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CLORDFS-Optimized Routing and Data Forwarding Scheme for Underwater Acoustic Wireless Sensor Networks using Cross-Layer Parameters

B. Uma Rani[1*] **A. R. Naseer**[2]

[1]*Computer Science and Engineering, JyothishmathiInstitute of Technology and Science Karimnagar, Affiliated to Jawaharlal Nehru Technological University Hyderabad, Telangana, India.*
[2]*School of Global Convergence Studies, INHA University, Incheon, South Korea & School of Computer and Information Engineering INHA University, Tashkent, Republic of Uzbekistan*
* Corresponding author's Email: umaranibodakunta@gmail.com

Abstract: Underwater Acoustic Wireless Sensor Networks (UAWSN) is a collection of sensor nodes that are strategically placed at different depths under water to monitor the activities of interest. In contrast to Terrestrial Wireless Sensor Networks (TWSN), a UAWSN is constrained by several challenges like limited bandwidth, multipath propagation, path-loss, noise, Doppler spread, etc. Also, other parameters like salinity, depth and pressure influence the propagation speed and in turn the achieved throughput. Most of the existing works in this direction focus on designing new medium access control protocols to minimize collisions and maximize bandwidth utilization. Other existing routing and data forwarding protocols use different metrics to maximize network objectives like network lifetime, increase network throughput, minimize energy drain, etc. In this paper, we propose a routing and data forwarding mechanism using link bandwidth by considering path-loss and multipath propagation effects. These cross-layer metrics allow us to select high-capacity links increasing overall network throughput. In addition, we propose different optimizations to the data forwarding and routing mechanisms to save energy and increase lifetime of the network. The simulation results show that the proposed mechanism improves 6% packet delivery ratio, 10% throughput, and minimizes energy consumption in comparison to state-of- the-art protocol CLOR.

Keywords: Underwater acoustic wireless sensor networks, Cross layer, Bandwidth, MAC, Routing and data forwarding.

1. Introduction

Underwater acoustic wireless sensor networks (UAWSN) employ acoustic communication to address different activities in different types of underwater applications. Typically, underwater wireless sensor networks are employed in the fields of science, military, business and commercial applications. These include monitoring for marine life, naval communication, ocean pollution monitoring, oil and natural gas industries, and aquatic applications. Over the years, the requirements of these UAWSN systems have grown significantly. Typical application requirements, for example, network throughput that is to be supported have grown immensely that there is a constant requirement to match network functionalities of its counterpart, terrestrial wireless sensor networks (TWSN) [1]. However, this is a challenging task to achieve due to the constraints posed by UAWSN that include the propagation speed of acoustic waves which is around 1500 meters/second that is several notches slower than radio waves. On the other hand, the transmission range of sensor nodes underwater can range up to 10 kilometres, whereas the nodes in TWSN support up to 100 metres. Also, sensor nodes deployed in the ocean are shown to be affected by sea currents and the displacement is anywhere between 2-3 metres/second [2]. Further, other issues include higher energy consumption of sensor nodes, replenishing their power resources, stability of the communication links, bit error rate (BER), signal-attenuation, etc. constrain the UAWSN. Sensor nodes in UAWSN consume higher energy as the topology is typically sparse and higher transmission power is needed to communicate over large distances. The sparse distribution of sensor nodes also means that if there is signal attenuation, retransmissions would result into further energy drain. Moreover, the power source of sensor nodes in UAWSN cannot be replenished due to the infeasibility of their location and difficult operational environment. The stability of wireless links is another major challenge that impacts the packet delivery ratio due to the high BER and signal attenuation. Considering all these above factors, it becomes imperative to design an optimized routing and data forwarding protocol that considers parameters from the medium access control sub-layer to make better routing decisions. Especially, the limited bandwidth availability in a UAWSN plays a major role in the choice of next-hop neighbour towards the destination. The bandwidth available for a device underwater is around 100 KHz, which is limited in comparison to its terrestrial counterpart. In addition, devices operate in the frequency ranges of 10 Hz – 100 KHz, which leaves a limited frequencies to transmit [3]. This, combined with noise impacts the throughput of the network. Also, if devices compete for the limited bandwidth, congestion increases and in turn network delay and at the end energy consumption of devices in the network. Further, the devices underwater are located far away from each other and therefore with the increase in distance between devices the data rate that is achievable also is lowered. For example, within distance of 1 KM, a data rate of 100 Kbps can be achieved but when the distance varies anywhere between 1 KM to 10 KMs, the same data rate falls to around 50 Kbps. The limited bandwidth along with multipath propagation and path losses severely impact the network throughput. These factors directly impact the performance metrics like packet delivery ratioand network throughput, and indirectly affect network lifespan, and energy consumption of devices.

Existing works in this direction primarily aim to address the different factors influencing the utilization of bandwidth, path-loss in the network, and multipath propagation losses by designing different MAC protocols to address specific network challenges. As MAC protocols primarily determine who goes next in utilizing the channel, an effective channel allocation protocol can minimize collisions, improve channel utilization and make effective use of available bandwidth [4]. Alternatively, different types of routing protocols have been designed to address different aspects of UWASN like mobility, reliability, energy efficiency, protocols suited to sparse networks, dense networks, etc. These protocols aim to optimize different aspects of routing and data forwarding to improve the network performance. Specifically, the works presented in [5, 6] are designed for sparse networks where the selection of next-hop is crucial. The adaptive routing protocol presented in [5] aims to achieve high packet delivery ratio by determining the priority of packet being sent, available resources to send the packet. On the other hand, the vector based forwarding protocol proposed in [7] employs a routing vector for each individual forwarder from source to destination. In this work, we consider cross-layer factors that affect the packet delivery ratio (PDR) and network throughput and design a routing protocol for UAWSN. We also present several optimizations during routing and data forwarding to minimize energy spending, thus improving the network lifetime. Specifically, this paper contributes:

I. Identifying the various factors that influence the PDR and network throughput in a UAWSN.
II. Design of a routing and data forwarding scheme to improve network performance in terms of PDR and network throughput.
III. Optimizations to the routing and data forwarding scheme to increase network lifetime and device's energy consumption.

The rest of the paper is organized as follows. In section 2, we list the related works that aim to address the above presented research challenges from the perspective of different network layers. Section 3 presents the network model and assumptions of an underwater acoustic wireless sensor network. The proposed set of routing optimizations are presented in section 4. Section 5 presents the analytical simulation results aimed at understanding the performance of the proposed scheme. It also highlights the comparison study with other state-of-the art schemes. Finally, section 6 provides the concluding remarks and future directions to this work.

2. Related work

In an underwater setting, the major concern of a wireless sensor network is to minimize the energy consumption of sensor devices, as these devices are battery powered. Majority of the research in this direction is centred on lowering the power consumption and increasing the network lifetime [8-11]. In this regard, the problem has been tackled layer wise where at the physical layer different modulation schemes have been proposed that do not require high processing capability, and therefore minimize energy consumption. The works discussed in [12, 13] present modulation schemes based on on-off keying and frequency-shift keying that are based on energy detection and do not require carrier phase tracking. However, these schemes are affected by inter-symbol and inter-carrier interference that are caused due to Doppler effect and multipath propagations. While, several MAC layer protocols proposed are meant to deal with the issues like limited bandwidth, collisions then retransmissions in huge number, transmission losses due to multipath effects, long delays and Doppler spread [14, 15]. The authors in [16] proposed a MAC protocol that uses power control to send data packets and control packets. The data packets are transmitted at minimum transmission power and control packets are transmitted at maximum transmission power. In addition, during data packets transmission, a notification signal is transmitted at maximum power to enable all neighbours to be aware of the current transmission. In this way, the MAC protocol avoids collisions and increases network throughput. Alternatively, the authors in [17] proposed a delay aware probability-based MAC protocol in which a neighbour estimates the delay of current transmission between a source and destination and aims to transmit such that the neighbour's transmission does not interfere with the transmission currently happening. To achieve this, a device needs to know the distance between a source and destination, therefore it can infer whether its transmission would cause a collision or not. It exploits the fact that acoustic waves have longer propagation delay, and concurrent transmissions without resulting in a collision. In [18], the authors aim to address the fundamental constraint of acoustic waves, that is, the transmission speed. Han et al. proposed the usage of multiple modes of transmission, namely acoustic and optical communication. It uses acoustic mode when the destination is not aligned and is located far away. On the other hand, if the destination is aligned and is within short distance, optical communication is used. The proposed mechanism is implemented at the MAC layer to coordinate among multiple devices. Some other MAC layer works that aim to address the aforementioned challenges design multi-channel MAC protocols [19, 20]. For effectiveness, each node in the network have to keep track of the status of different channels. Therefore, increased cooperation requirement [21, 22] from nodes in the network adds to the coordination overhead. But it helps nodes to choose a channel that is least busy, which improves the packet delivery ratio. In this regard, the packet size selection is also one of the important factors as mentioned in [23], where if it is done according to changes of environmental parameters, will result in finer effect. Another direction in which research has been carried out to improve the performance of UAWSN is through enhancements in the routing layer. Since routing and data forwarding plays a major role in relaying data from source to destination, it becomes imperative to address the performance issues from the perspective of the routing layer. However, majority of works are aimed at addressing one specific criterion of network performance or network requirements. For example, works presented in [24-26] focus on the mobility of nodes in the design criterion of a routing protocol. Mobility is an important aspect in UAWSNs as all sensor devices are subject to movement because of water currents. With frequent changes to the network topology, established routes change prompting route discovery. To minimize the routing overhead, protocols employ anchor nodes, location information and autonomous unmanned vehicles. Most of the other schemes are aimed at minimizing the energy consumption [27, 28], while few other works focus on the network topology like if the network is dense or sparse [29-31]. The location based clustering algorithm presented in [28] aims at minimization of nodes energy drain surrounding the sink node. In [32, 33] a clear description of localization techniques and algorithms is found. The cluster head is chosen based on its location. The communication between clusters happen through inter-cluster communication through cluster heads. [34] proposes a dual hop transmit delay allocation MAC, which aids in a better scheduling with a non-synchronized nodes. This work used lower relay routing mechanism. It includes a probing algorithm for throughput enhanced routing mechanism for the devised MAC. The work uses a technique of dual-hop redundant path finding for betterment of successful packet arrivals. As it is a kind of centralized scheduling, it can achieve improved network throughput approximately equal to channel capacity. This ensures its potentiality in practical implementation during the data gathering. The work in [35] introduces a cross-layer design methodology that focus on together optimization of link layer and as well as physical layer. This optimization is based on an objective of expanding network operations lifetime and to obtain a limit on cumulative transmission time of the entire links. A detailed solution for improved network flow at every link is coordinated to enhance network lifetime. If such timing threshold could not be attained, then a new iteration is started with a constraint on individual node energy intake relaxation with a gradual increase. This algorithm requires a smaller number of iterations to converge. This work makes use of an optimal transmission rate metric, which indicates the minimum energy required to transmit a bit. CLOR

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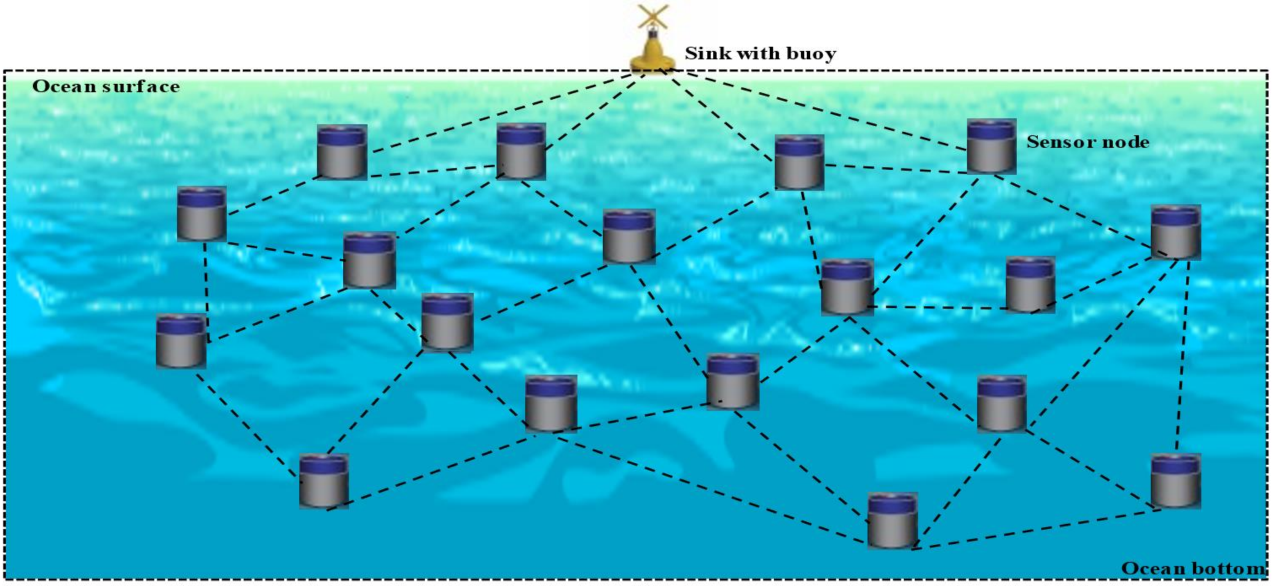

Figure. 1 Network architecture

[31] is a way to decreases the congestion in sparse multihop underwater networks as a contribution to the betterment of network performance. This is attained using the phases- negotiation and transmission. While in the negotiation phase the cross layer information is used to find optimal forwarder, the transmission phase uses a burst transmission mechanism along with network coding. The protocol uses metrics such as topological data and link condition. The choosing of burst size is treated as a crucial aspect, and for each transmission it should be set adaptively. Though CLOR uses a network coding mechanism to support the burst transmission, on the other hand it paves the way for coding overhead. This is caused because of coding matrix and control information. Even though a lot of complex mechanisms have been presented in the literature, most of the applications do not benefit from such schemes. In summary, for most of applications of submerged sensor networks, a more simplistic strategies can be beneficial if some cross-layer factors can be addressed. Instead of a complex multi-channel MAC protocol, a contention free MAC protocol like TDMA can be well-suited for an underwater environment monitoring application. Also, for applications without real-time implications, few optimizations to the routing and data-forwarding strategies can immensely improve performance without adding to the complexity of design by incorporating cross layer. This work aims at addressing the issues related to performance of UAWSN with a simplistic design at the core.

The following sections elaborate on the considered network model and the proposed routing and data forwarding mechanism for UAWSN.

3. Network model and assumptions

a. Network model and assumptions:

We consider a sparse UAWSN where the number of nodes are deployed based on application needs. The nodes are deployed at different depths based on the necessity of an application as seen in Fig. 1. The sensor nodes are susceptible to movement due to the water currents and the sink nodes are always on the surface. The sink nodes are capable of receiving acoustic signals and radio frequency signals enabling them to communicate with terrestrial stations. Each of the sensor node either communicates directly with the sink node, or relies on a multi-hop route towards the sink. There can exist multiple sink nodes and a sensor node aiming to communicate with a sink closest to it based on its location. We consider the existence of few anchor nodes (sink nodes) that are fixed and all the nodes aim to determine their relative distance to them through the concept of relative ranking.

b. Channel model:

We consider the channel model similar to the one proposed in [36]. The effect of attenuation of noise on the signals along the path (path loss) in acoustic communication is represented using Eq. (1).

$$A_t(d, f) = d^l a(f^d) \qquad (1)$$

The frequency of the signal is represented by f and d represents the distance. The spreading loss is represented by the path-loss exponent l whose typical range is between 1 and 2. The absorption coefficient

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is determined using the Thorp equation shown in Eq. (2).

$$10 \log a(f) = \frac{0.11 f^2}{(1+f^2)} + \frac{44 f^2}{(4100+f^2)} + 0.000275 f^2 + 0.0003 \quad (2)$$

The ambient noise (N) is dependent on the environment where the UAWSN is deployed. For example, in the ocean environment, the factors considered are shipping, turbulence, waves and thermal noise. The empirical formulae to determine the power spectral densities of these 4 components are obtained from [36]. Further, to accommodate interference of packets from multiple nodes, a packet is divided into multiple segments, *m*. Then, the signal to noise ratio (SINR) of each segment in terms of the carrier frequency *f* can be computed as

$$SINR_m = \int_B \frac{P_S(f)/A(f,d)}{N(f)+I_m(f)} \, df \quad (3)$$

The power spectral density is represented by $P_s(f)$ for the frequency f. The bandwidth in Hz is represented by `B` and $I_m(f)$ represents the interference power density of the m^{th} segment. The SINR of the packet is chosen as the minimum of the SINR of all the *m* segments.

4. The proposed routing and data forwarding scheme

The proposed routing and data forwarding scheme for an UAWSN is based on the core principle that if a network is sufficiently connected then a route with maximum available bandwidth can be chosen that can be based on neighbours' distance from a node, where a shorter communication link is shown to provide improved bandwidth in comparison to longer links in acoustic system. In turn, for a sparse UAWSN a contention free medium access control protocol, TDMA is chosen that also minimizes collisions and thus the number of retransmissions. Further, routing and data forwarding optimizations are proposed that enhance the network lifetime. First, we present the brief overview of the TDMA protocol employed, followed by the distance calculation and localization scheme, and the routing protocol.

A. The medium access control protocol:

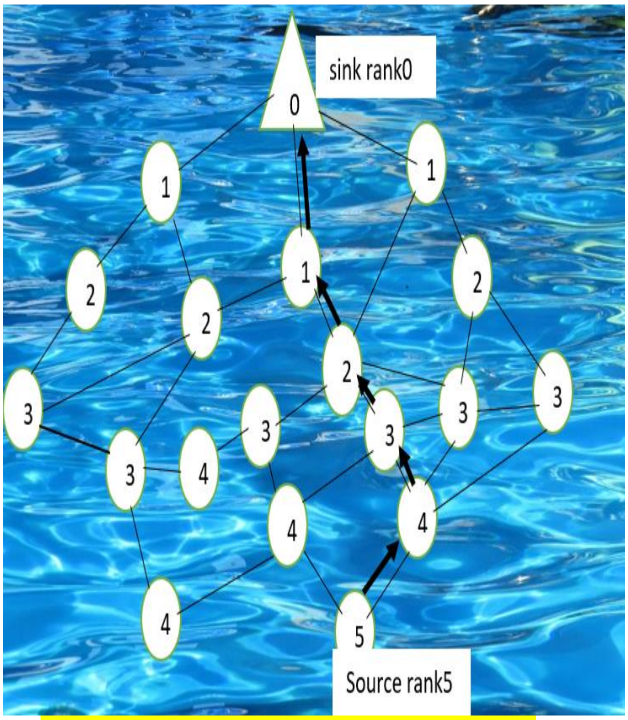
In majority of the UAWSN applications, the frequency of data transfer is not continuous unlike wireless networks that are deployed for data communications. Therefore, having a contention-free MAC protocol like TDMA is beneficial provided it can establish collision free schedules. Protocols based on the concept of time-division divide the channel time into slots and assign a slot to each node for transmission. Nodes schedule their transmissions in their allocated slots, therefore collisions are prevented. It also adds guard time between slots to prevent collisions between slots. It also minimizes the contention overhead that otherwise is incurred in contention based MAC protocols. Nodes can operate in low-power mode to lower energy consumption when it has no data to send or there are no transmission requests from neighboring nodes to which it is a forwarder. The major challenge herein is to compute a collision free schedule as it is shown that collisions occur mainly due to overlapping schedules between neighboring nodes. Therefore, we employ the distributed on-demand scheduling mechanism DOS that considers the schedules of two-hop neighbors as there is temporal-spatial reuse of the slots to compute non-overlapping schedules. The nodes in network are divided into clusters and cluster head is responsible for providing transmission slots for all the nodes connected to it. The communication between cluster heads enables exchange of schedules of all two-hop nodes whose transmission schedules are to be considered to prevent any overlap.

B. Proposed routing and data forwarding protocol:

The proposed protocol depends on a set of preliminaries that include distance estimation to its neighbors. The distance estimation is followed by available bandwidth calculation after considering the signal attenuation and path loss due to multipath propagation. Based on these cross-layer measurements, the routing is carried out to select optimal routes. The distance is predicted by measuring the received signal strength (RSS) by a node to its neighbors and comparing it with the reference distance d_0. The distance is used to select a neighbor which has the smallest distance and offers maximum bandwidth. The distance is calculated based on fact that the signal strength decreases with increase in distance between the transmitter and receiver. The loss of acoustic signal strength is due to attenuation, scattering, absorption and diffraction. It is computed as follows:

$$\frac{P_r(d_0)}{P_r(d)} = \left\{\frac{d}{d_0}\right\}^{\eta} \quad (4)$$

The $P_r(d)$ represents the RSS in distance d [mW] and $P_r(d_0)$ represents the reference distance. The



(Numbering on the nodes represent their rank)

Figure. 2 Network topology: data forwarding

reference distance is a measured distance between two particular nodes and its RSS. Thesedistance are represented in meters. Based on the log-normal shadowing model, the distance measurements can be obtained as follows:

$$\text{RSSI} = 10 \text{ x } \log \frac{P}{0.001} \; [dBm]$$

$$\Rightarrow \; P = 10^{\left(\frac{RSSI-30}{10}\right)} \; [mW]$$

$$\text{RSSI} = \text{RSSI}_{d_0} - 10 \text{ x } \eta \text{ x} \log\left(\frac{d}{d_0}\right) \; [dBm]$$

$$d = d_0 \text{ x } 10^{\left(\frac{\text{RSSI}_{d_0} - \text{RSSI}}{10 \text{ x } \eta}\right)} \qquad (5)$$

Based on the distance estimates, the available bandwidth to the selected neighbor is determined. To figure out the available coherence bandwidth, we use the pseudo-random binary sequence (PRBS) signal that is a fixed length bit-sequence that is modulated using BPSK modulation scheme. Coherence bandwidth is a parameter which represents the maximal bandwidth, for which the amplitude of the signal remains constant and its phase matches with the original transmission. The underwater acoustic communication link represents a channel that is characterized by time-varying signal impulse response for a defined observation time period t and delay τ [37]. If the multipath delay spread over the channel is S seconds, then the coherence bandwidth is approximately ($B_c \approx 1/S$). On computing the available bandwidth over the channel for a particular neighbor at a distance *d*, the neighbor is chosen that offers best packet delivery ratio. The decision to choose a neighbor based on distance not only improves the PDR, throughput and minimizes delay, it also makes sure that the nodes need not use higher transmission power to reach a farther neighbor. Therefore, it lowers the power consumption of devices and improves the overall network life-time.

Routing: The routing process is not carried out in isolation but is integrated with the data forwarding process. That is, when a sensor node has data to send, it chooses the next-hop towards the source based on the relative rank of the node with respect to the sink. Rank is count maintained by each node that determines their relative position with respect to the sink node. The rank of the sink node is zero. All the nodes that are one-hop away from the sink are at rank one, and nodes that are neighbors to these one-hop nodes are at rank 2. The rank computation process is initiated by the sink node by broadcasting a topology discovery message in the network. All the nodes that receive this message determine their relative position to the sink and determine their rank as shown in Fig. 2. This usage of rank prevents the nodes in UAWSN from employing location based approaches, which are complex and are shown to be ineffective. When a node has data to send, the next hop (after considering available bandwidth) is chosen based on its rank. Only nodes that are lower ranked or equal to the sender are chosen as next-hop. Each node on the route towards the sink determines the best-hop to be selected to reach the destination. If same ranked neighbors are encountered, the decision-making criteria shifts to the distance to the receiver (next-hop) and the bandwidth capacity, where a closer neighbor to the sender (or source) is chosen. This ensures that at each step a high capacity link is chosen that also incurs less transmission power, which ensures high PDR and low energy consumption. Lastly, a node can buffer packets to aggregate and transmit if the source marks the data packet as delay tolerant.

5. Performance analysis and experimental results

Performance analysis of the proposed routing mechanism is presented in this section. The simulations are carried out on NetSim v12.2, a discrete event network simulator. These results are compared with the protocol CLOR presented in [31], a cross layer opportunistic routing protocol for sparse networks like CLORDFS and another adaptive routing protocol designed for delay tolerant UAWSN presented in [5]. A network of 64 sensor devices is

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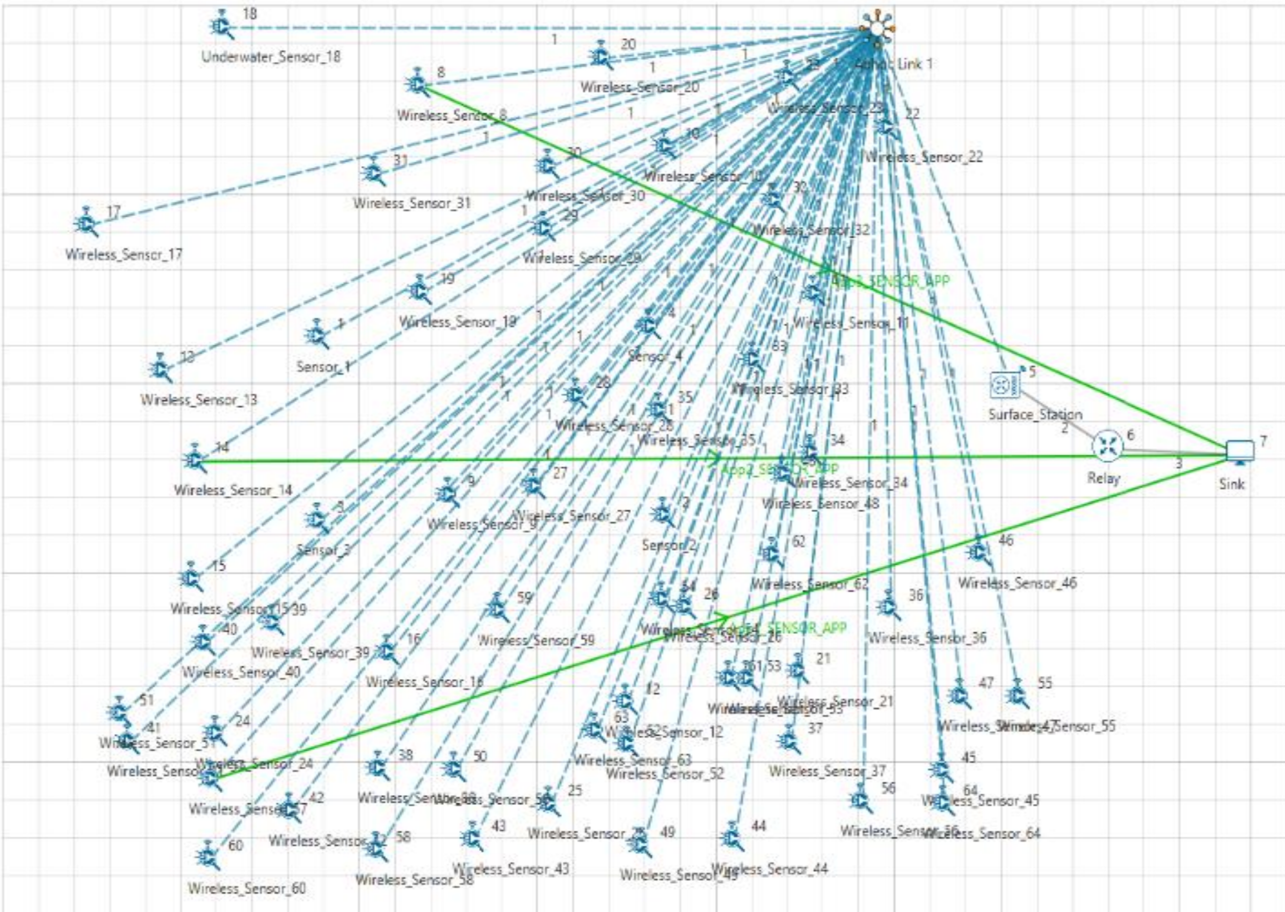

Figure. 3 Network topology

Table 1. Simulation parameters

Parameter	Value
Radio Propagation Model	Underwater Communication
Channel	Underwater Channel
Simulation Area	1000 Meters X 500 Meters
Depth (maximum)	300 Meters
Frequency	26.77 – 44.62 kHz
Path loss Model	Log Normal
Fading Model	Rayleigh
Shadowing Model	Log Normal
Path loss exponent (*l*)	2
Transmitting power (W)	2 or 8
Receiving power (W)	0.8
Sleep Mode Current (mA)	0.237
Maximum range	1 Km
Mobility	2-3 m/sec
Simulation Time (Seconds)	10000

set-up that are connected through the gateway to sink-node as depicted in Fig. 3. The sensor devices are designed to operate based on the characteristics of the LinkQuest UWM 2000H acoustic modem. A maximum data rate of 100 kbps is chosen.

The Table 1 shows some of the important simulation parameters.

We consider a three-dimensional network topology where the nodes are stationed at multiple depth anywhere between 0-300 meters. The nodes are uniformly distributed at different depths to make sure the node distribution is uniform and the network is connected. Doing this allows us to capture the behaviour of acoustic communication characteristics of water bodies. We consider the log normal path-loss and shadowing model to capture the effects of signal attenuation and noise in the network. The path-loss exponent is fixed at 2. It determines the rate at which the strength of the signal decreases with distance. The propagation speed of acoustic waves is 1500 m/sec and varies with the depth at which nodes operate. The node parameters are adjusted based on the commercially available acoustic modem, LinkQuest UWM2000H. The maximum range of these devices

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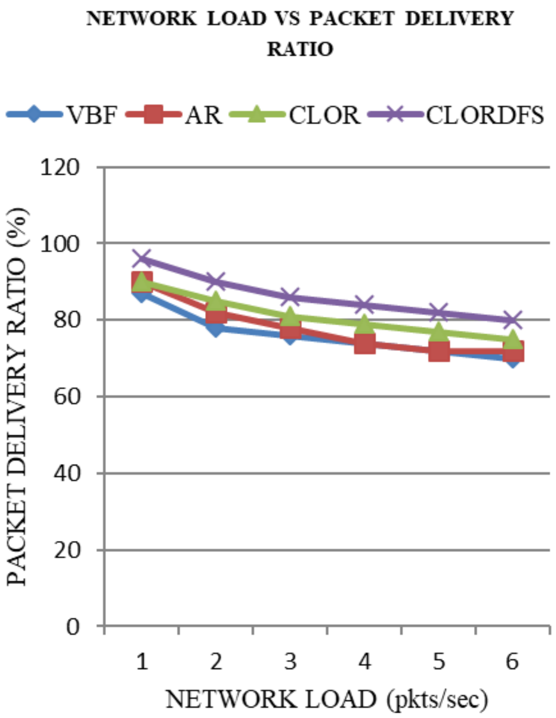

Figure. 4 Percentage of packet delivery ratio

is 1 Km. The total simulation time is set to 10000 seconds and the parameters employed to analyse the performance of the proposed scheme are packet delivery ratio (PDR), throughput, energy consumption, average end-to-end delay (E2ED), and network overhead. The PDR represents the ratio of number of packets sent to the number of packets received. It characterizes the packet loss in the network, which is important to analyse the performance of the proposed scheme as it captures the quality of links chosen for route formation. The average end-to-end delay represents the end-to-end delay experienced by the packets divided by the total number of packets generated in the network. The E2ED also helps in understanding the quality of links selected as higher quality links lower the delay. Similarly, throughput represents the total number of packets (represented in bytes) received in a given time period. The energy consumption is the sum of energy consumed by all the nodes in the network covering for all the activities including transmission, reception and idle energy spent. The energy consumed characterizes the ability of the proposed scheme to conserve energy. Finally, network overhead is the amount of control packets transmitted to establish routes and transfer data from source to the sink. This parameter helps in determining the percentage of network activity spent on data transfer with lower such overhead the better. It also helps to understand how much additional network activity needs to be done for the proposed scheme to meet its features. The proposed work is primarily compared with the state-of-the art cross-layer protocol CLOR [31] that also aims to exploit cross-layer parameters. In addition, the proposed protocol is also compared with other popularprotocols like vector-based forwarding (VBF) and the adaptive routing (AR)because of the similarities in operation. As VBF and AR are designed for sparse underwater networks that employ different priorities for network packets to make transfer data from the source to the sink [5], employing them for comparison can help in understanding the proposed protocol better. At first, we analyse and compare the performance of the schemes in terms of PDR. In a network of 64 devices, we examine the performance of both the schemes for a varying network load. The network load is represented in terms of number of packets generated per second in the network and the PDR is the number of packets successfully received at the sink. The comparison is presented in Fig. 4. It can be observed that the proposed mechanism offers better PDR compared to CLOR [31], VBF[7] and adaptive routing. The packet priority level in the adaptive routing scheme is set to high to emulate the need for processing the packet as soon as it is received. The higher PDR of the proposed scheme is attributed to the fact that it not only chooses high capacity links (using link metrics) but also ensures that a shorter route is selected to reach the sink node. On the other hand, the PDR of CLOR is lower than the proposed scheme as it chooses routes based on packet received rate (PRR) and advance to sink (ATS) and congestion degree (CD) metrics that only capture the performance of the route at the network layer. As the network considered is sparse and the link metrics frequently change, the use of PRR and ATS, and CD result in lower PDR. Specifically, the use of ATS and CD is based on moving average of previous measurements, it fails to capture the current or very recent performance of the link. But, the proposed scheme considers the channel conditions including the signal attenuation and available bandwidth. These link layer parameters capture the link state better than that of CLOR. Similarly, theadaptive routing protocol also results in low PDR as it chooses the forwarding area based on the priority of the packet and higher priority means choosing a higher-level forwarding area, which means closer to the sink node. This type of link selection does not necessarily translate into high PDR path, thereby a drop in the PDR. As it can be observed that the proposed scheme delivers an average increase of 6%, 8%, 10% higher PDR compared to CLOR, VBF and adaptiverouting respectively.

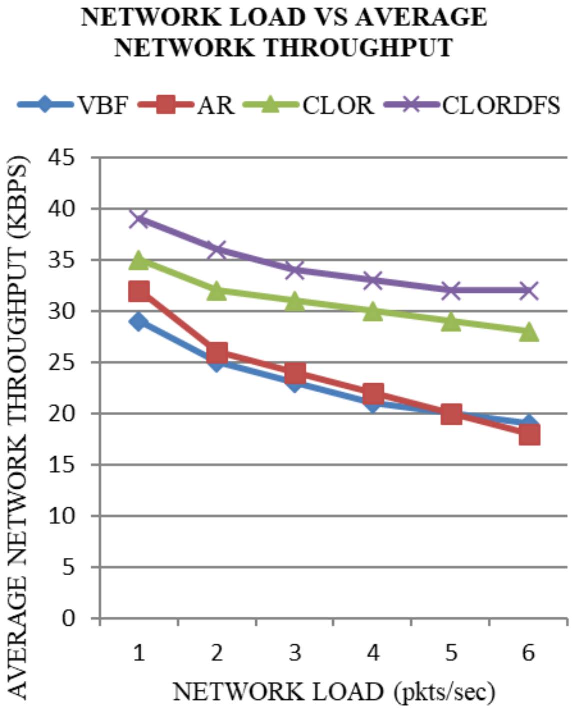

Figure. 5 Average network throughput

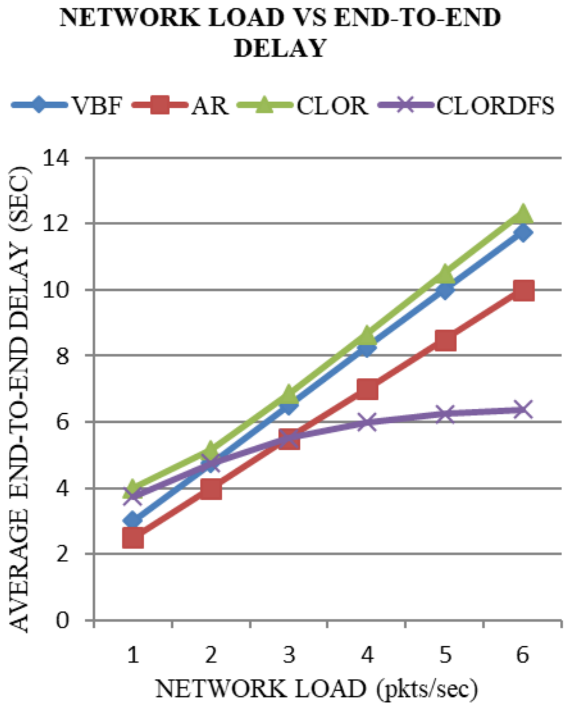

Figure. 6 Average end-to-end delay

Next, in experiment 2, we analyse the performance of these schemes in terms of network throughput. For varying network load that is expressed in terms of number of packets generated per second, the throughput achieved is measured. Fig. 5 presents the comparison of proposed scheme with other schemes for a network load of 0-3 packets/sec for a network size of 64 devices. As shown in the network topology, the sensor devices are placed at various depth and the speed of propagation of devices are set as a function of depth and other characteristics of water as per [1]. There is a direct correlation between the experiment to determine PDR and throughput, as most of the times increase in PDR results in higher throughput. The proposed scheme delivers higher throughput as the next-hop forwarder selection is rooted on distance plus link capacity. Selecting higher bandwidth links and using TDMA as the MAC protocol results in higher throughput. In comparison, CLOR uses PRR and other network layer metrics, the adaptive routing protocol using high priority packets sometimes selects routes based on the nearness to the sink than on the link capacity resulting in lower throughput. In addition, CLOR protocol comprises of a negotiation phase where the sender broadcasts arequest to forward packet. All the potential forwarders that receive this RTF send a clear to forward packet that contains the capability of a node to act as a forwarder. As this is a repetitive process, for varying network load, the network throughput is 10%lower compared to the proposed scheme. Alternatively, the adaptive routing protocol uses multiple preference levels while transmitting, therefore the average throughput is 10% lower, than the proposed scheme, and VBF is 11% lower than the proposed scheme.

Similar to the second experiment we measured the end-to-end delay for the same network setup. End-to-end delay characterizes the quality of links selected. The higher the quality of links, the better end-to-end delay metrics are achieved. The proposed scheme (Figure 6) performs better when the offered network load increases beyond a certain limit. This is due to the fact that the adaptive routing scheme in [5] uses multiple copies of the same packet while forwarding to the sink. Therefore, when the network load is low, it achieves slightly better end-to-end delay compared to proposed scheme. Even VBF shows better at low network load.In case of CLOR, the end-to-end delay is higher compared to all other protocols, which can be primarily attributed to the mandatory negotiation phase before sending ofpackets. In addition, whenburst of packets are sent using network coding, the end-to-end delay increases attributed to the decoding delay at the receiver. In case of VBF and adaptive routing, the initial gains diminish with the growth in network load as shown in Fig. 6.

Lastly, we analysethe performance of the proposed scheme along with CLOR, adaptive routing

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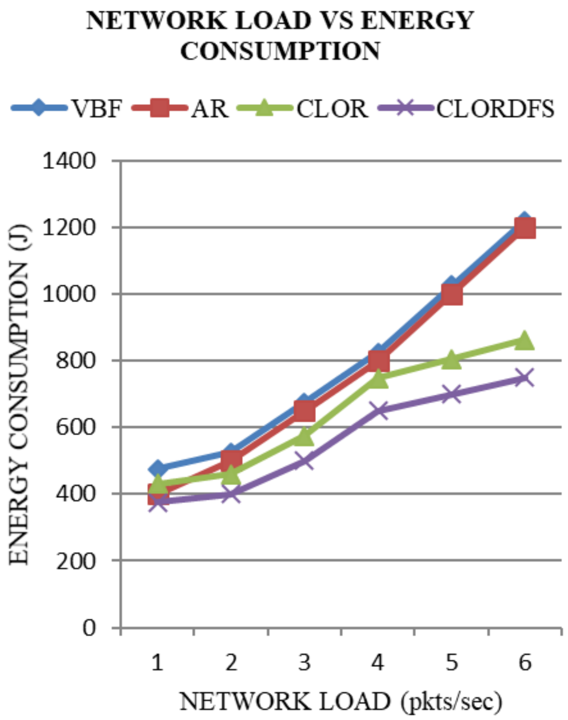

Figure. 7 Energy consumption

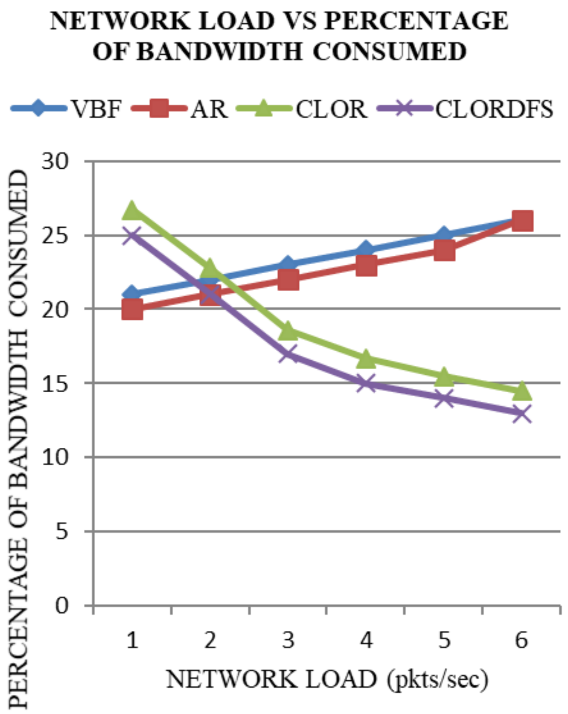

Figure. 8 Percentage of bandwidth spent in network

and VBF in terms of energy consumed and percentage of network overhead. The results are shown in Fig. 7 and Fig. 8. The two network activities that become the source of energy consumption in the proposed scheme are (i) computation of distance based on the received signal strength and (ii) to determine the bandwidth capacity to the selected neighbors. The distance calculation and determining the capacity of links of a node's neighbors is constant, even with increased network load the overall growth of energy consumption is linear in the case of the proposed mechanism. In other words, even though the network load increases, the number of neighboring nodes remains constant, therefore the energy consumption growth is linear. Similarly, in CLOR the energy consuming processes are: (i) negotiation process and (ii) forwarder node selection and (iii) network coding. As all three factors that influence energy consumption, which are solely dependent on thenumber of neighboring nodes, there is no effect on increase in network load. But, compared to CLORDFS, CLOR has higher energy consumption as significant energy is consumed in negotiation process and forwarder selection. In the case of adaptive routing, the periodic generation of *Hello* packets contributes to the energy consumption and in the case of VBF redundant paths used to maintain its robustness against packet loss contribute to energy consumption. As network load increases along with the network time, the energy consumption sharply increases. In addition, generation of multiple copies of same packet also affect the network's energy consumption. In the end, we compared the percentage of bandwidth spent in network activity apart from data transmission. This allows us to determine the effectiveness of a scheme, where the lower the bandwidth percentage on control data, the better. Similar to end-to-end delay, the control activities in the network are individual node centric and dependent on the degree of a node. As CLORDFS and CLOR are both dependent on degree of a node, which is the number of neighbours for a given sender, the percentage of network bandwidth utilized for control transmissions remains constant after a threshold point in the network. However, this is still much higher than the proposed scheme asCLOR utilizes significant percentage of bandwidth for negotiation process. The negotiation process involves request to forward and clear to forward messages that are used before actual message transmission. Where as, the adaptive routing scheme and VBF need lower percentage of bandwidth because of the lower packet generation. With the increase in network load, the number of redundant copies along with periodic hello packets generation contributes to the higher control bandwidth percentage.

6. Conclusion

In this paper, we proposed a cross-layer routing and data forwarding scheme for submerged acoustic

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wireless sensor networks. The protocol uses distance measurements to each of its neighbors to select links that are within shorter distance and offer high bandwidth capacity. The proposed mechanism exploits the feature that shorter links grant higher bandwidth compared to longer links in a system setup of acoustics. Also, with shorter distances the transmission power necessary to communicate would also be lower in contrast to longer links. In addition, the proposed scheme uses a unique rank based mechanism to direct data packets towards the sink without the need for location information that other routing mechanisms like vector based forwarding and hop-by-hop vector based forwarding protocols use. The performance of the proposed scheme is analysed and is shown to perform better in comparison to other contemporary schemes. Even though we incorporated all the characteristics of a channel underwater, as part of our future work, we aim to analyse the performance of the proposed scheme in a real test-bed setup where certain real world factors like salinity, temperature are shown to affect the performance.

Conflicts of interest

The authors declare no conflict of interest.

Author contributions

Conceptualization, B. Uma Rani and Dr. A. R. Naseer; methodology, B. Uma Rani; software, B.Uma Rani; formal analysis, B. Uma Rani; investigation, B. Uma Rani; resources, B. Uma Rani; writing—original draft preparation, B. Uma Rani; writing—review and editing, Dr. A. R. Naseer; visualization, B.Uma Rani; supervision, Dr.A. R. Naseer.

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