distance between the two nodes communicating. A certain threshold value α will be computed which will be the distance of transmitting node n1 from sink S and it will be denoted by d1. Now if n1 wants to transfer its data to another relay node n2, it will compute the distance from it given as d2.

If $d1 \geq d2$, the nodes will follow the path loss model $PL(d, f)$ given by [89]

$$PL(d, f)[dB] = a \times log_{10}(d) + b \times log_{10}(f) + N_{d,f} \tag{11.5}$$

To obtain the values of the co-efficients a, b and $N_{d,f}$, LMS algorithm was used and its values were computed as $a = (-)27.6, b = (-)46.5$, and $N_{d,f} = 157$.
If $d2 \geq d1$, the nodes will follow the path loss model given by [89]

$$PL(d, f)[dB] = PL_o + 10nlog_{10}(\frac{d_2}{d_o}) + \sigma \quad (11.6)$$

where PL_o is computed as follows:

$$PL_o = 10log_{10}(4\pi.df)^2 \times c \quad (11.7)$$

where d_o is the reference distance selected as $10cm$. n is the path loss co-efficient and its value varies from 3 to 4 for LoS communication and 5 to 7.4 for NLoS communication. σ is the standard deviation, f the operating frequency, and c is the speed of light.

11.4 Co-LAEEBA: The second proposed protocol

In Co-LAEEBA, the path selection is done in such a way that a path with minimum number of hops is selected for data transmission. Direct communication is done for emergency data and multi hop for normal data delivery. Relay nodes can easily forward the received data to sink due to higher energy levels. We analyze our protocol in terms of path loss and network life-time. For checking the improvement of the protocol we have compared our Co-LAEEBA protocol with the existing WBAN routing protocols LAEEBA, SIMPLE and M-ATTEMPT. Next subsections give detail of the system model of Co-LAEEBA protocol.

11.4.1 Network topology

In Co-LAEEBA, sink is placed at center of the human body. Eight sensor nodes are attached on the human body. Sink is responsible for collecting and forwarding data of all sensor nodes to external server. Coordinates of sensor nodes which are deployed on human body are shown in table 11.2. Network is heterogeneous as there are two types of nodes: advanced nodes and normal nodes. Advanced nodes have more initial energy than those of normal nodes. In figure 11.3, nodes 1, 4, 5, 7 and 8 are normal, whereas 2, 3, and 6 are advanced nodes. Normal source nodes transmit data simultaneously on two links through cooperation to avoid information loss. Whenever, the sensed data is of emergency nature or cooperative nodes are dead, normal nodes will transfer direct data to the sink. In case, the data is normal and different from previously sensed value, cooperative nodes will use single-hop communication, and normal nodes will follow cooperative routing. Nodes 1, 4, 5, 7 and 8 are forwarding their normal data to sink through their corresponding cooperative nodes. Nodes 2, 3, and 6 are cooperative nodes which collect and forward data of normal nodes to sink.

In LAEEBA, forwarder node is selected on the basis of residual energy, whereas in Co-LAEEBA, relays nodes are utilized to do cooperation which allows source nodes to utilize more than one link at a time.

TABLE 11.2: Sensor nodes' deployment on human body

Node no.	x coordinate(ft)	y coordinate(ft)
1	0.4	1.5
2	0.6	1.2
3	0.2	1.2
4	0.7	0.8
5	0.1	0.8
6	0.5	0.5
7	0.2	0.5
8	0.2	0.2

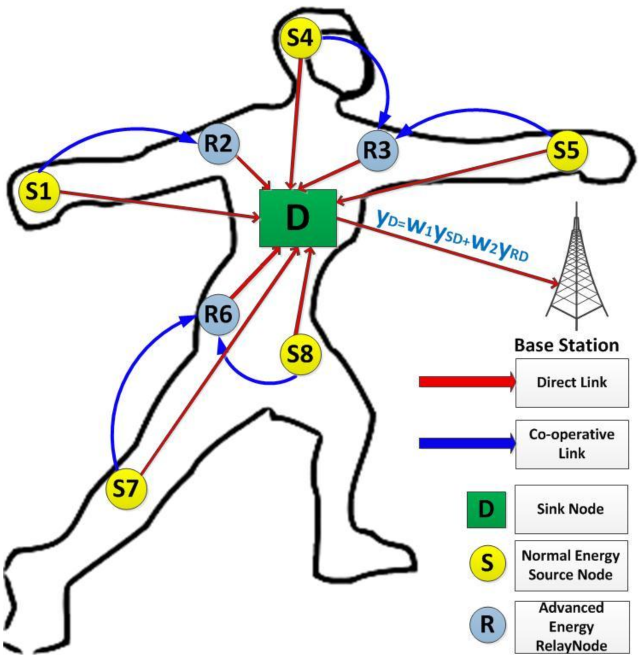

FIGURE 11.3: Nodes' deployment on human body

11.4.2 Basic assumptions

Co-LAEEBA is cooperation based protocol in which three advanced nodes act as cooperative nodes. Normal nodes are allowed to forward packets to cooperating nodes in each round. Incoming and outgoing flow for each node must be equal and satisfy the flow network restriction, except for a source node having more outgoing flow, and for sink having more incoming flow. A link between a cooperative node and sink is of high capacity as each source node forwards its own generated data along with that of the neighboring nodes. Data generation rate for each node in each round is set to be 4000 bits.

11.4.3 Initialization phase

This phase is similar to that of LAEEBA protocol and same three different types of tasks are performed in this phase.

11.4.4 Cooperation phase

A two-phase transmit scheme is considered which allows a non-overlapping transmission for source node and relay node. A single source-destination pair is considered which are separated by some distance. The whole process of cooperation is done in two phases as shown in section 3.1.4 and follows the same equations as given in (3.9) and (3.10).

Direct transmission between the source and sink in WBAN encounters deep fading and strong shadowing that leads to outage or failure of a link. Signal is attenuated mainly by the effects of free-space path loss and fading. Therefore both should be taken into consideration. The signal received at D from source S and relay R can then be modeled in terms of path-loss in dB as a function of distance according to Friss formula for free space, as given below

$$y_{SR} = [S_{SR}.(PL_{0SR} + 10n.log_{10}\frac{d_1}{d_0})]x_S + N_{SR} \tag{11.8}$$

$$y_{SD} = [S_{SD}.(PL_{0SD} + 10n.log_{10}\frac{d_1 + d_2}{d_0})]x_S + N_{SD} \tag{11.9}$$

In this research, thermal noise, shadowing and path-loss are considered in which path-loss i.e. PL_{0SR} and PL_{0SD} and shadowing (slow fading) i.e. S_{SR} and S_{SD} are multiplicative while noise is additive by nature. The main sources of noise are interference and electronic components which are complex Gaussian with mean zero and variance σ^2 i.e. modeled as $\mathcal{CN}(0, \sigma^2)$ [57]. The total noise power is given by $N = 2\sigma^2$. PL_0 is the free-space path-loss in dB.

Figure 11.4 below shows the flow-chart for the proposed Co-LAEEBA protocol. The $log-distance$ path loss model predicts the average path loss for a transmitter-receiver separation based on the measured path loss at a reference distance d_0 of 10cm and a given path loss exponent n [58]. n varies from 0.2 to 1.4 for LoS scenarios and from 1.7 to 2.7 for NLoS scenarios; as the distance dependency is

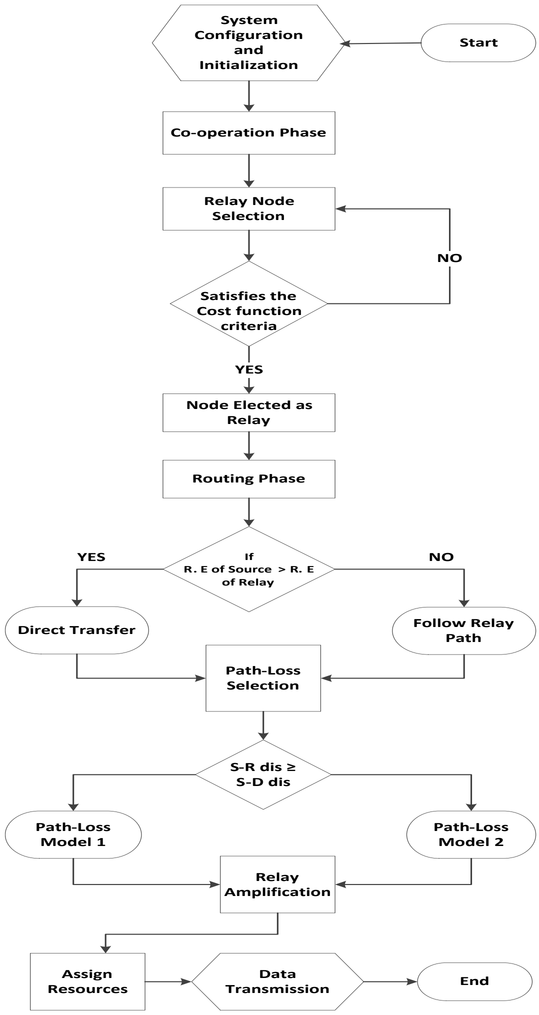

FIGURE 11.4: Flow-chart for Co-LAEEBA protocol

stronger in case of NLoS. In these expressions σ^2 can be modeled as $\sigma^2 = kd^{-\alpha}$ [89] where d will be either d_1 or $d_1 + d_2$ accordingly the transmission from S is towards R or D. α is the propagation loss factor and k is a constant depending on the environment.

In phase 2, R retransmits the signal to the destination D received from phase 1, after applying some processing. Hence the information received at D from phase 2 can be expressed as [57]:

$$y_{RD} = (S_{RD}.PL_{RD}(d_2))x_S f(y_{SR}) + N_{RD} \tag{11.10}$$

where $f(y_{SR})$ is the amplification function applied on the received signal as explained in previous sections, from source by the relay and then forwards to the destination. In terms of shadowing effects due to environment L_{eRD} and due to body movements L_{bRD} can be expressed as

$$y_{RD} = (L_{eRD} + L_{bRD})f(y_{SR}).[PL_{0RD} + 10n.log_{10}\frac{d_2}{d_0}]x'_S + N_{RD} \tag{11.11}$$

x'_S is the signal which is received at the destination node after passing from $S-R$ link which may be faded and may not be the same as x_S. Rest of the variables have their usual meaning in terms of relay to destination mode.

11.4.5 Relay selection and routing phase

To balance energy consumption among sensor nodes and to trim down energy consumption of network, Co-LAEEBA protocol elects its co-operating node or relay node in each round in contrast to the forwarding node in its previous version LAEEBA protocol. Sink is aware of its node ID, distance and residual energy status of all its constituent nodes. It computes the cost function of the relay node and decides whether the node should follow the co-operation path or to transmit its data directly to sink. The cost function $c(i)$ of an i^{th} relay node is dependent on the distance $d(i)$ between i^{th} node and sink, $E(i)$ its residual energy and is calculated by subtracting the current energy of node from its initial energy.
Relay node R has to transmit its own data and the received data from S. However, S may have more than one path to the sink so that it does not have to always use R. A lot of data should go through R and direct to sink as well. However, it is certain that a node with more relay responsibility should have less residual energy than the other as the time passes on. Therefore, in Co-LAEEBA, when S has more residual energy than R; S tries to do direct communication with the sink

so that R need not to be used. Hence,

$$\text{if } c(i) = \begin{cases} E_{re}(S) > E_{re}(R), & then \quad direct \quad transfer \\ \text{else} \\ E_{re}(S) \leq E_{re}(R), & follow \quad relay \quad path \end{cases}$$

With this condition, if multiple relay nodes are available in the path and the node S that has a sink node as its next-hop node, it never triggers co-operation.
In order to maximize the minimum residual energy left after data transmission and there are more than one candidates for co-operation, then it is obvious that S must choose (i) the node with higher E_{re} and (ii) the node R that has a shorter distance from S (to reduce the transmit power)if more than one relay path are available. The node that satisfies these two conditions is identified as the potential cooperative node.

11.4.6 Energy consumption phase

The dynamic routing strategy reduces energy consumption as nodes choose less distant node for data forwarding. Energy consumption to transmit data from a node i to another node j is proportional to the distance d_{ij}^n between two nodes. n is the path loss exponent and depends on the transmission environment. Transmission energy consumption depends on whether the node directly transmits data to sink or transmits cooperatively using neighboring nodes as relays. As all the nodes have information of their neighbors as well as of sink location, hence selected routes are steady fast and consume less energy. In case of emergency, all implanted nodes on the body can communicate directly with base station. In direct communication, delay is much lower as compared to multi-hop communication, because in multi-hop, each intermediate node receives data and then sends it to next node. This causes delay and it is considerably increased due to congestion and becomes unacceptable in some critical scenarios. So, single-hop communication is used to minimize this delay.

Energy consumed in single-hop communication is [89]

$$E_{S-HOP} = \frac{P_{amp,SD} + P_S + P_D}{R_b} \tag{11.12}$$

where $P_{amp,SD}$=$(\zeta\ /\eta)P_i$ is the power consumed by the transmit amplifier, which depends on the peak-to-average ratio ζ of the employed modulation scheme and on the drain efficiency η of the transmit amplifier. P_S and P_D are the RF circuitry power consumption for transmitting and receiving, respectively, and R_b corresponds to the bit rate in bits/s. The power P_i is the one required by a node i to transmit data, which depends on the distance between source i and its destination. Another aspect in analyzing the energy consumption of multi-hop communication is the exploitation of a feedback channel. The energy consumption of multi-hop differs if a feedback channel is present. If a feedback channel is not available, the relay will always retransmit the message from the source in the second time slot, independent of the result of the first transmission. As we need to avoid redundant transmissions to conserve energy, the relay node needs a feedback from destination to ensure whether the recent transmission was successful or not. No such feedback is needed in case of source-relay transmission. In this case, the total energy consumption of multi-hop can be expressed as [38]:

$$E_{M-HOP} = \frac{P_{amp,SR} + P_S + 2P_R}{R_b} + \frac{P_{amp,SD} + P_S + P_D}{R_b} \tag{11.13}$$

where the first term corresponds to the transmission from S to R, and the second term corresponds to the transmission from S to D. Since both R and D listen to S transmission in the first time slot, additional energy is consumed by the relay node given by $2P_R$. On the other hand, if multi-hop exploits a feedback channel from the destination so that the relay retransmits only if the destination could not receive the message correctly from the source in the first time slot. This clearly leads to an energy improvement when compared to multi-hop without feedback, since the transmission from the relay may not be always necessary. The energy consumption in this case can be expressed as [89]:

$$E_{M-HOP} = \frac{P_{amp,SR} + P_S + 2P_R}{R_b} + p_{SD}\frac{P_{amp,SD} + P_S + P_D}{R_b} \tag{11.14}$$

where the term p_{SD} represents the probability of erroneous reception at the destination of the message from the source after the first time slot.

11.4.7 Path-loss selection phase

A human body is partially conductive by nature, having varying thickness, impedance and dielectric constants embodied in it. High losses may occur in response to the communication protocol adopted for nodes, due to the operating frequency band. When nodes communicate, losses between them cause degradation in the performance of monitoring system.

Path loss includes all the consequences linked with distance and interaction of the propagating wave with physical objects in the environment between transmitter and receiver. In WBANs, this loss particularly depends on distance and frequency. In this mode, either of the two path loss models will be followed when the body is static or in motion and the nodes are in the process of transferring their data either to the sink or to the relay nodes. This selection will particularly depend on the varying distance between the nodes if the body is in motion. Now if the body is static, the nodes will follow the path loss model $PL_1(d, f)$ as in equation (11.6) of LAEEBA protocol given by [56]:

$$PL_1(d, f)[dB] = a \times log_{10}(d) + b \times log_{10}(f) + N_{d,f} \tag{11.15}$$

If the body is in motion and the distances between the nodes is varying with the body motion, the nodes will then follow the path loss model $PL_2(d, f)$ as below given by [89]:

$$\begin{cases} PL_2(d,f)[dB] = PL_o + 10nlog_{10}(\frac{d_1+d_2}{d_o}) + \sigma, \quad if \quad direct \quad transfer \\ \\ PL_2(d,f)[dB] = PL_o + 10nlog_{10}(\frac{d_2}{d_o}) + \sigma, \quad if \quad relay \quad path \end{cases}$$

where PL_o is computed as in equation (11.8) for LAEEBA protocol. $(d_1 + d_2)$ is the distance between the source and the sink whereas d_2 being the distance between the relay and the sink node.

11.4.8 Relay strategy

In this research, as we are considering the AF technique, the relay node R multiplies the received signal from S by an amplification factor β before forwarding to the destination node D i.e. $y_{RD} = \beta(y_{SR})$, following equations (3.15), (3.16) and (3.17). Hence, accordingly the signal received at destination D in phase 2 can be re-written as

$$y_{RD} = h_{RD}\beta(S_{SR}.PL_{SR}(d_1)x_S + N_{SR}) + N_{RD} \tag{11.16}$$

In this analysis, the amplitude of the received signal i.e., S to D, S to R and R to D is modeled as a Rayleigh distribution and the links are assumed to be independent and modeled as Rayleigh fading.

11.4.9 Combining strategy

The complete scheme of BAN implementation with co-operation is shown in figure 11.3, which highlights the different types of nodes being used with their communication links. The final combined output at the destination is being forwarded to a base station from where it can be directed to its final destination which will be a medical expert in case of BAN through internet.

Destination sensor node D implements a diversity combining technique to combine the received signals coming from source S and relay R. In case of BAN, as under consideration, FRC is used as the combining strategy and follows the equations (3.18) and (3.19).

11.5 Performance and evaluation

Key performance metrics evaluated for both protocols are defined as following:

1) ***Stability period:*** Stability period is the time span of network operation till the first node die. The time period after the death of first node is termed as unstable period.
2) ***Residual energy:*** Residual energy is defined as the energy left with the nodes after a particular set of rounds traversed and is actually the difference in the initial energy and the utilized energy during network performance.
3) ***Throughput:*** Throughput is defined as the total number of packets successfully received at sink.
4) ***Delay spread:*** Delay spread is a measure of the multipath richness of a communication channel or the arrival time difference between the earliest multipath component and the latest multipath component of the received signal.
5) ***Path-loss:*** Path loss is the difference between the transmitted power of transmitting node and received power at receiving node. It is measured in decibels (dB).

11.5.1 Results and discussions

Simulations are conducted to evaluate and compare the performance of the proposed Co-LAEEBA with existing BAN routing protocols LAEEBA, SIMPLE and M-ATTEMPT. The aim of this evaluation is to observe the effects of cooperative routing in Co-LAEEBA in contrast to non-cooperation based LAEEBA. Parameters used for simulation are presented in table 11.3. Results are averaged over five independent runs of monitoring.

TABLE 11.3: Simulation parameters

Parameter	**Value**
Number of nodes	8
Sink position	At the center of the body
Initial energy(E_i)	Advanced node: 0.3 J Normal node: 0.1 J
Packet size	1000 bits
Data generation rate	Cooperative node: 4000 bits/round
$E_{Tx} = E_{Rx} = E_{elec}$	50 nJ/bit
Free-Space Energy (E_{fs})	10 pJ/bit/m^2
Amplification Energy (E_{amp})	0.0013 pJ/bit/m^4

11.5.2 Stability period

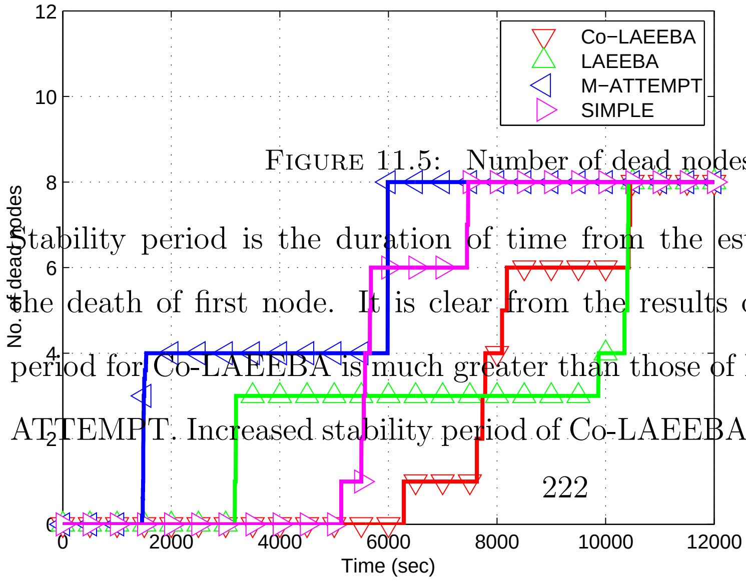

FIGURE 11.5: Number of dead nodes vs Time

Stability period is the duration of time from the establishment of network till the death of first node. It is clear from the results of figure 11.5 that stability period for Co-LAEEBA is much greater than those of LAEEBA, SIMPLE and M-ATTEMPT. Increased stability period of Co-LAEEBA and LAEEBA comparative to SIMPLE and M-ATTEMPT, respectively, is because of non-continuous data transmission. Data is transmitted only if some difference is found between current sensed value and previous value. It is also due to the fact that the advanced nodes die more slowly. As Co-LAEEBA is considering the path-losses as well and the links follow a different path-loss model depending on the signal quality, hence Co-LAEEBA shows much better results. The first node of M-ATTEMPT dies at around 1461 secs and of SIMPLE at 5130 secs after the start of the network in comparison to LAEEBA whose first node dies after 3168 secs. Co-LAEEBA shows a much greater improvement over all these protocols in which the first node dies after about 6283 secs as shown in table 11.4. After 7700 seconds, nodes in Co-LAEEBA die faster than nodes in LAEEBA because of the relay nodes in Co-LAEEBA consume more energy in the later simulation course. The relay nodes play the dual task of sensing as well as relaying whereas the nodes in LAEEBA only sense the data rather than sensing and relaying. The table also shows the efficiency of Co-LAEEBA in percentage as compared to other three protocols.

Table 11.4: Dead nodes after fixed intervals

Protocol	**First node dies at**	**Efficiency in percentage**	**2000 secs**	**4000 secs**	**6000 secs**	**8000 secs**	**10000 secs**	**12000 secs**
SIMPLE	5130 secs	292	NIL	NIL	6	8	8	8
M-ATTEMPT	1461 secs	100	4	4	8	8	8	8
LAEEBA	3168 secs	141	NIL	3	3	3	4	8
Co-LAEEBA	6283 secs	338	NIL	NIL	NIL	4	6	8

11.5.3 Residual energy

Networks are equipped with two types of sensor nodes in terms of initial energy. There are normal nodes with initial energy equal to 0.1 joules, whereas, advanced nodes have 0.3 joules as initial energy. Initial total energy of all the protocols was kept at 5.5 joules in order to have a fair comparison of all the 4 schemes featuring their energy consumption, which justifies the performance of our Co-LAEEBA protocol. It is observed from compared results of all protocols that non-continuous transmission in Co-LAEEBA and LAEEBA causes greater network lifetime. Figure 11.6 and table 11.5 show the residual energy comparison of all the analyzed protocols, and that the Co-LAEEBA shows a much better residual energy decay with the passage of time in the network life-time. The table 11.5 also shows the efficiency of the four compared protocols. The table also shows an improvement in average efficiency of Co-LAEEBA with reference to all the other three protocols. The weakness of the Co-LAEEBA protocol is also obvious from the plots in which the drop in residual energy in comparison to other 3 schemes is greater after 6000 seconds. This is due to the reason that Co-LAEEBA utilizes relay nodes which have the dual responsibility of data sensing as well as data relaying and those nodes consume more energy, making the drop in residual energy higher. The plots show a sudden drop in initial energy due to the fact that the protocol makes use of heterogeneous sensor nodes leading to higher energy consumption. M-ATTEMPT is performing better than SIMPLE and LAEEBA although worse than Co-LAEEBA because of the fact that the scheme follows a static network topology and an improper load balancing is observed in the scheme.

Table 11.5: Percentage of residual energy left after fixed intervals

Protocol	**Average efficiency (%)**	**2000 secs**	**4000 secs**	**6000 secs**	**8000 secs**	**10000 secs**	**12000 secs**
SIMPLE	21.51	72.7	36.36	14.54	5.45	0	0
M-ATTEMPT	23.85	50	36.36	29.5	18.18	9.1	0
LAEEBA	21.63	48	36.36	27.27	16.36	1.8	0
Co-LAEEBA	26.67	74.54	52.72	27.27	5.45	0	0

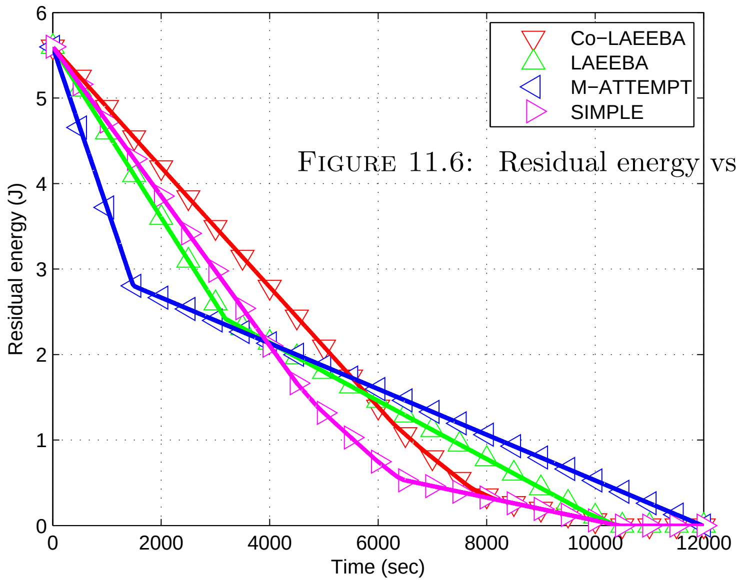

FIGURE 11.6: Residual energy vs Time

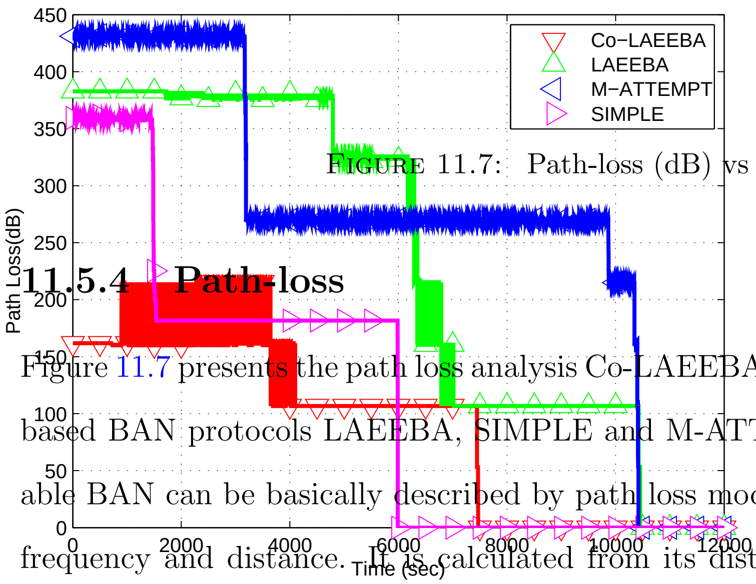

FIGURE 11.7: Path-loss (dB) vs Time

11.5.4 Path-loss

Figure 11.7 presents the path loss analysis Co-LAEEBA with other non-cooperation based BAN protocols LAEEBA, SIMPLE and M-ATTEMPT. Channel for wearable BAN can be basically described by path loss models with two parameters of frequency and distance. It is calculated from its distance to sink with constant frequency 2.4GHz. We use path loss coefficient 3.38 and 4.1 for standard deviation σ. Proposed Co-LAEEBA multi hop topology reduces the path loss (in dB) due to the fact that a threshold value is computed and on the basis of this multi hop transmission follows different path loss models according to the distance between the two nodes communicating with each other, which leads to minimum path loss. LAEEBA protocol shows an improvement over SIMPLE and M-ATTEMPT protocols by reducing the path loss from 432 dB to 382.7 dB and in accordance to these, our proposed protocol Co-LAEEBA shows a dramatic improvement on both of them by dropping the path-loss to 161.8 dB as shown in table 11.6 which is a considerable improvement over all three under-consideration BAN protocols. The table also shows the average efficiency in percentage of the four compared protocols considering the efficiency of Co-LAEEBA as 100% and then comparison of other protocols relative to it.

TABLE 11.6: Drop in path-loss after fixed intervals

Protocol	**Average efficiency (%)**	**0001 sec**	**2000 secs**	**4000 secs**	**6000 secs**	**8000 secs**	**10000 secs**
SIMPLE	63	359	181.6	181.6	0	0	0
M-ATTEMPT	41.2	431.2	431.2	269.7	269.4	269.3	215
LAEEBA	51	382.7	382.7	380.7	325.6	106.7	105
Co-LAEEBA	100	161.8	160	160	86.13	0	0

11.5.5 Throughput

Throughput is the number of successfully received packets per round at the sink. Communication is mediated by two different links in terms of bit rates. In Co-LAEEBA, links between cooperative nodes and sink are of high data rates, whereas, links between source nodes and cooperative ones have low data rates. Nodes which transmit data through cooperative nodes are allowed to send more packets per round than the nodes using non-cooperative or direct communication. It is clear from figure 11.8 that Co-LAEEBA achieves higher throughput than LAEEBA although both utilize the path-loss and cumulative noise effects of the links connecting the nodes but the earlier one also introduces co-operation in comparison to the later one.

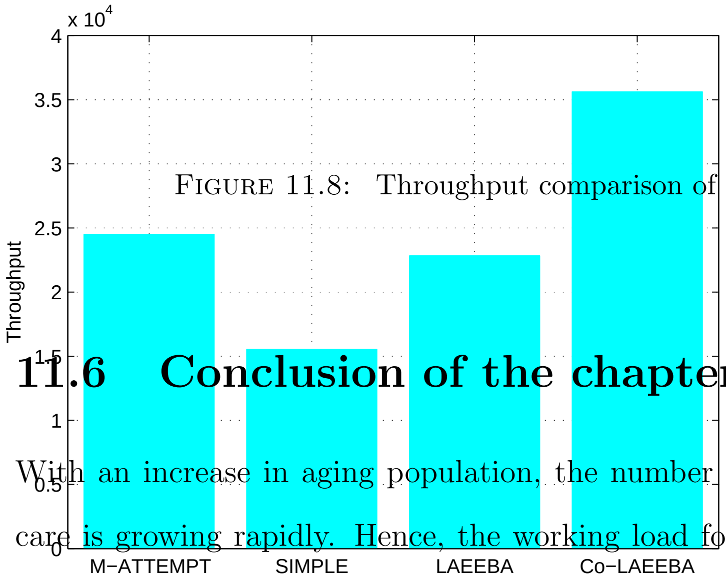

Figure 11.8: Throughput comparison of proposed protocols

11.6 Conclusion of the chapter

With an increase in aging population, the number of persons who need medical care is growing rapidly. Hence, the working load for medical doctors and nurses becomes heavier. Applying medical communication technology to medical and health-care services is one approach to improve the above situation and provide a high quality medical service. In this research, we have proposed mechanisms to route data in WBANs with minimum path-loss over the link; and in which the merits of single-hop and multi-hop are utilized. The proposed schemes use cost functions to select the most appropriate route to sink. These cost functions are calculated based on their distance from the sink as well as their residual energy. Nodes with lesser value of cost function are elected as parent node. Other nodes become children of that parent node and forward their data to parent node. The channel for wearable BAN are described by path loss models with two parameters of frequency and distance. Simulation results show that LAEEBA scheme has considerably enhanced the network stability time and has reduced the path-loss to a significantly low-level. This research also proposes Co-LAEEBA, a new cooperative routing protocol for WBANs. The purpose is to exploit cooperative routing in heterogenous network to enhance WBAN performance. By avoiding redundant data transmission, Co-LAEEBA achieves greater stability period, whereas, use of cooperative routes increases the throughput of the network. Moreover, comparison of proposed protocol with existing BAN protocols LAEEBA, SIMPLE and M-ATTEMPT shows that Co-LAEEBA performs better and is superior in terms of overall network throughput at the cost of some delay introduced in the network due to the use of co-operation. In future work, we shall also try to explore other combining strategies like MRC and SNRC etc at the sink and compare the performance with that of FRC technique. Also we shall try to explore the effects of BER and SNR in the mathematical modeling implemented in this research.

Chapter 12

Conclusion and Future Work

12.1 Conclusion of the dissertation

The objectives of this research are to encourage research efforts, lay down fundamental grounds for the development of new energy efficient routing mechanisms for UWSNs and WBANs. In this regard, we explored UWSN and WBAN communications, and presented new energy efficient routing schemes for these networks. We used the concepts of cooperative communication and routing to optimize the performance of underwater and body area wireless networks.

We proposed delay-sensitive protocol as an improvement of localization-free routing schemes of DBR, EEDBR and AMCTD. We validated the proposed scheme through extensive simulations in UWSNs. In DSDBR, we used F_i and W_F to devise better forwarder selection. In DSEEDBR, we introduced d_{th} variation and provided an analysis to estimate DSH_T. It is observed that distant transmissions in the low-depth region are the major causes of high propagation delays. Therefore, we eliminated large number of transmissions caused by turbulence and thermal activities. In the improved version of AMCTD, we devised PF formulae for sensor nodes with varying network density and selecting a sensor node with higher neighbors as an optimal forwarder for data packets. We succeeded in guaranteeing minimal end-to-end delay by employing adaptive mobility of courier nodes allowing a slight decrease in network throughput.

Utilization of cooperation and SNR enhanced the stability period and packet delivery ratio especially for delay-sensitive applications and even in sparse conditions. The transmission schemes, without cooperation are based on channel estimation, improve the received packet quality at receiver node. However, single link transmission may be affected when the channel conditions change with the passage of time. Our relay selection mechanism considered instantaneous path conditions and distance among neighbours to successfully forward packets to destination in

UWSNs. Variations in d_{th} increased the number of eligible neighbors, thus minimizing critical data loss. Features of single-hop and multi-hop communication techniques have been utilized to reduce path-loss and to prolong network lifetime. Optimal weight computation and role of cooperation not only balanced the load in the network, but also gave proficient improvement in the network stability period. Our newly proposed Co-EEUWSN and SPARCO schemes are cooperation-based routing protocols for underwater networks to enhance their performance in terms of the selected performance metrics. Simulations demonstrated that both Co-EEUWSN and SPARCO protocols function better in terms of end-to-end delay, and network lifetime comparative to non-cooperative routing protocols like DBR, EEDBR and iAMCTD. Moreover, the performance of our proposed schemes was also compared with the selected existing cooperation-based routing protocols for UWSN and it was shown that our proposals were comparatively better.

With an increase in aging population, the number of persons who need medical care is growing rapidly. Hence, the working load for medical doctors and nurses becomes heavier. Applying medical communication technology to medical and health-care services is one approach to improve the above situation and provide a high quality medical service. We have proposed mechanisms; LAEEBA and Co-LAEEBA, to route data in WBANs with minimum path-loss over the communication link by utilizing the merits of both single-hop and multi-hop communication modes. The proposed schemes use cost functions to select the most appropriate route to sink. These cost functions are calculated based on their distance from the sink as well as their residual energy. Node with lesser value of cost function is elected as parent node. Other nodes become children of that parent node and forward their data to it. Simulation results show that LAEEBA scheme has considerably enhanced the network stability time and has reduced the path-loss to a significantly low-level. The Co-LAEEBA exploits cooperative routing in heterogenous network to enhance WBAN performance. By avoiding redundant data transmission, Co-LAEEBA achieved greater stability period. Moreover, the usage of cooperative routes increased the throughput of the network. Comparison of our newly proposed protocol with existing BAN protocols; LAEEBA, SIMPLE and M-ATTEMPT, showed that Co-LAEEBA performed relatively better in terms of overall network throughput at the cost of delay.

12.2 Future work

Unlike other networks, WSNs are designed for explicit applications. Applications include, but are not restricted to, environmental monitoring, industrial machine monitoring, surveillance systems, and military target tracking. Each application differs in features and desires. To support this multiplicity of applications, the advancement of new communication protocols, algorithms, designs, and services are desired. These application-specific features and necessities tied with today's technology lead to diverse hardware platforms and software development. WSNs have the potential to improve and alter the way people interact with technology and the world. Hardware includes using low cost tiny sensor nodes that demand longer network lifetime, strength, self-organization, security, and fault tolerance. Application necessities differ in terms of computation, storage, and user interface and subsequently there is no distinct platform that can be applied to all requests. Future work in this area demands inspecting a more hands-on platform solution for problems in new applications.

Storage capacity in low-end sensor nodes is restricted. Rather than transferring large aggregates of raw data to the base station at the sea shore in case of UWSNs, a local sensor storage space is used as a distributed database to which queries can be sent to recover data. However, energy-efficient storage data structure is still an open area of research in UWSN which we would like to address in future. Use of cooperation may help us to optimize numerous categories of database queries both with respect to performance and energy efficiency.

Critical factors that affect system performance include but are not limited to scalability, communication protocols at different layers, and network management. Scalability issues can worsen system performance both in UWSNs and WBANs. Communication protocols are still trying to achieve a reasonable throughput when the size of the network increases especially in UWSNs. Optimizing and examining protocols at different layers can improve system performance and govern their benefits and restrictions. Sensor nodes can fail at any time due to hardware, software, or communication reasons. It is important that there are services to handle these failures before and after they occur. In this dissertation, the significance of cooperation has been highlighted, however, its further exploration is still needed in many areas like load balancing, network encoding, coverage enhancement, etc. Coverage efficiency depends on the number of active nodes. The more active nodes there are in the network, the higher is the degree of coverage. Coverage protocols should meet different levels of coverage requirements and be energy efficient. As relay nodes utilized in cooperation techniques are always the most active participants in a sensor network environment, hence they can contribute to the coverage issue to a large extent. Existing solutions have explored diverse degrees of coverage along with network connectivity. Our future research and development will also be focused on optimizing coverage for better energy conservation by the use of cooperation. Again the issue of coverage in UWSNs is not addressed to much extent in literature and needs to be considered in future research both by the use of cooperation and without the use of cooperation. A comparative analysis in this regard will be very beneficial in the development of future schemes for coverage efficiency.

Time synchronization eradicates event collision, energy wastage, and non-uniform updates. Future time synchronization protocols can target to synchronize local node clocks in the network and lessen energy overhead. In our future research, we would also like to focus on minimizing uncertainty errors over long intervals of time and dealing with precision both in UWSNs and WBANs. With large sums of data generated over time, the cost of conveying all of the detected data to the base station is expensive. This becomes more crucial when we are talking about UWSNs and WBANs in which the base station is far away from the sensing nodes and can lead to more uncertainty errors. Data compression and aggregation techniques support in dropping the amount of data to be transferred. The development of several compression and aggregation schemes for event-based or continuous data collection network is a challenging research topic and needs to be explored.

The physical layer in any WSN environment must be energy efficient. For example the design of the radio is very important as the radio has profound impact on the performance of other protocol layers. An energy-efficient radio should ingest the lowest possible energy essential to properly perform its functions and communicate. In our research, we made use of only cooperation as one parameter of physical layer which proved to be quite helpful in reducing energy consumption. Minimizing the energy consumption at the physical layer requires optimization of circuitry transmissions and receptions to minimize the energy consumption cost of sensors. Moreover, reduction of wakeup and startup times will prolong the network lifetime because the shorter the wakeup and startup duration is the lower is the amount of energy consumed. Modulation schemes have been suggested to minimize the energy for transmitting each bit. Future work demands new advances in low power radio design with evolving technologies, discovering ultra-wideband techniques as an alternative for communication, generating simple modulation schemes to reduce synchronization and energy cost, outlining the optimal transmission power, and designing more energy-efficient protocols and algorithms.

In the cross-layered approach, the protocol stack is treated as a system and not individual layers, independent of each other. Layers share information from the system. The development of various protocols and services in a cross-layered approach is optimized and improved as a whole. Various design solutions can be proposed to explore the benefits of a cross-layer approach. These can be network-MAC layered, network-MAC-link layered, transport-physical layered approaches, etc. As cross-layer design considers the sharing of information across layers, the optimizing problem computes the optimal transmission power, data rates, and link schedule. These will be studied in future considering UWSNs and WBANs.

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