SN Computer Science (2021) 2:362
https://doi.org/10.1007/s42979-021-00754-x

SURVEY ARTICLE

Cross-Layer Design Approaches in Underwater Wireless Sensor Networks: A Survey

Roshani V. Bhaskarwar[1] · **Dnyandeo J. Pete**[1]

Received: 16 January 2021 / Accepted: 15 June 2021

Abstract

The research in Underwater Wireless Sensor Networks (UWSNs) has gained momentum over the last two decades owing to the vast applications it supports like environmental monitoring, underwater exploration, disaster prevention, military, navigation assistance, etc. The sensor nodes deployed underwater have limited battery capacity. The main challenge is to design energy-efficient protocols facing the constraints due to peculiar characteristics and harsh underwater environment. The traditional layered approach is inadequate and insufficient for this purpose, hence Cross-layer Design (CLD) is the need of the hour that allows information exchange among the different layers to find an optimal solution with better utilization of scarce resources to improve the network performance. As far as we are aware, there is no survey paper available in the literature dedicated to CLD in UWSN's. We present the unique characteristics of the acoustic channel and its corresponding issues and challenges. The different proposals in the literature are categorized and compared based on the performance metrics. The basic approach for each scheme is detailed with its advantages and shortcomings which will help future researchers to overcome them to design efficient schemes.

Keywords Underwater Wireless Sensor Networks (UWSN) · Cross-layer Design · Quality of Service (QoS) · Energy efficiency · Throughput · Packet Delivery Ratio (PDR)

Introduction

The vast ocean covers almost 70% of Earth's surface and the reason for the existence of life on the earth. Even with its utmost importance to mankind, surprisingly only less than 10% of the whole ocean volume is explored so far. A large area is unexplored yet, therefore there is a vast scope for exploration and research. In the past century mostly the research in underwater communication has been done for military purpose, but with the advent of technology, aqueous research has gained momentum since few decades with growing applications in the field of environmental monitoring, underwater exploration, disaster prevention, military, navigation assistance, location applications, management of oil reservoirs, sea mine detection, etc. [1–4].

UWSN refers to an amalgamation of wireless technology and small micromechanical sensor technology possessing smart sensing, intelligent computing, and communication capabilities which are deployed underwater for sensing the physical parameters of water like temperature, pressure, quality, etc., and transmit it to the control station via sink [5]. These sensor nodes operate on battery power which is limited and impractical to replace in case of failures. So, there is a dire need to conserve this limited energy of the nodes at each step while performing its tasks till it delivers the data to the sink.

Extensive research has been carried out on the design and optimization of protocols and applications for underwater networks in the last two decades. However, to cope up with the challenges faced in designing the protocols due to dynamic underwater characteristics where the traditional layered approach is inadequate, many authors in the literature have advocated the use of cross-layer design for better utilization of the scarce resources and improve the network performance [1, 6, 7].

✉ Roshani V. Bhaskarwar
rvb.2510@gmail.com

Dnyandeo J. Pete
pethedj@gmail.com

[1] Department of Electronics Engineering, Datta Meghe College of Engineering, Sector 3, Airoli, Navi Mumbai 400708, India

The proposals based on cross-layer solutions in UWSNs for performance enhancement have gained momentum recently. So, this motivated us to present a survey on various cross-layer design techniques proposed in the literature so far, under a single umbrella. To the best of our knowledge, there is no survey paper dedicated to CLD in UWSNs. Ning Li in their survey paper [8] classify the routing protocols based on cross-layer and non-cross-layer designs in UWSN. In [9] Melodia et al. classify the proposed cross-layer solutions in Wireless Sensor Networks (WSN) on the basis of the network layers collaborated in the design, aiming to replace the traditional layered OSI stack. They point out the pros and cons of cross-layer designing along with precautionary guidelines for adopting it. Xiao et al. [10] point out that the traditional layered architecture is inadequate for guaranteeing security in WSN, and presents an overview of the existing cross-layer proposals on security in WSN. Mendes et al. in their work [11] give insights into the different problems in WSN and the cross-layer approaches addressing them. They also discuss the different technologies used at each layer from Application to Physical layer with identifying the open issues in the domain and providing future research directions. Different cross-layer solutions for efficient routing in WSN are surveyed in [12] by Dhage and Vemuru. Sah and Amgoth in their paper [13] gives a comprehensive survey on different parameters and applications for which the cross-layer protocols are opted in WSN. They have categorized the proposals mainly for three metrics such as energy, QOS and security. The authors have also given insights to the various challenges and possible solutions in implementing the CLD. Hasan Ali et al. in [14] presented different cross-layer techniques in wireless multimedia sensor networks that have growing applications in various fields. Mainly the techniques are discussed for Energy efficiency, QOS, security, and reliability. Dhivya Devi and Vidya in their survey [15] have shown the comparative analysis of the different cross-layer optimization proposals for various metrics in WSN with challenges and issues for applying it.

We investigate the key ideas proposed by the research community aiming to alleviate the different issues faced in UWSNs. We analyze and briefly explain the strategy of the protocol with their findings to familiarize the reader with the basic scheme of the protocol and gain insights for further development. As the cross-layer designs implemented in the protocols handle multiple parameters for optimization, it is crucial to categorize them. Here we have focused to categorize the different cross-layer solutions in the literature based on their performance metrics like prominently energy efficiency, QoS parameters viz., throughput, delay, reliability, Packet Delivery Ratio (PDR), Packet Error Rate (PER). Figure 1 shows the classification of CLD proposals in UWSN.

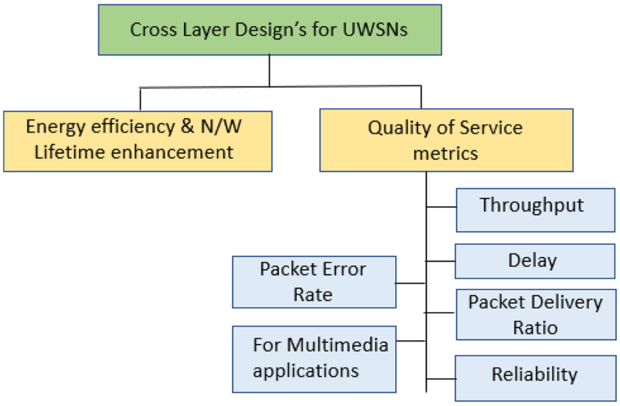

Fig. 1 Classification of cross-layer designs for UWSNs

The paper is organized as follows. "Background of UWSNs" describes the background of UWSNs with its characteristics and challenges. The need for cross-layer designs for UWSNs is emphasized in "Why Should Cross-Layer Design be used?". The cross-layer designs are surveyed and classified based on performance metrics in "Cross-Layer Designs in UWSNs". Finally, "Conclusion and Directions for Future Research" concludes the paper and proposes some directions for future research.

Background of UWSNs

UWSNs usually consist of several sensor nodes equipped with acoustic transceivers deployed at various depth levels with the help of floating buoys, one or more sinks floating on the surface of the water, and a base station on the shore. The underwater sensor nodes sense the physical attributes of the underwater environment according to the application needs and send this data to the surface sink via acoustic links. The sink further relays the gathered data through RF or satellite links to the on-shore base station for further processing. Depending on the applications, additional Autonomous Underwater Vehicles (AUV's) assist the sensor nodes to perform the tasks [1]. Figure 2 below shows the 3-dimensional underwater architecture [16].

Communication in UWSNs is possible in four different ways, Radio Frequency (RF), Acoustic, Optical communication, and Magnetic Induction [17]. RF communication is unviable in underwater networks as high-frequency signals face strong attenuation, absorption, severe fading, and non-gaussian noise unless low-frequency signals (3–300 Hz) are used with large antenna sizes [18]. To achieve higher data rates and low error rates than acoustic links optical modems can be used in conjunction with acoustic telemetry. However, optical signals can only propagate short distances (less than 5 m) [19] and it undergoes high scattering in waters

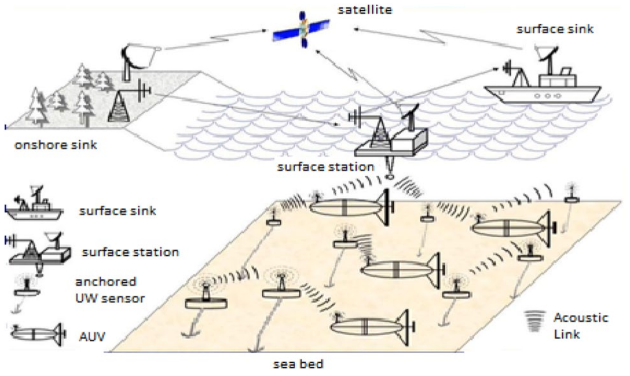

Fig. 2 Architecture for 3D underwater sensor networks with AUVs [16]

and achieves better performance for line of sight positioning. Magnetic Induction technology is mostly used for the Internet of Underwater things which enables real-time communication because of high data rates in near field communication and significant bandwidth as it is independent of impairments of the environment like multipath fading and time-varying signal distortion. This technology is restricted due to issues like path loss due to coupling and conductivity between coils.

The acoustic signal is the only reliable and feasible medium that works satisfactorily in underwater environments owing to its two major properties. First, due to its longitudinal nature, it faces low signal interference, and second, it can travel long distances due to its low frequency. Large transmission coverage is obtained in the range of thousands of meters which allows an efficient deployment of UWSNs.

Characteristics of Acoustic Propagation

The acoustic waves have unique propagation characteristics compared to other waves which are highlighted below.

Propagation velocity: the speed of sound in the water near the surface of the ocean is about 1520 m/s, which is four times faster than the speed of sound in air, but five orders of magnitude lower than the speed of light. This large propagation delay of approximately 0.67 s/km reduces the throughput of the system to a considerable extent. The speed of sound in water depends on the water properties like temperature, salinity, and depth. Approximately it increases 4.0 m/s for 1 °C rise in water temperature, 1.4 m/s with an increase in salinity by 1 Practical Salinity Unit (PSU) and 17 m/s with an increase in the depth (therefore also the pressure) by 1 km roughly [20]. Figure 3 shows the vertical profile of sound speed in seawater as the function of depth.

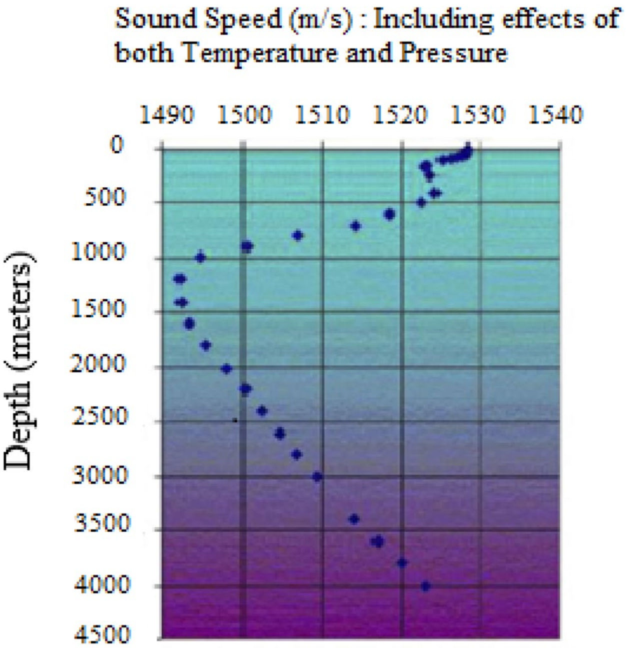

Fig. 3 A vertical profile of sound speed in seawater as the function of depth [20]

Path loss: when sound waves propagate through the water, loss in energy is due to attenuation, geometric spreading, and scattering. The attenuation is mainly produced by absorption which is the conversion of acoustic energy into heat. Geometric spreading refers to the spreading of sound energy which is due to the expansion of the wave fronts as it propagates. It is independent of frequency and increases with the distance covered by the wave front. Scattering, refraction, and dispersion of the acoustic waves also contribute to attenuation.

The path loss is a function of frequency and distance and is directly proportional to it. The path loss that occurs in an underwater channel over a distance s and signal frequency f is given by the equation below [21].

$$A(s,f) = A_0 s^k \alpha(f)^s \tag{1}$$

where A_0 is the normalizing constant, k is the spreading factor and $\alpha(f)$ is the absorption coefficient.

Noise: in underwater acoustic channels there exist different types of noise. These noises are classified into two broad categories as Man-made noise and Ambient noise which are described below.

Man-made noise: these are mainly caused due to shipping activities, heavy vessel traffic, seismic exploration, construction and industrial activities, explosions- dynamite fishing; military, and decommissioning. Aquaculture noise, low-flying aircraft, fishing activities, military activities including sonar and submarines, scientific sources like acoustic communication, and navigation causes interference in underwater acoustic communication [22].

Sometimes noise due to the movement of fishes, animals contribute to the disturbance of acoustic signals.

Ambient noise: it is related to the movement of water i.e. hydrodynamics due to storms, currents, tides, wind, and rain. It is also termed background noise which is a complex phenomenon and occurs due to unidentified sources. In the literature, it is modelled using four different sources: shipping, thermal, waves, and turbulence. The empirical formulae for the four noise components: shipping (R_s), thermal noise (R_{th}) turbulence (R_t), waves (R_w) gives the power spectral density as a function of frequency (k) in kHz as, [21]

$$10\ \log R_s(k) = 40 + 20(s - 0.5) + 26 \log k - 60 \log (k + 0.03) \tag{2}$$

$$10 \log R_{th}(k) = -15 + 20 \log k \tag{3}$$

$$10\ \log R_t(k) = 17 - 30 \log k \tag{4}$$

$$10\ \log R_w(k) = 50 + 7.5\ \mathrm{w}^{1/2} + 20 \log k - 40\ \log(k + 0.4) \tag{5}$$

Multipath: an acoustic wave can progress by taking multiple paths to reach a certain point. In shallow waters where the transmission distance is larger than the depth of water, waves reflecting from the surface and bottom generate multiple arrivals of the same signal. In deep waters, the bottom reflections affect the propagation speed causing a large and variable delay in acoustic communication. As the sound speed varies spatially, the wave refractions however can cause significant multipath phenomena. Acoustic signals are severely degraded due to multipath effects causing inter-symbol interference which makes acoustic data erroneous and difficult to transmit. The multipath geometry depends on the link configuration. The horizontal channels in underwater go through very long multi-path spreads, whereas the vertical channels are characterized by little time dispersion. The extent to which the wave spreads strongly depends on the depth and the distance between the transmitter and the receiver [1, 20, 23].

Doppler spread: underwater channels are very complex channels due to time and space variation. In multipath channels such as shallow waters, a sensor node receives the signal through several different paths and each path has a different delay. The relative motion between transmitter and receiver in a multipath channel introduces different Doppler shifts i.e. mean frequency shift. The largest difference between the path delays is termed delay spread and that of Doppler shifts is called Doppler spread. Doppler effect influences the acoustic channel in two ways: first is the compression or expansion of the pulse width and second is the frequency offset [23].

Issues and Design Challenges Faced in UWSNs

Along with the above-mentioned peculiar characteristics of underwater, the major challenges in designing the underwater acoustic networks due to the differences with the terrestrial networks are given below [1, 4, 24].

- Underwater sensors are expensive than terrestrial ones due to the complex underwater transceivers and protection needed to sustain the harsh environments.
- While terrestrial sensor networks are densely deployed, underwater sensor nodes are sparser as they are expensive and because of the challenges associated with the deployment itself.
- Underwater acoustic communication needs higher energy than terrestrial radio communications to cover large distances and for complex signal processing required at the receivers to compensate for impairments of the unreliable channel. Terrestrial sensor nodes are mostly assumed stationary therefore different topologies can be applied, but underwater sensor nodes are continuously moving in 3D volume due to water currents approximately at 1–3 m/s. Due to this node mobility, it suffers from dynamic network topology changes which is a very challenging task to deal with.
- Accessible bandwidth is severely limited in UWSNs due to acoustic communication, while it is high in the case of terrestrial networks due to the use of RF. Low available bandwidth leads to low data rates, which again depends on both the frequency and communication range. The long-range systems operating over kilometres range cannot exceed the bandwidth of more than a few kHz, whereas short-range systems that operate over tens of meters offer bandwidths of more than a hundred kHz.
- Propagation delay in underwaters is of five orders of magnitude higher than in radio frequency (RF) terrestrial channels, and extremely variable which is a major concern in designing the protocols.
- Spatial correlation in underwater networks is unlikely due to sparse deployment, whereas they are often correlated in terrestrial networks due to dense deployments.
- Underwater sensors require larger memory capacity for some data caching as the channel may be intermittent whereas terrestrial sensor nodes have limited storage capacity.
- Reliability is a major issue in underwaters than terrestrial networks due to inhospitable conditions. The communication links are subjected to temporary losses and high bit error rates due to the unpredictable nature of the underwater environment.
- The underwater sensors are liable to routine underwater challenges like algae collection on the lens of the camera and salt accumulation, reducing the effectiveness of the

device. They are also prone to failures due to fouling and corrosion.
- As terrestrial networks support microwave frequencies, GPS systems can be used for localization purposes, whereas such high frequencies are inappropriate for UWSNs so GPS cannot be used for localization purposes. Therefore, have to rely on other distributed GPS-free localization or time-synchronization schemes.
- Underwater sensor nodes are equipped with batteries, which are limited in power, and it's impractical to replace or recharge them.

Moreover, underwater conditions are highly unpredictable, variable water pressures, unforeseeable underwater activities and uneven depths of the underwater surface makes it difficult to design and deploy UWSNs.

Why Should Cross-Layer Design be Used?

The traditional Open System Interconnection (OSI) model is widely utilized in conventional communication architecture which provides a networking framework for implementing the protocols in seven layers. Each layer is designed and operated independently to attain a specific function. The interfaces between the different layers are static. The protocols in each layer manage the issues of that particular layer based on the services provided by the lower layer and grants the services to the upper layer. This kind of protocol stack allows interaction among the adjacent layers but prevents communication between non-adjacent layers in the stack. It has clear logic, easy to implement, robust, has good expansibility, transparency, and modularity within the networks.

The principle of a layered approach based on the OSI model was originally developed for wired networks that were featured by high bandwidth, less propagation delay, high reliability, no mobility, and less packet loss. With the advent of wireless technology, proposed new challenges in the design of communication protocols, which are required to adapt to the new features of the networking environment like limited bandwidth, shared channels, high error rates, increased latency, and mobility. In UWSNs, as the sensor nodes are driven by limited battery capacity, one of the major challenges of these networks is to prolong the network lifetime by designing and implementing energy-efficient techniques at each layer of its network. Moreover, the challenges mentioned in "Issues and Design Challenges Faced in UWSNs" needs to come up with solutions that require collaborative decisions at different layers. This is not possible in the traditional layered approach that follows strict layering principles and a lack of communication between non-adjacent layers. So, a diversion from the traditional layered approach to an integrated cross-layer design approach is required.

The violation of seven-layered OSI protocol stack to merge or interact with different layers and create new interfaces or additional interdependencies between two or more layers can be termed as CLD [25] or Normally, any effort to violate the black box characteristic of the TCP/IP model is considered as a cross-layer design [26].

The authors in [1, 65] advocate the use of cross-layer design to integrate exclusive communication functionalities for improvising the network performance and avoiding the duplication and communication overheads in the layered approach.

Different from the traditional approach, cross-layer design exploits the information exchange among the different layers to find an optimal solution for the challenges experienced in the harsh underwater environments aiming towards efficient energy and power management, improvise the QoS metrics, design efficient routing protocols, and network lifetime maximization. However, utilizing cross-layer design does not abandon the layered structure completely; it just debilitates the bounds and increases the interfaces between different layers. Intensive research is carried on cross-layer designs in WSN and UWSN since the last decade. The various cross-layer design approaches proposed in the literature are surveyed in [27] and summarized into the following basic categories as shown in Fig. 4

1. **Creation of new interfaces among non-adjacent layers**: in several cross-layer designs, new interfaces are created between non-adjacent layers for information exchange at runtime which is prevented in a layered approach. This category is divided into three subcategories depending on the direction of information flow along the new interfaces shown in Fig. 4a–c

- **Upward information flow**: when an upper layer protocol needs some information from the lower layer(s) at runtime, creates a new interface from the lower layer(s) to the higher layer i.e. in the upward direction. An example would be the selection of next-hop relay node in routing decisions made at the network layer based on the information of channel conditions and residual energy of the nodes from the Physical layer.
- **Downward information flow**: some of the approaches set the parameters of the lower layer of the stack using information from some higher layer creating a new interface in the downward direction. As an example, applications can inform about their QoS requirements to the link-layer like delay requirements and the link-layer can treat those delay-sensitive packets with high priority.

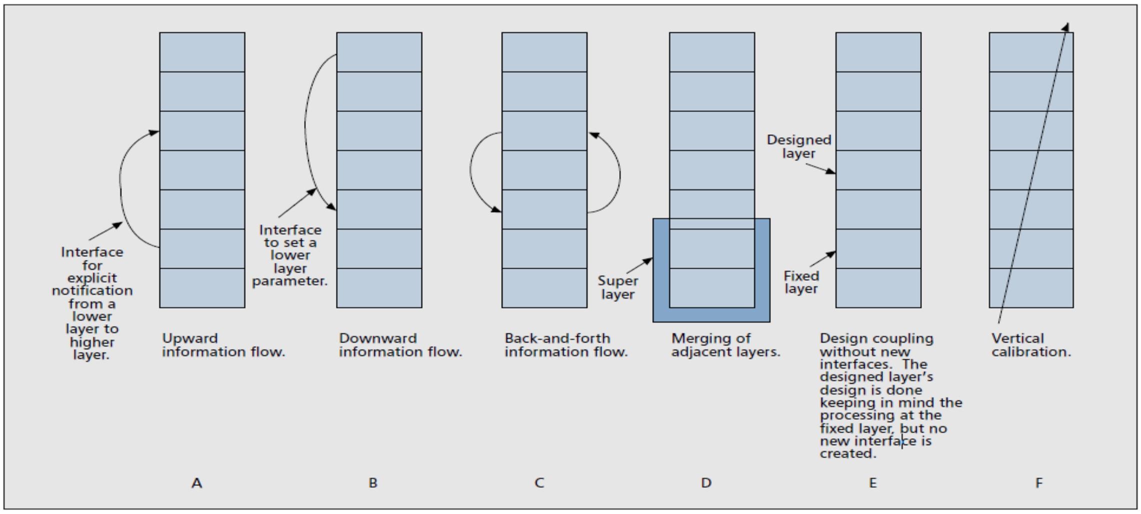

Fig. 4 Illustration of the different kinds of cross-layer design proposals [27]

- **Back-and-forth information flow**: two different layers can collaborate with each other for information sharing at run time. This leads to the formation of two interfaces with an iterative loop among the two layers where information flows to and fro between them. This kind of approach is seen in proposals that perform joint scheduling and power control in sensor networks.

2. Merging of adjacent layers: this kind of approach is to merge two or more adjacent layers to provide joint functionality of the constituent layers which could help in reducing the overheads as illustrated in Fig. 4d
3. Design coupling without creating new interfaces: this category involves the designing of a layer keeping in mind the processing at another layer (fixed layer) without creating any new interface for information sharing at runtime shown in Fig. 4e
4. Vertical calibration over the layers: it refers to jointly tune the parameters that span across the layers to achieve better performance as in Fig. 4f

Cross-Layer Designs in UWSNs

Energy Efficiency Issues in UWSNs and Cross-Layer Designs for Energy Efficiency

Underwater sensor nodes are battery-operated with limited power. It is impractical to recharge them in underwater scenarios where solar energy also cannot be exploited in case of depletion or failures. In most terrestrial radio networks, the power required for transmission and reception is approximately the same with the respective energies being determined by the time spent in the transmit or receive states. In the case of underwater acoustic networks, the power required for transmission is typically about 100 times greater than that required for the reception [28]. Moreover, due to its unique characteristics of frequency-dependent attenuation, the transmission power significantly depends on bandwidth and distance. Energy conservation of the sensor nodes should be the key concern as it plays an important role in deciding the overall lifetime of the sensor network. This is made possible by planning several factors such as make all the components of the system to operate at low duty cycle as possible, efficient use of transmission power while designing the protocols, design of energy-efficient routing protocols, minimizing the circuit's energy, energy-efficient node scheduling at MAC, proper power management, etc. The various CLD proposed in the existing works to increase the energy efficiency and hence the lifetime of the underwater network's [29–39] are reviewed in detail and the comparison is given in Table 1 with their findings.

Enhancing their previous work of Focused Beam routing (FBR) protocol, Jornet et al. in [29] have proposed a cross-layer optimization solution modelled on the relationship between acoustic link capacity and distance. In the proposed solution the PHY, MAC, and the network layer functionalities are tightly coupled through the wise allocation of power and bandwidth to optimize the performance in multi-hop communication to cover large areas in acoustic networks. The FBR protocol at the network layer which requires knowing about its location and that of final destination is coupled with distance aware collision avoidance protocol (DACAP) at MAC. The routing protocol FBR decides the transmission power level based on different criteria and the DACAP at MAC adapts to the different waiting or back off mechanisms according to the transmission distance, finally, the actual

Table 1 Comparison of Cross-layer design proposals for energy efficiency

Protocol	Authors and year of publication	Layers used	Approach	Outcome	Findings
[29]	Jornet et al. (2010)	Physical, MAC, Network layer	FBR at the Network layer and DACAP at MAC are coupled to choose a centre frequency, bandwidth, and transmission power to reduce the energy consumption	Reduced energy per bit consumption	The exchange of control packets in the FBR routing protocol leads to delays and for sparse networks it has to repeatedly expand the size of the arc to find the next-hop nodes. There is also a limitation to the number of power levels
RMAC-PC [30]	Samad et al. (2011)	Physical, MAC	Transmission power is controlled based on the knowledge of the distance between the nodes from MAC	Energy efficiency	Increasing the number of power levels increases the complexity of modem design. It is well suited for a network with stationary nodes
[31]	Dong et al. (2013)	Physical, MAC, Network layer	The traditional five-layered approach is redesigned with a cross-layer architecture reduced to three layers Application layer, Network, and Physical layer to reduce energy consumption	Energy efficiency	Implemented for a given topology and the issues of the mobility of the nodes are not addressed
CL-VBF [32]	Parmar et al. (2014)	MAC, Network layer	Implementing CLD to VBF reduces the extra energy consumption of the nodes that lie outside the pipe by assigning different power levels to the nodes which actually participate in the transmission and low power to the rest of the nodes in tandem with the B-MAC protocol	Energy efficiency, better end to end delay	Very low packet delivery ratio
[33]	Mythrehee et al. (2015)	MAC layer, Network layer	ANFIS gives depth information by taking inputs from sensory measurements and a game-theoretic model is used for localization of the sensor nodes. Using the depth information, DBR protocol reports the events to the localized sensor nodes that are close to the sea surface, which in turn forwards it to the sink	Energy efficiency	There is a trade-off between packet delivery ratio and energy consumption which depends on the depth threshold
[34]	Prajapati and Trapasiya (2016)	PHY, MAC, Network layer	The propagation loss is calculated to predict the next location of node at PHY layer, MAC layer allows calculation of energy consumption and buffer space and network layer improves routing policy based on energy mobility and depth of the nodes	Energy efficiency and Network lifetime enhancement	The propagation loss information can vary due to the dynamic characteristics of the underwaters

Table 1 (continued)

Protocol	Authors and year of publication	Layers used	Approach	Outcome	Findings
FF-MAC [35]	Wahid et al. (2017)	MAC, Network layer	The fitness function calculates a node's suitability to make forwarding decisions based on parameters like depth, residual energy, and transmission delay	Energy efficiency, latency	Exchange of control packets RTS/CTS and ACK leads to increased delay in the network
[36]	Koseoglu et al. (2017)	Physical, MAC layer	Assigns higher MAC layer resources to the nodes placed at longer distances from the sink as the PHY layer efficiency depends on the distance	Reduced energy per bit consumption	Single-hop scenario is considered
[37]	Dhongdi et al. (2017)	PHY, Data link, Network layer	A 3D network with clusters of sensor nodes deployed at varying depths is coupled with DCB-TDMA MAC protocol along with time-synchronization and power level management for energy efficiency	Energy efficiency throughput, end-to-end delay	The nodes are assumed to be static in designing the protocol stack, mobility is not considered
[38, 39]	Zhou et al. (2019)	PHY, MAC layer, Network layer	Initially, the nodes are set to transmit at the most energy-efficient transmission rate derived using an underwater acoustic channel model. Then a constrained least square problem is formulated which gives an analytical solution of the optimal network flow at each link	Network lifetime maximization	Increase in the number of common nodes and decreasing α in linear topology shortens the lifetime of the network

switching to a new transmission power level takes place at the Physical layer. For every node, they have demonstrated the benefits of properly choosing the centre frequency, bandwidth, and transmission power according to the network conditions to reduce the energy consumption per bit. The exchange of the RTS, CTS control packets in the FBR routing protocol leads to delays in the UWSN and when the network is sparse it has to repeatedly enlarge the size of the arc to find the next-hop nodes. There is also a limitation to the number of power levels in the modem as its complexity increases with the increasing number.

The authors in [30] propose an extension over R-MAC protocol RMAC-PC which uses cross-layer optimization of MAC-PHY layers. A node goes through the latency detection phase to know the latencies to all its neighbors from which internodal distances are calculated at the MAC layer. This information is passed on to the PHY layer to calculate the optimum transmission power required for a node to transmit based on its distance, rather than using uniform maximum power for all the nodes. The energy required for transmission is always higher than the required for the reception of signals. Transmission power grows exponentially as the distance increases, so here by using different power levels for transmission based on the knowledge of distances can reduce the energy/bit consumption of the network. The energy efficiency can be improved by increasing the number of discrete power levels, but this increases the complexity of modem design. The RMAC-PC is well suited for the network with stationary nodes.

Intending to reduce energy consumption in the networks deployed for Coastal and Arctic Maritime Operations and Surveillance sensor networks (CAMOS), Dong et al. in [31] have proposed a cross-layer architecture wherein they have re-organized the layers of the traditional OSI model, into a new design with three layers—Physical Layer, Network Layer, and Application layer. A new middleware called cross-layer interaction is added to enable information sharing among the layers and the information transferred between layers is divided into two classes: CTRL stands for control information; and DATA for user data. This is implemented for a given topology and the issue of mobility of the nodes is not addressed.

To improve the energy efficiency in UWSN, the authors in [32] proposed a cross-layer approach which is a modified version of VBF protocol called CL-VBF where the routing layer carries out power management along with the MAC layer. VBF routing protocol is based on the concept of a hypothetical routing pipe with a predefined width based on some threshold value in the network. In VBF, the transmission of packets is done through nodes that lie within the range of the pipe and are discarded by the rest of the nodes that lie outside the range but are part of communication. CL-VBF reduces this extra energy consumption of the nodes which lie outside the pipe by assigning different power levels to the nodes which actually participate in the transmission and low power to the rest of the nodes in tandem with the B-MAC protocol. Implementing the cross-layer approach to the VBF, the simulation results show significant improvement in energy efficiency and a better end-to-end delay but have a very low PDR.

For non-time-critical applications like marine environment monitoring, a cross-layer technique is proposed by Mythrehee in [33] keeping energy efficiency in mind. The proposed methodology uses three types of sensor nodes deployed underwater such as the ordinary nodes, localized nodes, and multiple sink nodes on the surface. Here, the sensor inputs obtained from the PHY layer such as temperature, pressure, salinity are given to an adaptive neuro fuzzy based interference system (ANFIS) to determine the depth of the sensor nodes. Opportunistic localization by topology control (OLTC) a game-theoretic model is used for localization of the sensor nodes close to the sea surface. Using the depth information DBR protocol reports the events to the localized sensor nodes that are close to the sea surface, which in turn forwards it to the sink. The functional block diagram of the proposed scheme is shown in Fig. 5. Simulation results show better energy efficiency as compared to the counterparts.

The authors in [34] suggest a cross-layer optimization of PHY, MAC, and Network layers for the network lifetime enhancement and energy efficiency. The propagation loss is calculated to predict the next location of node at PHY layer, MAC layer allows calculation of energy consumption and buffer space and network layer improves routing policy based on energy mobility and depth of the nodes.

Wahid et al. in [35] proposes a cross-layer MAC protocol called fitness function based medium access control (FF-MAC) which integrates network and MAC layers for improvement of latency and energy consumption. They have used a Fitness function which calculates a node's suitability to forward or not based on three parameters i.e. depth, residual energy, and transmission delay. The node with the highest value of FF is selected as a forwarder. Handshaking and scheduling algorithms are used for a fair share of the channel in the network. The proposed protocol improves energy and

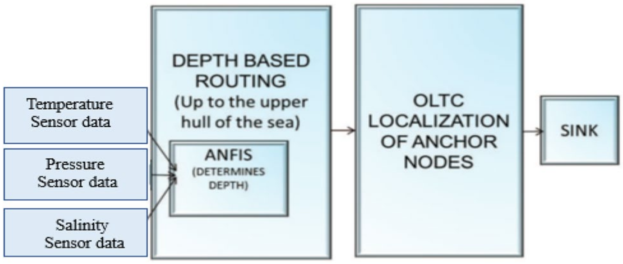

Fig. 5 Functional Diagram of the Proposed Work [33]

lowers delay compared to Improved Vector-Based Forwarding (I-VBF). The exchange of control packets RTS/CTS and ACK will lead to an increased delay in the network.

With the objective of energy minimization, the authors in [36] first analyze the optimization of PHY and MAC layers separately. Then, they investigate the channel access rate for the ALOHA MAC layer which helps to minimize the energy consumption per successfully transmitted bit. Further, they develop a cross-layer optimization problem that jointly optimizes PHY and MAC layers for minimizing energy consumption. Energy per bit consumption is reduced significantly by assigning higher MAC layer resources to the nodes which are at longer distances from the sink because the PHY layer efficiency depends on the distance which makes it less efficient for distant nodes but here the authors have considered a single-hop scenario. It is observed that using cross-layer optimization there is a 66% reduction in energy per bit consumption as compared to separate optimization of both layers.

To increase the energy efficiency and improvement in overall network performance in harsh underwater environments Dhongdi et al. in [37] has developed an entire cross-layer protocol stack for long-term ocean column monitoring applications in three-dimensional underwater acoustic sensor networks. The stack encompasses functionalities of TCP/IP layers such as PHY, Data link, Network, and Transport layer with various network management planes like localization, time synchronization, clustering, and power management. The proposed protocol stack was effectively implemented on an open-source UnetSim simulator on a 3D network architecture. It is evident from the comparison with a basic protocol stack that effective power level management leads to improved network performance of the proposed protocol stack in terms of, throughput, end-to-end delay, channel utilization, and energy consumption. They further suggest that the various parameters such as dimensions of the column, power levels of CH nodes, duty cycle of TDMA MAC and time slot duration can be adapted based on the requirement of the application. In the design of this protocol stack, they have assumed the nodes to be static.

Intending to maximize the network lifetime in UWSNs Yang et al. have proposed a cross-layer optimization solution in their work [38]. To formulate the optimization problem, they consider link scheduling and the computation of transmission power and transmission rates of the nodes for fairly balancing energy consumption among the nodes with adopting time division multiple access (TDMA) scheme. Then, an iterative algorithm for solving the optimization problem which alternates between link scheduling and computing the transmission powers and transmission rates is proposed. Further, Zhou et al. in their paper [39] have developed a cross-layer design methodology to maximize the lifetime of the network operation for given network topology and a bound of the total transmission time of all links. They jointly consider transmission power and transmission rate control at the Physical layer, link schedule at the MAC layer, and the link flow at the network layer. A linear and a rhombus configuration of the network are used to illustrate the design. Simulations show good performance in terms of longer network lifetime. However, with an increase in the number of common nodes and decreasing α in linear topology, the lifetime of the network shortens.

Cross-Layer Designs for Quality of Service in UWSNs

Initially, UWSNs were deployed for environment monitoring applications which required low bandwidths and could tolerate delays, but with the advancements in the digital, MEMS and communication technologies, they are used for a variety of applications ranging from, picture and video acquisition and classification, multimedia coastal and tactical surveillance, disaster prevention, assisted navigation, mines tracking, undersea explorations, etc. These applications, however, require the UWSN paradigm to be reconsidered because of delivering the contents with a certain level of QoS to provide desired latency, throughput, reliability, energy consumption, fairness, etc. UWSN characteristics such as frequency-dependent transmission loss, high propagation delay, multipath, limited battery power, variable channel capacity, and node mobility make the achievement of desired QoS metrics a challenging task. The design of a standardized or universal QoS protocol for UWSNs is a very difficult task due to its dependence on the application requirements and the nature of the monitored environment. The difference between traditional layered and cross-layered approach is that the traditional approach investigates the optimization of protocols in individual layers, leading to the achievement of the desired QoS in a specific layer, while in cross-layer approach the QoS is provisioned by jointly optimizing the interactions among all layer protocols to achieve an individual objective. The primary advantage of the cross-layer approach is that it leads to optimize the overall performance of the UWSN and provide overall QoS provisioning. The network design's aims to achieve a good trade-off between the QoS and energy consumption.

The state-of-the-art in cross-layer techniques for QoS provisioning are reviewed in "Cross-Layer Designs for Enhancing Throughput and End-to-End Delay Metrics" "Cross-Layer Designs for QoS in Multimedia Applications" below [40–67] with comparison given in Table 2.

Cross-Layer Designs for Enhancing Throughput and End-to-End Delay Metrics

Doukkali et al. have proposed a cross-layer MAC protocol to reduce the handshaking delay for a star topology network

Table 2 Comparison of Cross-layer design proposals for QoS metric enhancements

Protocol	Authors and year of publication	Layers used	Approach	Outcome	Findings
Cross layer design's for enhancement of throughput and end-to-end delay					
[40]	Doukkali et al. (2007)	PHY layer and MAC layer	CDMA is used at the Physical layer for transmissions and Rake receiver for the reception.MAC layer is based on CSMA/CA protocol which allows simultaneous transmissions by the nodes without exchange of control packets to reserve the medium	Throughput, average delay	There is a limit to the number of nodes by the spreading factor value
FBR [41]	Jornet et al. (2008)	PHY, MAC, Network layer	A geographical distributed routing protocol that dynamically establishes routes to reach the destination using a power control mechanism to select the next relay nodes lying in the cone region whose axis joins the source and the destination	Reduced energy per bit consumption and end-to-end packet delay	Unsuitable for sparse networks and it is a less flexible network
[42]	Shashaj et al. (2014)	PHY MAC, Network layer	A set of 4 different scheduling and routing policies like FIFO, LOAD, LWS, FAIR and FAN, LIGHT, SP, and LIN respectively along with power control are used to select the node and its best transmission time to achieve interference aware and reliable communication	Throughput, energy efficiency and link interference	Too many assumptions for scheduling and routing policies makes it complex to implement
[43]	Su et al. (2015)	MAC layer and Network layer	Equal bandwidth is allocated to all the contending nodes. If the node cannot use its bandwidth because of constraints elsewhere, then the residual bandwidth is distributed among others. It gives the permitted rates to single-hop sub-flows and then arranges conflict-free transmissions of every sub-flow accordingly	End-to-end throughput, channel access delay, max–min fairness among competing flows	A lot of computation and information is required for fair sharing

Table 2 (continued)

Protocol	Authors and year of publication	Layers used	Approach	Outcome	Findings
DBR-MAC [44]	Li et al. (2016)	MAC layer, Network layer	Aiming to reduce the collisions in the DBR protocol, DBR-MAC is a cross-layer approach that integrates depth-based routing and a handshaking MAC. The angle, depth, and overhead of the neighbor nodes are considered for the shallow nodes i.e. key nodes that are heavily loaded to access the channel with higher priority than the rest of the nodes	Throughput, end-to-end delay and energy efficiency	Prioritizing the shallow nodes overburdens them, which drains their battery power, and will die soon. This creates energy holes in the network leading to packet loss
CLC-MAC [45]	Fan et al. (2016)	PHY layer, MAC layer	A node computes and stores multi-path and propagation delay with its neighboring nodes, and uses a handshaking mechanism through the exchange of RTS and CTS control packets along with propagation and multipath delay time whenever it wants to transmit data	Throughput, average transmission delay, and energy efficiency	Three-way handshaking leads to Increased delay
[46]	Emokpae et al. (2018)	PHY, Data link, Network layer	Wireless Acoustic Line Link (WALL) routing approach uses information obtained from lower layers about the links that have satisfied QoS to find efficient and minimum latency paths	Throughput, energy efficiency	Network lifetime increases with increasing density of nodes but throughput reduces which is a QoS measure
WBFL [47]	Ning Li et al. (2018)	PHY layer, data link, Network layer	Weight-based Fuzzy logic algorithm is used to optimize more number of cross-layer parameters to select balanced relay nodes for routing towards the destination	Network throughput	Each node should know the location of every other node in the network and introduces delay by exchanging RREQ and RREP messages
CEETHCOR [48]	Dang and Kim (2019)	PHY layer, MAC, Network layer	A joint relay node is selected based on cross-layer information for each two-hop cooperative communication to save the transmission energy of the nodes	Throughput, end-to-end delay, energy efficiency	exchange of RTS/CTS control messages and ACK introduces an end-to-end delay

Table 2 (continued)

Protocol	Authors and year of publication	Layers used	Approach	Outcome	Findings
TRMAC [49]	Zhao et al. (2019)	MAC layer and PHY layer	Time Reversal nature is exploited to harvest the multipath energy from the highly scattered underwater environment and focus it towards the intended node in the network, so that parallel transmissions are allowed with significantly reduced interference	Throughput, minimized delay, and reduced data drop ratio	The handshaking mechanism used to reserve the channel introduces a delay
[50]	Kim and Kim (2020)	MAC, Network layer	A relay node is selected among the set of candidates based on the minimum routing cost provided by a routing protocol at the network layer	Average delay	The details of the routing protocol at the network layer are based on assumptions
Cross layer designs for enhancement of Packet Delivery Ratio (PDR) and end-to-end delay					
CARP [51]	Basagni et al. (2015)	PHY layer and Network layer	The protocol exploits link quality information for next-hop selection based on the recent history of successful transmissions to its neighbor nodes maintained in the senders. The selection of relays is based on the hop count, quality of the link, buffer space, and residual energy	PDR, energy consumption, latency	The link quality of the same transmission can vary frequently due to the dynamic characteristics of UWSNs, therefore it is hard to maintain the updated link status information needed for data transmission, and the fact that the short control packets exchanged between two nodes correctly does not guarantee for longer data packets also to be received safely
NCRP [52]	Wang et al. (2017)	Network layer, Transport layer	Implements receiver side routing scheme with two phases, initial routing construction, and route maintenance. Network coding is proposed to solve high energy consumption and low data delivery ratio in multicast networks	PDR, end to end delay, and average energy	The secondary nodes also join to forward data packets, which wastes energy
[53]	Bharamagoudra et al. (2017)	PHY, Network layer	Agents based routing scheme taking into consideration link quality, depth, residual energy, hop count, queue size	PDR, end to end delay. Energy consumption	Communication overhead increases due to multiple transmission of control packets

Table 2 (continued)

Protocol	Authors and year of publication	Layers used	Approach	Outcome	Findings
NADIR [54]	Petroccia et al. (2018)	PHY, Network layer	The selection of the best relay node and different coded modulation schemes are based on the network and channel conditions. The various factors considered are the number of hops, the link quality information, the energy required for transmission depending on the selected modulation scheme, and the residual energy	PDR and energy consumption	Requires design of complex modems to realize it
RECRP [55]	Liu et al. (2018)	PHY, Network layer	location free scheme and implements in two phases of routing table updating phase and routing phase adopting the information from PHY layer such as Doppler scale shift and RSSI to dynamically adjust the transmission power and channel frequency for efficient routing	PDR, end-to-end delay	In the periodic updating phase, the sensor nodes broadcast with maximum power which can drain the nodes affecting the lifetime
[56]	Dang and Kim (2019)	PHY layer, Network layer	Cross-layer cooperative routing which selects RR and CR based on link quality metrics such as SNR, TOA, and hop count	PDR, end-to-end delay, energy consumption	exchange of control messages generates more overheads and there is one extra transmission by CR at every hop
[57]	Ghannadrezaii et al. (2019)	PHY layer, Network layer	A statistical model of the acoustic channel is used to predict the future state of the channel using the probability distribution of the channel amplitude and delay spread from previous observations, based on which the optimum link is acquired	PDR and energy consumption	Energy is expended in listening to the beacons and the memory capacity and complexity of acoustic nodes increase with SDN

Table 2 (continued)

Protocol	Authors and year of publication	Layers used	Approach	Outcome	Findings
Cross-layer designs for enhancement of reliability					
[58]	Sun et al. (2017)	PHY, MAC, Network layer	The nodes deployed at the same depth organizes a cluster. At the network layer, the CH transmits the aggregated data to the CH shallower than itself, MAC layer avoids inter-cluster collisions by implementing a CSMA/CA based protocol and intra-cluster collisions by using a pre-defined schedule. At the Physical layer, the nodes self-adaptively change transmission power and transmitting frequency to minimize energy consumption	Transmission reliability and decreasing transmission delay	The issue of node mobility, connectivity voids is not addressed and delays are introduced in sending ACK from one hop nodes to cluster heads
SUN [59]	Toso et al. (2017)	PHY, Network layer	Reactive source routing uses buffering of the packets to be transmitted and received from the lower layers along with stop and wait ARQ mechanism at the Network layer	Lower error rates and energy efficiency	High end-to-end delay due to path discovery and maintenance procedures
SDH-TDA-MAC [61]	Moroz et al. (2019)	MAC layer, Network layer	A centralized scheduling MAC without synchronization of the sensor nodes is adopted along with the fewest relay nodes selection and route diversity strategies at the network layer	Improved reliability and throughput	It improves the network reliability at the cost of reduced network goodput due to transmission of duplicate packets and increased dual-hop links
QoSRP [62]	Faheem et al. (2019)	PHY layer, Network layer	The routing scheme implements three basic mechanisms during time crucial data gathering process i.e. the underwater channel detection, then assignment of the underwater channel, and packet-forwarding	Data delivery rates, PER, throughput, latency, congestion, and load balancing	High energy consumption due to communication overheads

Table 2 (continued)

Protocol	Authors and year of publication	Layers used	Approach	Outcome	Findings
[63]	Rahmati et al. (2019)	PHY layer, MAC, Link layer	The use of chaotic CDMA codes at MAC in combination with HARQ is exploited to adjust physical and Link layer parameters to compensate for the poor quality of underwater communication links to achieve high throughput and reliability	Improved reliability and throughput	The collaborative implementation of the protocol with the closed-loop strategy of sending ACK/NACK by receivers introduces delays, moreover, the retransmission of packets after timer expiry reduces the throughput and increased delay
Cross-layer designs for multimedia applications					
[64]	Pompili et al. (2006)	PHY, MAC, Network layer	The delay tolerant approach allows each node to jointly select its best next-hop, transmitted power, and FEC code rate for each packet, with the objective of energy minimization considering the channel conditions. Whereas, in the delay-sensitive case, the algorithm is further constrained by avoiding retransmissions of corrupted packets at the Link layer	Energy efficiency	Adopts a single-packet transmission scheme and receives ACK for correct reception which introduces delay
[65, 66]	Pompili and Akyildiz (2008)	PHY, MAC, Network layer	The solution combines a 3D geographical routing algorithm at the network layer, a distributed CDMA/ALOHA scheme at MAC, and an optimized solution for jointly selecting modulation and transmit power at the PHY layer	High energy conservation and fair efficient sharing of UWA medium	Such jointly designed cross-layer solution complicates the decision-making process and the time needed for the optimal decision affects the feasibility of real-time applications
UMIMO [67]	Kuo and Melodia (2012)	PHY, MAC, Network layer	The UMIMO-routing strategy uses MIMO OFDM links to leverage the trade-off between multiplexing and diversity gain to minimize the energy consumption and selects the next-hop by taking into account the number of hops to the sink, transmit power, and packet error rate	Energy efficiency and improves packet drop rate and end to end delay	More than one antenna on the node for MIMO communication is not profitable due to limitations of size and cost

[40]. In the proposed scheme, CDMA is used at the Physical layer for transmissions and the Rake receiver for the reception. MAC layer is based on CSMA/CA protocol which allows simultaneous transmissions by the nodes in the shared channel without the exchange of RTS/CTS control packets to reserve the medium. This minimizes the delay in delivering the packets as the inherent long propagation delay characteristic in UWSN induces increased latency due to the exchange of control messages for handshaking. The protocol is compared with CSMA/CA with two transmitters transmitting to the same receiver. Simulation results show a lower bit rate than CSMA/CA but better performance for a large transmitter–receiver distance. Performance increases with an increasing number of transmitting nodes, however, there is a limit to the number of nodes by the spreading factor value.

Flooding-based routing protocols in which the location information of nodes is not known in advance, lead to an increase in the broadcast queries overburdening the network and reducing the throughput. Jornet et al. in [41] have proposed a cross-layer solution named FBR to reduce such unnecessary flooding of packets for acoustic networks. It is assumed that every node is aware of its location information and the source node is aware of the destination location without any information of intermediate nodes. The proposed scheme is a distributed algorithm where the routes are established dynamically as the data packets traverse in the network to reach their final destination. The next-hop relays are selected at every step when the suitable nodes propose themselves.

The FBR routing mechanism is described in Fig. 6. The node A wants to transmit a data packet to destination B whose location is already known therefore A multicasts RTS control packets which include the source and destination location to its neighbors. Initially, this transmission is done at the lowest power level among a set of discrete power levels P_1 to P_N and this level will be increased if no neighboring nodes are found in the selected powers communication range. The neighbors which receive these RTS packets find their location relative to an imaginary line AB that joins the source and destination. This is required to find out whether they lie within the cone of angle ± $\Theta/2$ which emanates from the transmitter to the receiver. If the candidate lies in the transmitters cone, it responds with a CTS-like control packet and will be selected as the next-hop relay. Improved average packet end-to-end delay and energy per bit consumption is obtained compared to the routing with pre-established routes. However, this protocol will be very efficient if the next relay nodes are found with every first RTS packet sent with the least power level, but due to water movements, the nodes can become sparse and will not tend to lie within their transmitters forwarding cone. Hence, the source retransmits the RTS with enhanced power levels which leads to an increase in communication overheads and affects the data forwarding in the sparse regions. The assumptions of static sink also make the network less flexible.

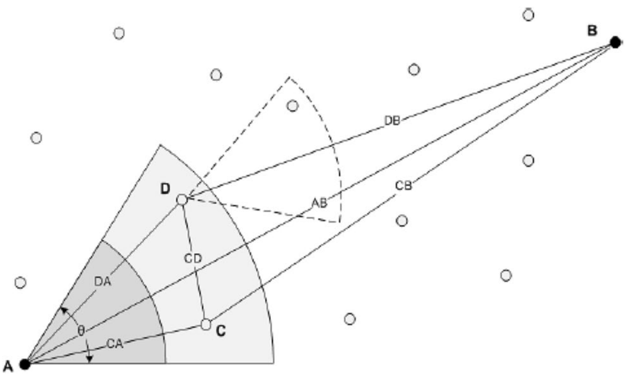

Fig. 6 FBR protocol illustrating nodes within the transmitters cone Θ as candidate relays [41]

Shashaj et al. in [42] have come up with a cross-layer heuristic scheme that efficiently uses the scarce resources of UWSN like bandwidth and energy. They have developed a class of scheduling and routing policies along with the use of power control. Transmissions of the node are therefore scheduled following different policies: (1) It offers precedence to the nodes that are ready for transmission earlier than others thus minimizing delay in packet delivery (FIFO), (2) priority to the nodes which have more number of packets in their buffers (LOAD), (3) priority to the nodes placed far away from the sink (LWS) and (4) to the nodes that have sent fewer packets compared to others (FAIR). The routing policies adopted to select the next-hop node are: (1) It aims to minimize the time gap between the instant at which it is ready to send the packet and its effective transmission time (FAN), (2) reduce their buffer size (LIGHT), (3) limiting the number of hops to reach the sink (SP) and (4) reduction in the data traffic (LIN). Such policies along with the use of a set of transmission power levels allocate each node its best transmission time, reliable link, and transmission power level to achieve interference aware, reliable, and low power communications. Different combinations of scheduling and routing policies are studied to obtain optimal results, where it is observed that a fair scheduling strategy with a routing solution yields the best performance in terms of reduction of network load. Also, power control helps in the improvement of network energy consumption and increases throughput. However, too many assumptions for routing and scheduling policies make it complex to implement and the nodes need to be active all the time which consumes energy.

Intending to develop an underwater MAC protocol that provides high end-to-end throughput, low channel access delay, and fair bandwidth sharing among the flows which compete for the medium sharing in multi-hop underwater sensor networks Su et al. in [43] has proposed a cross-layer

MAC protocol. It aims to interact with a max–min fair rate allocation scheme on the network layer, which first allocates bandwidth equally to all the contending nodes. If the node cannot use its bandwidth because of constraints elsewhere, then the residual bandwidth is distributed among others. It gives the permitted rates to single-hop sub-flows and then arranges conflict-free transmissions of every sub-flow accordingly. In this framework, the transmission time is slotted and a node listens to the medium to get the information of the rates and then exchanges it with its neighbors. The proposed scheme has distributed operation and is applicable to both static and dynamic flows with a short convergence time. It seems that a lot of computation and information is required for fair sharing.

The directional packet transmissions in depth-based routing lead to load imbalance where shallow nodes undertake the most loads (called key nodes) which can eventually deplete them. The authors in [44] have proposed a cross-layer MAC protocol that prioritizes the low-depth nodes to access the channel. Each node in DBR-MAC uses the angle, depth, and the transmissions overheard from one-hop neighbor node's for scheduling the transmissions and giving the key nodes higher priority. If it finds that the packet is going to collide with a neighbor, from the knowledge it has gained by calculation of the neighbor's transmission and reception schedule, it backs off for a certain period. Hence it minimizes the collisions and increases the throughput, energy consumption, and delay at the cost of fairness between the nodes. However, prioritizing the shallow nodes overburdens them, which will drain their battery power, and will die soon. This creates energy holes in the network which will lead to packet loss.

Due to the peculiar characteristics of the channel in UWSNs, designing a MAC protocol is a challenging task. Fan et al. in [45] have proposed a cross-layer contention-based MAC i.e. CLC-MAC where a node computes and stores multi-path and propagation delay with its neighboring nodes. When a node wants to transmit data, it uses a handshaking mechanism through an exchange of RTS and CTS control packets along with propagation and multipath delay time. It reduces the packet drop ratio leading to high network throughput compared to slotted FAMA and RIPT, but at the cost of increased delay due to three-way handshaking.

To address the drawbacks of a traditional layered approach to optimize the network for QoS, the authors in [46] propose a cross-stack design to meet some desired QoS performance requirements. The proposed scheme uses cross-layer communication between the physical, data link, and network layers. The cross-layering of the lower layers enables to identify the links that meet certain QoS requirements. Then this links information is exploited by the network layer to establish energy-efficient routes with low end-to-end delays. A routing protocol is developed termed as Wireless Acoustic Line Link (WALL) which uses the link information those qualifying certain QoS obtained from the lower layers along with the known relative positions of the nodes to establish paths to maximize the total network lifetime and to minimize the end-to-end delay. The results obtained show the improvement over energy, throughput as compared to its counterparts. The network lifetime increases with the increasing density of nodes as more paths are generated which balances the network traffic increasing the residual energy. However, the network throughput reduces with density.

Fuzzy logic has been widely used in the design of routing protocols for WSN and ad-hoc networks. Obtaining a balanced solution for routing algorithm with CLD is possible with fuzzy logic, but the drawback is that with the increasing number of inputs, the fuzzy rules increases exponentially therefore these algorithms cannot handle more number of cross-layer parameters simultaneously. To overcome these drawbacks Ning Li et al. in [47] have proposed a weight-based fuzzy logic algorithm (WBFL) which is a cross-layer opportunistic routing approach. The advantage of using WBFL algorithm is that with an increase in the number of inputs the number of fuzzy rules does not increase and hence more cross-layer parameters can be considered to locate the balanced relay nodes. Due to the dynamic underwater environment, the nodes move freely hence the authors propose a residual link lifetime prediction algorithm using triangle geometry theory and relative velocity of the source, destination, and relay nodes. They have proposed a weight-based fuzzy logic algorithm WBFL assuming that each node knows the location of every other node in the network. The source node transmits RREQ packets to its neighbors which consists of the location of the source and destination nodes. The receiving neighbors will calculate the distances to the destination nodes and the ones whose distance to reach the destination are greater than that of the source node will drop the packet while those with smaller values than the source will reply with RREP messages to the source. The source node upon receiving RREP messages extracts the cross-layer parameters from it like residual energy, the estimated transmission count of the communication link, relay nodes queue length and delays, the speed, moving direction, and distance to the destination node. Then to select an appropriate relay node they introduce a weight-based multi-attribute utility approach into WBFL algorithm. The simulation results show that the given approach uses many cross-layer parameters without increasing the calculation complexity. It improves the network throughput by 50% compared to its counterpart Ex-OR algorithm. However, each node should know the location of every other node in the network, and the exchange of control packets RREQ and RREP introduce delay.

Aiming to reduce the energy for transmission, a cross-layer channel-aware cooperative routing protocol CEETHCOR is proposed by Hoa et al. in [48]. The design incorporates physical, MAC, and network layers to develop a protocol that delivers data keeping in view the status of nodes up to two hops away from the sender. CEETHCOR is a sender-based protocol that appropriately selects three nodes, a next-hop node, a relay node, and a next two-hop node based on link quality indicators. The sender node forwards the data packets to the next two-hop node via the next-hop node and the relay node. It operates in four phases: (1) Network initialization phase where the information regarding neighbor's hop count, SNR, TOA, residual energy is acquired. (2) exchange of control packets RTS/CTS to reduce the packet collisions at MAC layer. (3) Relay selection phase involves the selection of potential relays in the neighborhood based on link quality and symmetry after handshaking of RTS/CTS messages. (4) data packet transmission and acknowledgment phase where actual data is transmitted and being acknowledged. Although it shows better performance in terms of reliability and hence PDR by taking advantage of cooperative communication through relay nodes, it involves redundant transmissions every two hops which increase the communication overhead and contention leading to energy consumption.

Zhao et al. in their paper [49] show how the Time-reversal process plays an important role in boosting the performance of multi-hop underwater acoustic networks due to its capability to utilize the multi-path energy from the highly scattered underwater environment and focus it in both spatial and temporal domains. They develop a TRMAC protocol which is a joint PHY and MAC layer solution that aims to minimize collision and maximize channel utilization depending on the node's knowledge of the channel impulse response to precode their transmissions. This is achieved by using four frames for handshaking: Probe request frame (P-R), Probe frame used for active TR (Pro), Data frame time-reversed before being transmitted (TR-Data), Acknowledgment (ACK) frame time-reversed before being transmitted (TR-ACK). The handshake mechanism is shown in Fig. 7 Simulation results show significant improvement in throughput, minimized delay and reduced data drop ratio. The handshaking mechanism used to reserve the channel can introduce delay.

To achieve better network performance in UWNS's with long propagation delays, Kim et al. in [50] have come up with a cross-layer-based cooperative communication solution to transmit data packets from the source to the sink node. The proposed design selects a relay node among the set of candidates based on the minimum routing cost provided by a routing protocol at the network layer. The routing protocol in the chosen relay node provides the information of the next-hop address towards the sink to the MAC layer. The MAC layer then forwards the incorrect data packet to the next-hop node instead of a receiver node. Simulation results show better performance in terms of average delay and the number of passed nodes. Here the design includes one-way interaction from network to MAC for the selection of relay nodes which is a limited one and the details of the routing protocol at the network layer are based on assumption.

Cross-Layer Designs for Enhancing Packet Delivery Ratio (PDR) and End-to-End Delay Metrics

Basagni et al. in [51] has proposed a distributed cross-layer solution for delivering data in multi-hop UWSN. The CARP routing protocol exploits link quality information for next-hop selection. The link quality of a sensor node is evaluated based on successful packet transmission history to its neighbor nodes. It also combines hop count, residual energy, buffer space with a power control strategy to deliver packets around connectivity holes and shadow zones. The field

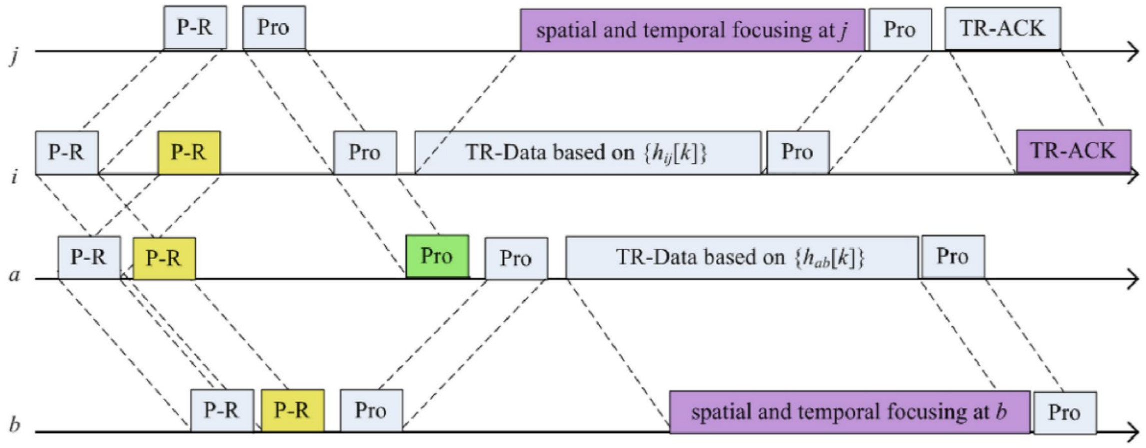

Fig. 7 Channel reservation and recording through P-R/Pro/TR-Data with Pro/TR-ACK handshake in TRMAC [49]

trials and the results show that CARP doubles the PDR as compared to FBR and EFlood. It also outperforms them in terms of energy consumption and latency. However the link quality of the same transmission varies frequently due to the dynamic characteristics of UWSNs, therefore it is hard to maintain the updated link status information needed for data transmission, and the fact that the short control packets exchanged between two nodes correctly does not guarantee for longer data packets also to be received safely. Also, the constant checking of the successful packet transmissions history in the dense networks introduces end-to-end delay. It also faces issues like congestion and data path loops.

The authors in [52] propose a novel cross-layer routing protocol based on network coding which greedily forward data packets to sink nodes efficiently. Network coding is proposed to solve high energy consumption and low data delivery ratio in multicast network. NCRP designs an efficient way to find a reliable data transmission link by fully utilizing a multicast feature in UWSNs combining the Transport and Network layer. The scheme is divided into two parts where initially route is constructed and then maintained. Beacon message is sent from the destination node to find a reliable path to forward data in the initial route construction phase. Then a real-time route maintenance protocol is designed for updation after detecting the ineffective relay nodes. Then the data packets are encoded with random network coding to ensure a low probability of sending repetitive data packets. NCRP does not limit the transmission range for one-hop transmission and the receivers can jointly decode messages with encoded received packets from several neighboring nodes. The next-hop relay is selected based on the current channel quality which makes the data transmissions more reliable and avoids the occurrence of void areas. Figure 8 illustrates the network coding with nodes A and C exchanging packets via relay node B. The simulations are done on NS-3 which shows better results in an end to end latency, packet delivery ratio, average delay as compared to VBF, HHVBF, DBR, and VAPR. However, the secondary nodes also join to forward data packets, which will waste energy.

To deal with the problems of network partitions, connectivity voids due to node failure and/or link failure as well as shadow zones during network operations, a novel agent-based routing scheme is proposed by Bharamagoudra et al. in their paper [53]. The scheme employs a set of static and mobile agents at the sensor nodes, AUV's, UW-GWs, and SG. The routing operates in two phases (1) route discovery phase and (2) route maintenance phase. The route discovery procedure selects the relay nodes from the source to a surface gateway based on link quality, depth, residual energy levels, hop count, and queue size. A cross-layer approach is adopted to estimate the link quality from lower layers. The route maintenance process is initiated once the paths are set up during the route discovery phase and the data transmission has started. This phase is necessary to observe the availability of the paths from source to SG during link breakages or failure of nodes. In the case of network partitions when the routes to the gateways are not available to improve the connectivity and reliability in such cases software agent-based AUVs reorient the direction to act as relays and maintains a route. Simulation results show improvement in energy consumption, packet delivery ratio, end-to-end delay as compared to CARP, however, the protocol involves multiple transmission of control packets which increases the communication overheads to enhance the throughput.

Recently Petroccia et al. in their paper [54] have evaluated through simulation a monitoring network deployed in a very harsh polar environment where propagation delays and packet error rates are very high. They propose a distributive and adaptive cross-layer routing protocol termed NADIR for both static and mobile devices which uses energy consumption as one of the key metrics to find out how to route packets in the network. This protocol is designed to select the best relay node and different coded modulation schemes according to the network and channel conditions. The different factors considered to route the packets are the number of hops, the quality of link information obtained from the Physical layer, the energy required for transmission depending on the selected modulation scheme, and the residual energy of the neighboring nodes. The protocol takes into account the energy balancing which avoids connectivity holes. The results show better network performance in terms of packet delivery and energy consumption in unreliable conditions,

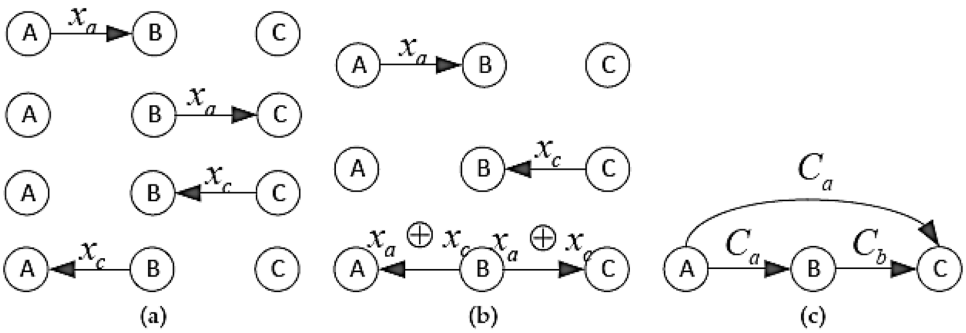

Fig. 8 **a** The conventional approach of multi-casting; **b** The network coding approach of bi-direction transmission; **c** The network coding approach for unidirectional transmissions [52]

but the proposed strategy would require the design of complex modems to realize it.

RECRP proposed by Jun Liu et al. in [55] is a location-free single-copy cross-layer routing protocol. To improve the two-hop packet delivery rate and balance the energy in the network they have proposed Mixed Integer Linear Programming (MILP) model with a max–min method that dynamically adjusts the transmission power and channel frequency for energy-efficient forwarding. As the protocol is based on CLD it adopts the information of the Physical layer such as Doppler scale shift to estimate the relative speed between the nodes and RSSI for adjusting the transmission power and frequency for efficient transmission. These parameters help in selecting the relays without hardware costs. The proposed scheme operates in two phases routing table updating phase and routing phase. In the routing updating phase, the sink node periodically broadcasts a route updating message which helps to build the routing table at each node. After updating its routing table each node sends only one routing update message during the updating phase which avoids the loops hence a single copy. In the routing phase, based on the routing table information the communication frequency, transmission power, and the next-hop relays are selected dynamically to achieve better energy efficiency. RECRP achieves better end-to-end delay and packet delivery ratio but the periodic updating phase in which the sensor nodes broadcast with maximum power can drain the nodes and affect the network lifetime.

Hoa Tran and Dong Kim in their research [56] have designed a cross-layer cooperative routing protocol that takes into account the channel quality. It concurrently selects the Routing Relays (RR) to forward the data on routing paths and Cooperative Relays (CR) for carrying one-hop cooperative communication. When the source has data to send, it independently selects the RR and CR among the neighbors based on the link quality metrics such as Signal to Noise Ratio (SNR), Time of Arrival (TOA), hop count obtained from the Physical layer. The selection of RR is based on two parameters i.e. propagation delay and channel capacity of the links, while CR selection is based on minimum propagation delay to the RR, to minimize the delay spread. The neighbor tables are updated frequently to cope with the dynamic and unreliable characteristics of the underwater channel. The cooperative routing undergoes four essential phases of neighbor table updating, control message exchanges, relay selection, data transmission, and acknowledgment. The routing scheme selects reliable links to forward the data which is based on minimum unsuccessful transmissions. The reliability is improved further by incorporating cooperative relays at every hop. The proposed scheme achieves better performance in end-to-end delay, packet delivery ratio, and energy consumption compared to SPF but the exchange of control messages generates more overheads in the network as well as there is one extra transmission by the CR at every hop.

Hossein Ghannadrezaii et al. in [57] propose a cross-layer solution for a network of self-configured software-defined underwater acoustic nodes (SUANs). It operates in two phases for communication. In the first network control phase, periodic beacons are sent by the sink node by flooding mechanism to the nodes in a cluster to provide prior knowledge about the topology and the routes to the neighbors along with the link quality information. The second phase involves data transmission from the transmitter node to the sink. The nodes predict the quality of the potential links to its one-hop neighbors as well as relays using built-in software. Using the probability distribution of the channel amplitude and delay spread from the previous observations, a hidden Markov process predicts the next state of the channels. Every transmitting node assesses the link quality to its next-hop neighbor relay nodes and accordingly assigns a normalized weight representing the channel quality to each of them. The metrics used for defining the channel quality are channel gain and its delay spread. For evaluating the network performance in practical conditions, the output of a statistical model combined with the Bellhop ray tracing software is compared with experimental data. Each transmitter node selects its next hop optimum relay node based on the prediction of the channel status rather than relying on the expired information in the control packet exchanges. Thus, minimizing overheads in control exchanges saves energy per bit consumption while also maintains a high packet delivery ratio and low latency.

Cross-Layer Designs for Enhancing Reliability

To overcome the QoS issues in UWSN like bit error rate, latency, reliability Sun et al. in [58] came with a cross-layer solution integrating Physical, MAC, and Network layers. In the proposed model, the nodes deployed at the same depth organizes a cluster. At the network layer, the nodes residing at different depths transmit the packets to their CH hop by hop and further CH retransmits the aggregated data to the CH which is shallower than itself until the data arrives at the sink node on the water surface. At the MAC layer, the inter-cluster collisions are avoided by implementing a CSMA/CA based protocol, and intra-cluster collisions are avoided by using a pre-defined schedule to allocate the channel to the CH's. At the Physical layer, the nodes self- adaptively change transmission power and transmitting frequency to minimize energy consumption. The issue of node mobility, connectivity voids is not addressed here and delays are introduced in sending ACK from one hop nodes to cluster heads.

Due to increased overheads caused by route discovery and maintenance, source routing is less used as compared to other routing paradigms. To reduce this overhead and adapt to the peculiar underwater characteristics Toso et al. in [59] have proposed SUN a tailored reactive source routing protocol for underwater acoustic channels. Unlike proactive protocols, SUN conserves, the scarce acoustic bandwidth with its reactive nature. The protocol enables the source to decide the entire route to the destination thereby eliminating the inherent delays and control signalling required in the hop by hop relaying selection. Moreover, it does not require any location information, depth knowledge for routing, and its dynamic design is capable to adapt to the topological changes in the network because of nodes mobility, variations in the channel conditions, etc. It implements CLDs. A buffering system at the network layer buffers the packet received from the lower layers as well as the packets to be transmitted. Another cross-layer feature implemented is the stop-and-wait ARQ mechanism which detects unreliable paths, congested links, and link breakage due to the node movements. The experiments conducted show that SUN manages to route in both static and mobile networks achieves lower error rates and energy consumption compared to its counterparts ICRP while experiences high end-to-end delay due to path discovery and maintenance procedures.

In [60] Moroz et al. have proposed a new Transmit Delay Allocation MAC (TDA-MAC) which exploits the knowledge of propagation delays to achieve high network throughput by centralized scheduling of data without the need of clock synchronization at the sensor nodes. Extending the work ahead in [61] they have proposed a Sequential Dual Hop TDA-MAC (SDH-TDA-MAC) which adopts a cross-layer centralized MAC and routing protocol to achieve high network throughput without clock synchronization in dual-hop network topologies. For achieving maximum throughput in SDH-TDA-MAC, it incorporates the policy of fewest relay nodes as routing strategy at network layer which also makes it vulnerable to link failures leading to packet loss which is common in the harsh underwater environment. To overcome this loss and improve the reliability of the network it uses the concept of route diversity by sending packets onto a redundant set of secondary routes. This method improves the network reliability at the cost of reduced network goodput due to the transmission of duplicate packets.

With the motivation to overcome the issues in UWSNs such as to provide low-cost reliable data delivery, data path loops, the problem of void regions, lack of dynamic channel adaptation Faheem et al. in [62] propose a cross-layer QoS-aware routing protocol (QoSRP) for the internet of UWSNs based delay-sensitive marine monitoring applications. The entire routing mechanism has been modelled using mixed-integer linear programming (MILP). The proposed routing scheme employs three basic mechanisms during time crucial data gathering process i.e. the underwater channel detection (UWCD), then assignment of the underwater channel (UWCA), and packet-forwarding (UWPF). The UWCD technique finds the unoccupied channels with a greater probability of detection and low probability of missed detection and false alarms. UWCA assigns higher data rates channels to sensor nodes with longer idle probability and UWPF implements a hybrid angle-based and greedy routing mechanisms to forward the collected data to the sink avoiding congestion, data path loops, and balancing the energy consumption load of the network. The simulation results show better performance in terms of data delivery rates, PER, throughput, latency, congestion, and load balancing but at the expense of high energy consumption due to communication overheads.

To maximize the throughput in applications like Internet of Underwater Things (IoUT) which are severely affected due to weak and poor communication links in harsh and dynamic underwater environment Mehdi Rahmati et al. has proposed a solution in [63] to improve the reliability of the network against errors in poor communication links by adopting an adaptive hybrid ARQ scheme in combination with a DSSS-CDMA based approach. They have used chaotic sequences in CDMA to increase the security of the links as well as HARQ and CDMA properties are exploited to adjust the parameters of the Physical and Link layer to compensate for the poor quality of underwater communication links by reducing retransmissions and controlling the power. Using the collaborative technique, the nodes decide on the selection of bits for various parameters like data rate, transmission power, spreading parameters, navigating different trade-off's collaboratively with other neighboring active nodes. Experimental analysis is carried out for shallow and deep waters at CMRE LOON testbed and REP18-Atlantic sea trial respectively. The joint implementation of the protocol which uses HARQ for data protection and CDMA using chaotic codes for secured and interference-free transmissions depends on the closed-loop policy in which the receivers send back short ACK/NACK messages. Here the feedback link from receivers is assumed to be error-free which is impossible and the packets need to be retransmitted again if the timer expires so this feedback and exchange of ACK/NACK introduces delay and affects the throughput. Moreover, the neighboring nodes have to be active all the time overhearing which consumes energy.

Cross-Layer Designs for QoS in Multimedia Applications

Recently with the advancements in micro and digital electronics, Underwater Multimedia Sensor Network (UMSN's) have gained momentum in enabling various applications like undersea explorations, coastal multimedia surveillance, image acquisition and classification, target tracking, disaster detection, etc. However, to practically realize these applications efficient routing mechanisms for multimedia content delivery with a desired level of QoS is required. Pompili and Melodia in their research [64] analyze the function between packet size and the corresponding node distance. Two geographical routing algorithms are proposed based on this function. They consider the channel quality, transmission power, and application requirements into consideration for selecting the next-hop relay nodes. Further extending their work Pompili and Akyildiz in [65, 66] have explored the cross-layer interactions of pivotal underwater functionalities like FEC, modulation, MAC, and routing to develop a cross-layer communication protocol that facilitates several devices to efficiently and fairly share the delay prone and bandwidth limited underwater acoustic medium. They have considered four traffic classes based on delay and loss sensitivity which need different QoS requirements for multimedia applications. To satisfy these QoS requirements, a resource allocation framework is developed relying on a distributed optimization problem that jointly controls the parameters at different layers. The proposed solution combines a 3D geographical algorithm, a distributed CDMA/ALOHA based MAC scheme, and an optimized solution for jointly selecting modulation, FEC scheme like BCH, and transmit power at PHY leading to high energy conservation and fair and efficient sharing of UWA medium. However, such a jointly designed cross-layer solution certainly complicates the decision-making process and the time needed for this optimal decision affects the feasibility in real-time applications.

For multimedia underwater applications that have different QoS requirements, Kuo and Melodia in [67] have come up with a novel distributed cross-layer UMIMO with two separate routing algorithms for delay-sensitive and delay insensitive applications for a three-dimensional underwater environment. UMIMO routing utilizes Multiple-Input-Multiple-Output (MIMO) and Orthogonal Frequency Division Multiplexing (OFDM) links which adaptively exploits the trade-off between diversity and multiplexing gain. As a cross-layer approach, the protocol adapts its behaviour to the changing conditions of underwater channels, environmental noise, and interference to find a suitable transmission mode, allocating optimal transmit power on different subcarriers. It minimizes the energy consumption according to QoS needs of the multimedia applications achieved through the cooperation of transmitter and receiver The delay insensitive UMIMO—routing strategy selects the next-hop by jointly considering the packet error rate, transmit power, and the number of hops to reach the sink, whereas in delay-sensitive approach the corrupted packets are not retransmitted. Both aim to minimize the energy consumption and satisfy the QoS requirements of the applications by leveraging the trade-offs between multiplexing and diversity gain based on channel conditions. Using OFDM modulation reduces intercarrier interference which improves the performance of the system. The simulation results show excellent performance in reducing energy consumption, average end-to-end delay, and packet dropping rate but deploying more than one antenna on a node for MIMO communication as well as different power levels is unprofitable due to limitation of size and cost.

Conclusion and Directions for Future Research

Implementing CLD in protocols have become the need of the hour for enhancing and optimizing the performance of UWSNs due to the constraints faced owing to its peculiar features. A survey of CLD proposals in the literature based on the performance metrics like energy efficiency, QoS parameters, network lifetime maximization is presented and compared in this work. We have discussed the unique characteristics and the challenges in acoustic propagation. The basic approach for each scheme is detailed with the advantages and shortcomings which helps future researchers to overcome them to design efficient schemes.

Based on the literature surveyed, it has been observed that although CLDs have aimed to alleviate the challenges encountered in optimizing the performance of UWSNs, some of the factors are unattended. The effect of continuous node mobility which is prevalent in underwaters leads to topology changes creating void regions is seldom addressed in the studies. Designing mobility prediction models for underwaters can help mitigate the issue.

Efficient routing algorithms with minimum control overhead is required for longevity of network lifetime. Transmission of data reliably with minimized overheads also needs attention from the researchers.

The sparse deployment of sensor nodes in the harsh underwater environment with its unique characteristics makes them vulnerable to various types of threats and malicious attacks. Therefore, security should be the key concern while designing the protocols for the smooth conduction of network operations. However, it is found that research in underwater security is in the nascent stage. Different attacks resilient MAC and Routing algorithms are proposed in the literature [68–75]. In [76] the authors argue that layered security techniques only focus on one particular layer which is insufficient and inadequate to tackle the security issue energy efficiently and recommend CLD to minimize resource consumption for required security and robustness. Ateniese et al. in [77] come up with a security framework with CLD but not implemented.

Finally, data aggregation and compressive sensing techniques implemented for energy efficiency in terrestrial WSN’s can be attempted in UWSN.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42979-021-00754-x.

Funding No funding sources.

Availability of Data and Materials Not Applicable.

Code Availability Not Applicable.

Declarations

Conflict of Interest The authors declare that they have no conflict of interests.

Ethical Approval This article does not contain any studies with human participants or animals performed by any of the authors.

References

1. Akyildiz IF, Pompili D, Melodia T. Underwater acoustic sensor networks: research challenges. Ad Hoc Netw. 2005;3(3):257–79.
2. Heidemann J, Ye W, Wills J, Syed A, Li Y. Research challenges and applications for underwater sensor networking. IEEE Wireless Communications and Networking Conference. 2006. p 28–235 doi: https://doi.org/10.1109/WCNC.2006.1683469
3. John H, Milica S, Michele Z. Underwater sensor networks: applications, advances and challenges. Philos Trans R Soc A. 2012;370:158–75.
4. Felemban E, Shaikh FK, Qureshi UM, Sheikh AA, Qaisar SB. Underwater sensor network applications: a comprehensive survey. Int J Distrib Sens Netw. 2015;11:896832.
5. Sozer EM, Stojanovic M, Proakis JG. Underwater acoustic networks. IEEE J Oceanic Eng. 2000;25(1):72–83. https://doi.org/10.1109/48.820738.
6. Foukalas F, Gazis V, Alonistioti N. Cross-layer design proposals for wireless mobile networks: a survey and taxonomy. IEEE Commun Surv Tutor. 2008;10:70–85.
7. Shakkottai S, Rappaport TS, Karlsson PC. Cross-layer design for wireless networks. IEEE Commun Mag. 2003;41(10):74–80. https://doi.org/10.1109/MCOM.2003.1235598.
8. Li N, Martínez J-F, Meneses Chaus JM, Eckert M. A survey on underwater acoustic sensor network routing protocols. Sensors. 2016;16:414.
9. Melodia T, Vuran MC, Pompili D. The state of the art in cross-layer design for wireless sensor networks. International workshop of the EuroNGI network of excellence. Springer, Berlin, Heidelberg. 2005
10. Xiao M, Wang X, Yang G. Cross-layer design for the security of wireless sensor networks. 2006 6th World Congress on Intelligent Control and Automation. Vol. 1. IEEE. 2006
11. Mendes LDP, Rodrigues JJPC. A survey on cross-layer solutions for wireless sensor networks. J Netw Comput Appl. 2011;34.2:523–34.
12. Dhage MR, Vemuru S. A Survey on cross layer solutions for routing in wireless sensor network. Int J Eng Res Technol. 2015;4.8:397–402.
13. Sah DK, Amgoth T. Parametric survey on cross-layer designs for wireless sensor networks. Comput Sci Rev. 2018;27:112–34.
14. Khattak HA, et al. Cross-layer design and optimization techniques in wireless multimedia sensor networks for smart cities. Comput Sci Inform Syst. 2019;16.1:1–17.
15. Devi CD, Vidya K. A survey on cross-layer design approach for secure wireless sensor networks. International conference on innovative computing and communications. Singapore: Springer. 2019
16. Akyildiz IF, Pompili D, Melodia T. State-of-the-art in protocol research for underwater acoustic sensor networks. Proceedings of the 1st ACM international workshop on Underwater networks. 2006
17. Jouhari M, Ibrahimi K, Tembine H, Ben-Othman J. Underwater wireless sensor networks: a survey on enabling technologies, localization protocols, and internet of underwater things. IEEE Access. 2019;7:96879. https://doi.org/10.1109/ACCESS.2019.2928876.
18. Jiang S. On reliable data transfer in underwater acoustic networks: a survey from networking perspective. IEEE Commun Surv Tutor. 2018;20:1036–55.
19. Xiaohong H, Maode Ma. A performance model for differentiated service over single-hop passive star coupled WDM optical networks. J Netw Comput Appl. 2011;34(1):183–93.
20. Liu L, Zhou S, Cui JH. Prospects and problems of wireless communication for underwater sensor networks. Wirel Commun Mob Comput. 2008;8:977–94.
21. Stojanovic M. On the relationship between capacity and distance in an underwater acoustic channel. ACM SIGMOBILE Mob Comp Commun Rev. 2007;11(4):34–43.
22. Christine E. Underwater acoustics: noise and the effects on marine mammals. A Pocket Handbook 2011;164:9–10.
23. Awan KM, Shah PA, Iqbal K, Gillani S, Ahmad W, Nam Y. Underwater wireless sensor networks: a review of recent issues and challenges. Wirel Commun Mob Comput. 2019;2019:1–20. https://doi.org/10.1155/2019/6470359.
24. Ayaz M, Baig I, Abdullah A, Faye I. A survey on routing techniques in underwater wireless sensor networks. J Netw Comput Appl. 2011;34:1908–27.
25. Karuna B, Randhawa R. Cross-layer designs in wireless sensor networks. Computational Intelligence in Sensor Networks. Springer, Berlin, Heidelberg. 2019. p 141–166
26. Bo F, Xiao Y, Deng H, Zeng H. A survey of cross-layer designs in wireless networks. IEEE Commun Surv Tutor. 2014;16(1):110–26.
27. Srivastava V, Motani M. Cross-layer design: a survey and the road ahead. IEEE Commun Mag. 2005;43(12):112–9.
28. Partan J, Kurose J, Levine BN. A survey of practical issues in underwater networks. In Proceedings of ACM WUWNet'06. 2006.
29. Jornet JM, Stojanovic M, Zorzi M. On joint frequency and power allocation in a cross-layer protocol for underwater acoustic networks. IEEE J Ocean Eng. 2010;35(4):936–47. https://doi.org/10.1109/JOE.2010.2080410.
30. Samad SA, Shenoy SK, Kumar GS. Improving Energy Efficiency of Underwater Acoustic Sensor Networks Using Transmission Power Control: A Cross-Layer Approach. Advances in Computing and Communications ACC. Communications in Computer and Information Science, vol 192. Springer, Berlin, Heidelberg. 2011. doi:https://doi.org/10.1007/978-3-642-22720-2_9
31. Dong Y, Dong H. Simulation study on cross-layer design for energy conservation in underwater acoustic networks. San Diego: OCEANS - San Diego; 2013. p. 1–5. https://doi.org/10.23919/OCEANS.2013.6741315.
32. Parmar JK, Mehta M. A cross-layered approach to improve energy efficiency of underwater wireless sensor network. 2014 IEEE International Conference on Computational Intelligence and Computing Research, Coimbatore. 2014. p. 1–10. doi: https://doi.org/10.1109/ICCIC.2014.7238407
33. Mythrehee H, Julian A. A cross-layer UWSN architecture for marine environment monitoring. 2015 Global Conference on

Communication Technologies (GCCT), Thuckalay. 2015. p. 211–216. doi:https://doi.org/10.1109/GCCT.2015.7342654.
34. Prajapati A, Trapasiya SD. Cross-layer design approach for energy optimization in underwater acoustic sensor network. 2016 IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT), Bangalore. 2016. p. 1282–1286. doi: https://doi.org/10.1109/RTEICT.2016.7808038.
35. Wahid A, Ullah I, Khan OA, Ahmed AW, Shah MA. A new cross-layer MAC protocol for data forwarding in underwater acoustic sensor networks. 2017 23rd International Conference on Automation and Computing (ICAC), Huddersfield. 2017. p. 1–5. doi: https://doi.org/10.23919/IConAC.2017.8082037
36. Koseoglu M, Karasan E, Chen L. Cross-layer energy minimization for underwater ALOHA networks. IEEE Syst J. 2017;11(2):551–61. https://doi.org/10.1109/JSYST.2015.2475633.
37. Dhongdi SC, Nahar P, Sethunathan R, Gudino LJ, Anupama KR. Cross-layer protocol stack development for three-dimensional underwater acoustic sensor network. J Netw Comput Appl. 2017;92:3–19. https://doi.org/10.1016/j.jnca.2017.03.024.
38. Yang H, Zhou Y, Hu Y, Wang B, Kung S. Cross-Layer Design for Network Lifetime Maximization in Underwater Wireless Sensor Networks. 2018 IEEE International Conference on Communications (ICC), Kansas City, MO. 2018. p. 1–6. doi: https://doi.org/10.1109/ICC.2018.8422176.
39. Zhou Y, Yang H, Hu Y, Kung S. Cross-layer network lifetime maximization in underwater wireless sensor networks. IEEE Syst J. 2020;14(1):220–31. https://doi.org/10.1109/JSYST.2019.2920681.
40. Doukkali H, Houcke S, Nuaymi L. A Cross-layer Approach with CSMA/CA based Protocol and CDMA Transmission for Underwater Acoustic Networks. 2007 IEEE 18th International Symposium on Personal, Indoor and Mobile Radio Communications, Athens. 2007. p. 1-5. doi: https://doi.org/10.1109/PIMRC.2007.4394663
41. Jornet JM, Stojanovic M, Zorzi M. Focused Beam Routing Protocol for Underwater Acoustic Networks. Proc. Third ACM Int'l Workshop Underwater Networks (WUWNET). 2008. p. 75–81
42. Shashaj A, Petroccia R, PetrioliC. Energy efficient interference-aware routing and scheduling in underwater sensor networks. 2014 Oceans - St. John's, St. John's, NL. 2014. p. 1–8, doi: https://doi.org/10.1109/OCEANS.2014.7003110
43. Su X, Chan S, Bandai M. A cross-layer MAC protocol for underwater acoustic sensor networks. IEEE Sens J. 2016;16(11):4083–91. https://doi.org/10.1109/JSEN.2015.2440301.
44. Li C, Xu Y, Diao B, Wang Q, An Z. DBR-MAC: a depth-based routing aware MAC protocol for data collection in underwater acoustic sensor networks. IEEE Sens J. 2016;16(10):3904–13. https://doi.org/10.1109/JSEN.2016.2530815.
45. Fan G, Chen N, Wang X. A cross-layer contention-based MAC protocol for underwater acoustic networks. 2016 3rd International Conference on Systems and Informatics (ICSAI), Shanghai. 2016. p. 655–658. doi: https://doi.org/10.1109/ICSAI.2016.7811034
46. Emokpae LE, Liu Z, Edelmann GF, Younis M. A Cross-Stack QoS Routing Approach For Underwater Acoustic Sensor Networks. 2018 Fourth Underwater Communications and Networking Conference (UComms), Lerici. 2018. p. 1-5. doi: https://doi.org/10.1109/UComms.2018.8493217
47. Li N, Martinez Ortega JF, Diaz VH, Lopez Santidrian L. Cross-Layer Balanced Relay Node Selection Algorithm for Opportunistic Routing in Underwater Ad-Hoc Networks. 2018 IEEE 32nd International Conference on Advanced Information Networking and Applications (AINA), Krakow. 2018. p. 556–563. doi: https://doi.org/10.1109/AINA.2018.00087.
48. Tran-Dang H, Kim D. Channel-aware energy-efficient two-hop cooperative routing protocol for underwater acoustic sensor networks. IEEE Access. 2019;7:63181–94. https://doi.org/10.1109/ACCESS.2019.2916185.
49. Zhao R, Long H, Dobre OA, Shen X, Ngatched TMN, Mei H. Time reversal based MAC for multi-hop underwater acoustic networks. IEEE Syst J. 2019;13(3):2531–42. https://doi.org/10.1109/JSYST.2018.2890101.
50. Kim K, Kim S. Cross-layer based cooperative communication protocol for improving network performance in underwater sensor networks. Int J Eng Technol Innov. 2020;10(3):200–10.
51. Basagni S, Petrioli C, Petroccia R, Spaccini D. CARP: a channel-aware routing protocol for underwater acoustic wireless networks. Ad Hoc Netw. 2014. https://doi.org/10.1016/j.adhoc.2014.07.014.
52. Wang H, Wang S, Bu R, Zhang E. A novel cross-layer routing protocol based on network coding for underwater sensor networks. Sensors. 2017;17:1821.
53. Bharamagoudraa MR, Manvi SS, Gonen B. Event driven energy depth and channel aware routing for underwater acoustic sensor networks: agent oriented clustering-based approach. Comput Electr Eng. 2017;58:1–19.
54. Petroccia R, Pelekanakis K, Alves J, Fioravanti S, Blouin S, Pecknold S. An Adaptive Cross-layer Routing Protocol for Underwater Acoustic Networks. 2018 Fourth Underwater Communications and Networking Conference (UComms), Lerici. 2018. p. 1-5. doi:https://doi.org/10.1109/UComms.2018.8493225
55. Liu J, Yu M, Wang X, Liu Y, Wei X, Cui J. RECRP: an underwater reliable energy-efficient cross-layer routing protocol. Sensors. 2018;18:4148.
56. Tran-Dang H, Kim D. Channel-aware cooperative routing in underwater acoustic sensor networks. J Commun Netw. 2019;21(1):33–44. https://doi.org/10.1109/JCN.2019.000004.
57. Ghannadrezaii H, Bousquet J, Haque I. Cross-layer Design for Software-defined Underwater Acoustic Networking. OCEANS 2019 - Marseille, Marseille, France. 2019. p. 1-7. doi: https://doi.org/10.1109/OCEANSE.2019.8867186
58. Sun N, Shi H, Han G, Jin Y, Shu L. A Cross-Layer Protocol with High Reliability and Low Delay for Underwater Acoustic Sensor Networks. In: Lee JH, Pack S, editors. Quality, reliability, security and robustness in heterogeneous networks. QShine. Lecture notes of the Institute for computer sciences, social informatics and telecommunications engineering. Cham: Springer; 2016. https://doi.org/10.1007/978-3-319-60717-7_37.
59. Toso G, Masiero R, Casari P, Komar M, Kebkal O, Zorzi M. Revisiting source routing for underwater networking: the SUN protocol. IEEE Access. 2018;6:1525–41. https://doi.org/10.1109/ACCESS.2017.2779426.
60. Morozs N, Mitchell P, Zakharov Y. TDA-MAC: TDMA without clock synchronization in underwater acoustic networks. IEEE Access. 2018;6:1091–108.
61. Morozs N, Mitchell PD, Zakharov Y. Dual-hop TDA-MAC and routing for underwater acoustic sensor networks. IEEE J Ocean Eng. 2019;44(4):865–80. https://doi.org/10.1109/JOE.2019.2933130.
62. Faheem M, Butt RA, Raza B, Alquhayz H, Ashraf MW, Shah SB, Ngadi MA, Gungor VC. QoSRP: a cross-layer QoS channel-aware routing protocol for the internet of underwater acoustic sensor networks. Sensors. 2019;19:4762.
63. Rahmati M, Petroccia R, Pompili D. In-network collaboration for CDMA-based reliable underwater acoustic communications. IEEE J Ocean Eng. 2019;44(4):881–94. https://doi.org/10.1109/JOE.2019.2910940.
64. Pompili D, Melodia T, Akyildiz IF. Routing Algorithms for Delay-insensitive and Delay-sensitive Applications in Underwater Sensor Networks. Proc. ACM MobiCom. 2006

65. Pompili D, Akyildiz IF. A cross-layer communication solution for multimedia applications in underwater acoustic sensor networks. 2008 5th IEEE International Conference on Mobile Ad Hoc and Sensor Systems, Atlanta, GA. 2008. p. 275–284. doi: https://doi.org/10.1109/MAHSS.2008.4660052.
66. Pompili D, Akyildiz IF. A multimedia cross-layer protocol for underwater acoustic sensor networks. IEEE Trans Wirel Commun. 2010;9(9):2924–33. https://doi.org/10.1109/TWC.2010.062910.100137.
67. Kuo L, Melodia T. Cross-layer routing on MIMO-OFDM underwater acoustic links. 2012 9th Annual EEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON), Seoul. 2012. p. 227–235. doi:https://doi.org/10.1109/SECON.2012.6275782.
68. Xu M, Liu GZ, Guan JH. Towards a secure medium access control protocol for cluster-based underwater wireless sensor networks. Int J Distrib Sens Net (IJDSN). 2015;2015(1):325474.
69. Ibragimov M, Lee J-H, Kalyani M, Il Namgung J, Park S-H, Yi O, Kim CH, Lim Y-K. CCM-UW security modes for low-band underwater acoustic sensor networks. Wirel Pers Commun. 2016;89(2):479–99.
70. Dong YZ, Liu PX. A Comparison of Two Secure Routing Protocols in Underwater Acoustic Network. In Proc. Int. Congress on Acoustics (ICA), Sydney, Australia. 2010
71. Rustad H. A Lightweight Protocol Suite for Underwater Communication. In Prof. Int. Conf Adv. Inf Networking & App. WS. (WAINA), Bradford, UK. 2009. p. 1172–1178
72. Dini G, Duca AL. SeFLOOD: A secure network discovery protocol for Underwater Acoustic Networks. In Proc. IEEE Sym. Computers & Commun. (ISCC), Kerkyra Greece. June/July 2011
73. Zhang Y, Zhang Y. Wormhole-resilient secure neighbor discovery in underwater acoustic networks. In Proceedings of INFOCOM 2010, IEEE. March 2010. p. 1–9
74. Wang W, Kong J, Bhargava B, Gerla M. Visualisation of wormholes in underwater sensor networks: a distributed approach. Int J Secur Netw. 2008;3(1):10–23.
75. Kim Y-P, An J-W, Park S-H et al. Data encryption and authentication mechanism based on block cipher mode for underwater acoustic sensor networks. Proceeding of the 2012 International Conference on Information Science and Technology, Part 1, Shanghai, China. April 28–30 2012. p. 374–376
76. Cong Y, Yang G, Wei Z, Zhou W. Security in underwater sensor network. In Communications and Mobile Computing (CMC), 2010 International Conference on (Vol.1, p. 162–168). IEEE
77. Ateniese G, Capossele A, Gjanci P, Petrioli C, Spaccini D. SecFUN: Security Framework for Underwater acoustic sensor Networks. In Proceedings of OCEANS-Genova. 2015. p. 1–9.