Telecommun Syst (2017) 65:139–153
DOI 10.1007/s11235-016-0220-0

Routing protocols for underwater wireless sensor networks based on data forwarding: a review

Mukhtiar Ahmed[1] · Mazleena Salleh[1] · M. Ibrahim Channa[2]

Published online: 30 August 2016

Abstract Nowadays, underwater wireless sensor network (UWSN) is an important field for researchers due to its well know applications like seismic monitoring, disaster prevention, offshore exploration, pollution monitoring, oceanography data collection, equipment monitoring, assisted navigation, and tactical surveillance. Many research challenges are available for UWSN; the design of routing protocol is one of them. The majority of the researchers have designed the routing algorithms but still, the data forwarding mechanism needs improvement. The reliable communication between the source and sink nodes is really a complicated task due to the limitation of the acoustic channel, water pressure, and limited bandwidth. This review paper focuses on the problems of those routing protocols which are based on data forwarding. In this review paper, we further present the route development, data forwarding, and route maintenance of the proposed routing protocols. The key aspects of this review article present the limitations and advantages of data forwarding routing protocols. We also present analysis of data forwarding routing protocols with analytical and numerical simulation methods with their critical analysis. This review article helps the researchers to create further research in the field of routing protocols based on data forwarding.

Keywords Deployment · Route discovery · Data forwarding · Hop count · Route maintenance

✉ Mukhtiar Ahmed
mukhtiar.a@gmail.com

1 Department of Computer Science, Faculty of Computing, University Technology Malaysia (UTM), Skudai, Johor Bahru 81310, Malaysia

2 Department of Information Technology, QUEST, Nawabshah, Pakistan

1 Introduction

Nowadays the research community is well interested in the field of underwater wireless sensor networks (UWSN) because UWSN refers the well-known application oriented information like oil and gas monitoring, underwater mines, offshore explorations, equipment monitoring, assisted navigations etc [1,2].

Some important applications of underwater acoustic wireless sensor networks are:

i. *Distributed tactical surveillance* Acoustic Underwater Vehicles and underwater sensor nodes collectively monitors the area for *surveillance, reconnaissance,* and *intrusion* detection systems [3–6].
ii. *Assisted navigation* Sensors can be used to find dangers on the seabed locate dangerous rocks in shallow waters, berth positions, flooded crashes, and to perform bathymetry profiling [4,7,8].
iii. *Equipment monitoring* Sensor networks in underwater can monitor the expensive equipment and can also detect the problems in equipment [9–11].
iv. *Environmental monitoring* UWSN can monitor the environmental conditions of sea or ocean; these conditions are biological and chemical changes in underwater. Environmental conditions also refer the nuclear status in water. Through UWSN we can improve detection in climate changes, weather forecasting and we can also predict the effect of human activities on marine echo system. Through UWSN we can also observe the marine underwater life and changeable conditions of water which are hazard for human being [12,13].
v. *Disaster preventions* Through UWSN we can also observe the submarine earthquakes and can prevent the human living in coastal areas [14].

vi. *Undersea exploration* UWSN can help to detect the oil-fields and valuable minerals under the sea or marine [15].

A design of a reliable routing protocol for underwater environment is one of the challenging areas. Although there are many routing protocols designed, some of them are localization protocols while some are localization free routing protocols. However, the design of these routing protocols still facing some challenging issues.

The design of routing protocols is affected due to the following challenges:

i. Due to the low speed of sound (1500 m/s) the propagation delay factor is the challenging issue because electromagnetic waves propagation is five orders in magnitude more than sound waves [15,16].
ii. Acoustic channel is harshly reduced, due to time-varying multipath and fading [17,18].
iii. The acoustic bandwidth for transmission is lower than 1 KHz due to noisy underwater environment and water absorption power is greater than 50 Hz; so bandwidth approximately 10 KHz is available at tens of kilo meters [19,20].
iv. Due to shadow zones the high bit error rate will affect the connectivity [15,21].
v. Due to fouling and corrosions the underwater devices (acoustic modems, sensor nodes, AUVs) may become failure [22,23].
vi. In underwater environment the batteries are energy constrained so cannot be recharged easily [24,25].

The contribution of this paper is as follows.

- We have classified the routing protocols based on data forwarding with its classification like flooding addressed based (FAB), flooding depth based (FDB), clustering source based (CBS), and path based (PB). The classification focuses the data forwarding mechanism from source to sink with different methodologies. The limitations and advantages of the proposed routing protocols will help the researchers to further research in the area of the routing protocols based on data forwarding.
- The analytical analysis method focuses the analysis of the proposed routing protocols with different architectural and performance based parameters which guide the researchers to find the research gap in the proposed area.
- The numerical simulation analysis with critical approach is the main novelty of this review paper which focuses the performance of proposed routing protocols; this kind of approach will help the researchers by selecting the best performer routing protocol for further research.

Table 1 Classification of routing protocols based on data forwarding

Flooding address based (FAB)	Flooding depth based (FDB)	Clustering source based (CSB)	Path based (PB)
H2-DAB	AURP	HydroCast	PER
TCBR	EEDBR		MDT
			MPT
			LMPC
			LAFR
			MRP

2 Background and literature review

We have classified the routing protocols based on data forwarding as mentioned in Table 1.

2.1 Flooding address based (FAB) routing protocols

Routing protocols which are based on flooding addresses and utilizing the approach of transmitting the packets to all sensor nodes are called the FAB routing protocols. FAB protocols consume the more energy because of duplicate packets forwarding. FAB routing protocols are H2-DAB and TCBR.

2.1.1 Hop-by-hop dynamic addressing based (H2-DAB)

H2-DAB is multi-sink energy efficient routing protocol [26]. H2-DAB assigns the flooding depth dynamic addresses to the sensor nodes according to the depth level from surface to bottom of water. The surface level buoys are collecting the information and will transfer it through dynamic addresses till bottom depth. The dynamic addresses are generated by the surface sinks with addition of *Hello packet*. The packet format of H2-DAB is based on *hello packet* and *data packet* formats. A sensor node which receives the data packets will forward the data packets to the upper level through greedy method algorithm. When *data packets* are received by surface sinks the delivery is considered as successful; all the surface sinks are linked between each other with radio communication link; surface sinks are also responsible to forward the data to the onshore center.

2.1.2 Temporary clustered based routing (TCBR)

TCBR protocol for UWSN is a multi-hop routing protocol and designed for balanced energy consumption for entire network [27]. The authors have used the two types of nodes for the designing of TCBR; one is ordinary node and other is courier node. The courier nodes with its' embedded mechanical module can move vertically up and down; ordinary sensor nodes will collect the data packets from source nodes and forward them to the courier nodes; the courier nodes will forward the data packets with usage of embedded mechanical module to the surface multiple sink nodes which are deployed on water surface. In TCBR the courier node shares the *hello* message up to 3-hops to show its presence for ordinary sensor nodes; on arrival of *hello* message the ordinary sensor node first confirms the presence of courier node and will forward the data packets to the courier nodes. TCBR uses the acoustic channel in underwater. Surface sink nodes are connected with onshore data center through RF signaling.

2.2 Flooding depth based (FDB) routing protocols

FDB routing protocols are data forwarding protocols and based on addressing mechanism of sensor nodes till the water depth. The descriptions of these protocols are given below.

2.2.1 AUV-aided underwater routing protocol (AURP)

In [28] AURP is proposed; this routing protocol considers some important issues like: (i) propagation delay due to distance (ii) high bit error rate and (iii) low available data rate due to acoustic signaling. The AURP architecture is based on acoustic underwater vehicles (AUVs), sink node, underwater sensor nodes (U-sensors), surface unit, gateways and mothership. The U-sensor nodes will sense the data and will forward the data to the gateway directly or through hop-by-hop mechanism by using the acoustic channel. When the gateway node receives the data it will forward the data to nearest AUV, AUVs are mobile nodes works on long range acoustic communication for control signaling. When AUV is nearer to sink node it will forward the aggregated data to the sink node and the sink node will forward the data to the surface unit with help of powerful signaling (optional fiber optical signaling). AUV can also directly transfer the urgent data to surface units with the help of long range acoustic channel. The surface unit is connected with Mothership through radio communication signaling.

AURP uses the *PHE* (Phenomenon) message type for path identification. AURP is also based on three links for data forwarding one is direct link, second is multi-hop link, and third is direct or multi-hop links. The *PHE* message is based on the length of path. The number of *PHE* messages is depending on O (n) mechanism; whereas n focuses the number of U-sensors.

2.2.2 Energy efficient depth-based routing (EEDBR)

In [29] EEDBR is proposed. EEDBR is the enhanced version of DBR. EEDBR eliminates the problems of DBR through energy balancing mechanism. The functionality of EEDBR is consists of two phases; one is knowledge acquisition phase and second is data forwarding phase. EEDBR refers the simple network architecture which uses the ordinary sensor nodes and sink nodes; ordinary sensor nodes are deployed from top to bottom regions in underwater with acoustic signaling; whereas sink nodes are deployed on the water surface with acoustic and RF signaling. In EEDBR the knowledge acquisition phase will share the information to the neighbor sensor nodes with its *Hello* message; the *Hello* message format is consists of Sender_ID, Residual Energy and Depth. The neighbor nodes only stores smaller depth information for sensor node. The nodes which have smaller depth are only involved in data forwarding mechanism; this kind of mechanism will reduce the extra burden from the sensor node and will also save the energy level of the sensor nodes. In EEDBR the data forwarding phase is based on residual energy and depth. The nodes nearer to sink nodes are called data forwarder nodes; the selection of these nodes is based on high residual energy. Forwarder nodes selection criterion will balance the energy consumption between sensor nodes. EEDBR calculates the holding time with residual energy. The packets forwarding mechanism is based on priority list, holding time, residual energy, sender ID and depth parameters.

2.3 Clustering source based (CSB) routing protocol

CBS routing protocols refers the formation of the clusters. The cluster formation consists on cluster head nodes and cluster member nodes. Cluster head node collects the data packets from the cluster member nodes and forward the data packets to the destination or sink nodes. In this survey paper we only focus the HydoCast routing protocol which is based on data forwarding mechanism. The description of HydroCast is given below.

2.3.1 HydroCast

HydroCast is the geographic distributed localization mobile routing protocol [30] HydroCast forwards the packets to surface buoys through measured pressure levels. HydroCast is stateless and hydraulic pressure protocol which prefers the inexpensive distributed localization. HydroCast protocol forms the clusters without hidden information of terminal nodes. In HydroCast architecture; the clusters are formed with the maximum progress of those nodes which are closer to the destination. Maximum progress can be calculated with packets delivery probability. A sensor node which is the part of the cluster, the information of that node will be embedded in the packet format. In data forwarding mechanism the maximum progressive node has highest priority. The maximum progress node has shortest time-out for transmission. In HdroCast the local maximum recovery method has been used which performs the limited flooding mechanism approach. In the flooding mechanism the local maximum node is called the performer node. The tetra horizontal method has also been used in the designing of HydroCast; this method will identify the neighbour nodes for local maximum node (surface node). The local maximum nodes will forward the information to other local maximum nodes with limited number of hops; and in this way the information will be forwarded to the destination nodes placed on water surface. For removal of void regions the HydroCast refers the greedy based mechanism.

2.4 Path based (PB) routing protocols

PB routing protocols are based on the development of the single or multiple paths from source to sink nodes. The multipath data forwarding protocols enhances the data delivery ratio; if the path establishment method is strong than these kind of routing protocols are efficient as compare to prior discussed types. The different multipath routing protocols are described below.

2.4.1 Power-efficient routing (PER)

In [31] PER routing protocol is proposed. PER eliminates the problems of DBR like: (i) DBR will drop the packets in shallow water due to its fixed domain and (ii) DBR in dense environment cannot work well because the high energy consumption and delay in packets delivery has been observed in dense environment. PER architecture is consists of ordinary sensor nodes and sink nodes. Ordinary sensor nodes are deployed in underwater and equipped with acoustic channel whereas sink nodes are deployed on water surface and equipped with acoustic and RF channel; acoustic channel connects the underwater nodes and RF channel connects the sink nodes between each other and onshore data centre. PER consists of two modules for the data forwarding; one is the forwarding node selector and other is the forwarding tree trimming. The forwarding node selector is further consists of three parameters for data forwarding, these parameters are: (i) transmission distance (ii) included angle and (iii) remaining energy. PER has selected the two candidate nodes in the forwarding mechanism. PER uses the transmission distance and included angle parameters for candidate neighbour nodes which are also involved with data forwarding mechanism, the remaining energy parameter is used for the rest of the sensor nodes. In PER fuzzy logic interference system and decision tree mechanisms are used for the selection of candidate node. In PER forwarding tree trimming mechanism is used for unnecessary power consumptions by sensor nodes.

2.4.2 Multipath division transmission (MDT)

In [32] MDT routing protocol is proposed. MDT routing protocol is based on following assumptions:

i. Divided the underwater communication space into multiple layers called multiple layer divisions (MLD) and the tree-based multi-path technique has also been adapted.
ii. Energy efficiency has been considered as a distributed optimization problem and they resolved this problem with Tabu search algorithm (TSA).
iii. Simulations experiments are based on energy efficiency and total packets error ratio (PER).

MDT network architecture is based on the deployment of sensor nodes at 1000 m depth; 3D deployment has been converted into 2D. The source node will forward the information to the intermediate nodes or cross nodes and cross nodes further forwards that information to other intermediate nodes and in this way information will be forwarded to the water surface nodes. The underwater sensor nodes communicate between each other through the acoustic link and water surface nodes; water surface nodes are also linked with the sink through the RF signaling. The water depth is divided into different levels with different ID numbers. In packets transformation mechanism the source node will develop the multiple tree based paths. The source node transmits the multicast data packets to the neighbor nodes. In MDT the use of cyclic redundancy check (CRC) detects the correct packets for border nodes; the border nodes are actually the cross nodes and placed on multiple levels (borders) of water. The border nodes further forwards the packets to other border nodes and in this way the process will repeated with CRC till successful delivery to the sink node. The sink node will recognize the packet according to the sequence ID numbers embedded in the packets' header. The sink first check the CRC number if it is correct; that means the original packets has been received. Assume that if the original packet has not been received to the sink then sink will collect all the corrupted packets and will generate the original packet. In MDT the coding scheme for converting the bit error rate (BER) into packets error ratio (PER) is also used. The use of LDC algorithm for multiple layer divisions is also adapted in MDT.

2.4.3 Multipath power-control transmission (MPT)

In [33] MPT routing protocol is proposed. MPT focuses the main problem to minimize overall energy consumption for time critical application in underwater environment. MPT is the cross layer architecture; this protocol focuses the power-control factor and the mechanism of packets combining at destination level. The MPT has used the distributed power-control scheme on physical layer to improve the overall energy efficiency. MPT has degraded the hop-by-hop approach. MPT functionality is divided in three phases one is multipath routing, second is source initiated power control, and third is destination packets combining. MPT has used the *multisink* network model; the network model is based on ordinary sensor nodes deployed at the bottom level of water and linked through acoustic signaling. The surface gateway nodes are linked with the ordinary sensor nodes through acoustic signaling and at the same time also linked with the control center through RF signaling. The authors of the MPT have explained; that the *multisink* network model is used for load balancing and multi-path finding.

Multi-path finding phase is the first phase and this phase is composite of *Route Request* and *Route Reply* messages for packets forwarding mechanism. The source node will transfer the packets to the neighbor nodes with *Route Request;* when the message has been received to the neighbor nodes or intermediate nodes; these nodes will forward the message to other intermediate nodes and in this way the message will be received by the destination nodes. The destination node will make a path selection with node dis-joint path mechanism and will send the *Route Reply* message towards source node. When the source node receives the *Route Reply;* the route path will be established. The source node will follow the m^* selection criteria with node-disjoint method for m paths.

Source-initiated power control is the second phase of MPT, through this phase the MPT adds power parameters in the packets format for energy saving purpose. The packet format of MPT is composed of *packet header*, *Data* and *CRC* fields; the packet header is further consists on *Source_id*, *Destination_id, Sequence_no, Power level parameters* and*FEC*. The *Power level parameter* is used to identify the required power level and will make the intermediate node as a relay node. In the packets header the forward error coding (*FEC*) is used to decode the packets. The cyclic redundant check (*CRC*) is used to check the errors in the data part. When the intermediate node will receive the packet format from source node; it will check the packet header; if the header is correct with *FEC* then it will forward the packet to the next hop with specific power level; if the packet is not correct then intermediate node will drop the packet. In large end-to-end delay the MPT will not allow for the transmission.

Destination packets combining is the third phase of MPT; in this phase the correct form of packets successfully transferred to the destination node; if the packets are corrupted then these packets will temporarily be stored in the buffer and after the receiving of the corrupted packets the destination packets combining will recover the original packets and will transfer them to the destination node.

2.4.4 Layered multiple powered control (LMPC)

Layered multiple powered control (LMPC) scheme has been introduced in [34]. The authors of this scheme have considered the noise attenuation problem.

The network architecture focuses the binary tree pattern; there are four kinds of nodes are used in the architecture; source nodes are deployed at depth of the water, surface gateways are deployed on the water surface, cross nodes are placed on multiple layers and sink node is deployed above the water surface. In underwater environment the LMPC communication is based on acoustic channel and on surface to sink level RF channel is used.

The source node will broadcast the packets to the neighbor nodes with next-hop mechanism and neighbor nodes will forward the packets to the cross nodes and further the cross nodes will forward the packets to the surface gateways. The surface gateways forward the packets to the sink node. The next-hop mechanism follows the IP multicast mechanism for data forwarding. The multiple copies of data have been transmitted from source to surface gateways to reduce the packets retransmission. The surface gateways will combine the multiple copies and will generate the original data for sink.

The authors claimed that; LMPC protocols fulfills the targets like (i) reduce noise attenuation in underwater environment (ii) sensor nodes consumes low energy (iii) enhanced the packets delivery ratio.

2.4.5 Link-state adaptive feedback routing (LAFR)

Link-state adaptive feedback routing (LAFR) protocol has been introduced in [13]. LAFR resolves the issues for the deployment of 3-D in underwater environment with the behavior of underwater acoustic modem. LAFR architecture states that in 3-D area the sensor nodes are deployed from bottom to top of the water. The Sink node is placed on the water surface which is also called the destination node. In underwater environment the sensor nodes are linked with sink nodes through acoustic signaling; the sink nodes are also linked with onshore data center through RF signaling. The beam width based methodology of LAFR set the coordinates of sensor nodes as 3D (x_o, y_o, z_o) on 2π-$2\,\theta$ and its communication radius considered as R. Packets forwarding mechanism considered as angular with respect to beam width from bottom sensor node to neighbor nodes. The sensor nodes have ability to establish the multi-hop paths for packets transmission towards sink nodes. The packets transmission mechanism has been considered as upstream and downstream with link detection message format. The link detection method may be symmetric or asymmetric. Route discovery of LAFR is based on link detection, route recovery, route feedback, and route maintenance with routing table.

2.4.6 Multi-layer routing protocol (MRP)

In [35] MRP is proposed. MRP is the localization free and eliminated the issues like: (i) large propagation delay, (ii) limited bandwidth, and (iii) high bit error rate. The architecture of MRP is based on the static super nodes which are deployed from top to bottom of water on different layers, the sensor nodes are deployed at the bottom level of the water, sink nodes are placed on the water surface. The sensor nodes and sink nodes are linked with the acoustic signals, and sink nodes are also connected with the onshore data center through RF signaling. The authors have focused the layers development mechanism around the super node with 2D scenario and assigned the layer ID and sensor node ID for packets forwarding mechanism. MRP has used the different power level schemes for packets forwarding. The use of super nodes improves the packets delivery ratio and enhances the battery life of the ordinary sensor nodes.

2.5 Advantages and limitations of routing protocols based on data forwarding

Table 2 focuses the advantages and limitations of routing protocols based on data forwarding according to classifications.

3 Performance analysis

In this section we focus the performance analysis of routing protocols based on data forwarding with analytical and numerical simulation methods.

3.1 Analytical method

The analytical performance method is very complicated; this kind of method is based on past and present data finding evaluations. This method tells us that how to retrieve the accurate data from the existing research articles and convert that data in some tabular form which focus the novel performance metrics. In our case Tables 3 and 4 are the response of analytical evaluation method for routing protocols based on data forwarding for UWSN. Table 3 focuses the comparison of data forwarding routing protocols through characteristics. We derived the characteristics from the data forwarding mechanism of the routing protocols from source to sink nodes under network architecture. Table 4 focuses the comparison of routing protocols through performance metrics. The performance metric is based on the simulation response of the proposed routing protocols; for example if we compare the data delivery ratio of H2-DAB with MDT; MDT routing protocol's data delivery is low as compare to H2-DAB. From performance metrics it is observed that the PB routing protocols are more efficient as compare to FAB, FDB, and CBS routing protocols due to usage of more efficient adapted data forwarding methodologies.

3.2 Numerical simulation method with critical analysis

The numerical simulation method is based on simulation, in this section the NS2.30 with AquaSim simulator has been used to find out the data delivery ratio, energy consumption and network lifetime of FAB, FDB, CBS, and PB routing protocols based on data forwarding. We considered the general parameters for simulation; the total numbers of nodes are deployed 350 in underwater environment to test the simulation results, deployment size is set on 1500 m $\times$ 1500 m $\times$ 1500 m, layer distance is set on 250 m, packet size is set on 512 bytes. Remaining parameters we considered as given for FAB [26,27], FDB [28,29], CBS [30], and for PB [13,31–33,35] .

3.2.1 Packets delivery ratio

Packets Delivery Ratio (PDR) can be measured the ratio of packets forwards by source node(s) and the packets delivered by the destination node(s). Equation 1 focuses the PDR.

$$PDR = \sum No.\,of\ packets\,received \Big/ \sum No.\,of\ packets\,send \qquad (1)$$

We have evaluated the PDR for FAB, FDB, CBS, and PB routing protocols separately. In Fig. 1 the packets delivery ratio of TCBR is higher than H2-DAB because the methodology used by TCBR is flooding address based with formation of temporary clusters which refers the less number of hops as compare to H2-DAB.

Figure 2 focuses the PDR for FDB routing protocols; PDR of EEDBR is higher than AURP specially in dense environment because EEDBR refers the data delivery ratio with respect to water depth and limited number of nodes are also involved in data forwarding mechanism; where as in AURP the weak methodology is used for communication link which reduces the PDR as compare to EEDBR.

Figure 3 shows the simulation scenario of PDR for CBS routing protocol; the simulation scenario focuses the PDR for HydroCast routing protocol. If the numbers of nodes are 350 the PDR is 99 % which shows that if the number of nodes are increases from 50 to 350 the PDR will also be increases.

Figure 4 focuses the simulation scenario of PDR for PB routing protocols. MRP routing protocol has higher PDR than PER, MDT, MPT, LMPC, and LAFR because use of super node with layer ID is only the reason which enhances the PDR of MPR routing protocol. PDR for MDT routing protocol is less than MRP, PER, MPT, LMPC, and LAFR due to the distance factor between ordinary sensor nodes to border nodes.

Figure 5 focuses the PDR versus number of nodes among higher PDR routing protocols for FAB, FDB, CBS, and PB routing protocols. In Fig. 5 PDR of MRP is higher than TCBR, EEDBR, and HydroCast. It is observed that MRP has used the super nodes and division of water levels with

Table 2 Advantages and limitations of routing protocols based on data forwarding

Classification	Protocols	Advantages	Limitations
FAB routing protocols	H2-DAB	i. No special hardware is needed for the designing of H2-DAB	i. Sensor node will die earlier due to multi-hop technique
		ii. Dynamic node can easily move without use of routing tables	ii. Greedy algorithm not properly defined which may affect the network performance
			iii. Energy efficient algorithm not properly defined which may affect the energy efficiency
	TCBR	i. Use of courier node enhances the packets delivery ratio	i. Design of mechanical module of courier node is much more expensive and mechanical module can also reduce the life of the courier node
		ii. Use of courier node also enhances the battery life of the ordinary sensor nodes	ii. TCBR is not beneficial for critical time applications
FDB Routing Protocols	AURP	i. Controlled mobility AUVs enhances the packets delivery ratio	i. Use of multiple sensor nodes enhances the overall cost of network
		ii. Better usage of acoustic channel enhances n/w performance	ii. Communication links are inappropriate for data forwarding
			iii. Data forwarding reliable algorithm is needed
			iv. Multiple use of links reduces the overall performance
	EEDBR	i. Reduced number of transmission improves the network lifetime	i. Depth calculation mechanism degrades the PDR in sparse area
		ii. Limited number of node selection method enhances the battery life of the sensor nodes	ii. Energy consumption mechanism is not properly defined
CBS routing protocols	HydroCast	i. HydoCast is good enough for the removal of void regions	i. Multiple copies of the same packets have been received by the sink node which will enhance the extra load on network
		ii. Acoustic channel characteristics are well considered by authors which enhances the packets delivery ratio	ii. Energy efficiency parameters are not defined and results related to the energy efficiency are questionable
PB routing protocols	PER	i. Tree trimming mechanism of the PER saves the unnecessary power consumption of the sensor nodes	i. Packets forwarding mechanism is not as simple as described by authors in underwater environment
		ii. Methodology of PER is energy efficient due to the usage of fuzzy logic and decision tree mechanism	ii. Packets delivery ratio is low as compared to DBR due to selected simulation parameters
			iii. In PER architecture the void regions are the major issue so due to the availability of the void regions the overall network performance will be affected
	MDT	i. Packets collection and correction mechanism is better	i. The attenuation problem cannot completely be resolved and obviously the energy level of the sensor node will be affected and in resultant the sensor node will die earlier
		ii. Methodology adapted by MDT reduces the end-to-end delay	ii. Packets delivery ratio will also be affected due to the distance between sensor nodes and border nodes
			iii. CRC check is time consuming; so obviously the number of packets can also be dropped by sensor node(s) due to CRC delay
	MPT	i. MPT is better for time critical applications	i. Packets will not be transferred during large end-to-end delay which will reduce the network performance
		ii. Use of multi-sink model enhances the packets delivery ratio	ii. MPT refers the hop-by-hop mechanism; so authors claimed is false that the technique not refers the hop-by-hop mechanism

Table 2 continued

Classification	Protocols	Advantages	Limitations
			iii. Authors claimed that the MPT is energy efficient but scheme shows that MPT is not energy efficient..
			iv. Packets combining mechanism is time consuming which may affect the packets delivery ratio (PDR).
	LMPC	i. Removal of noise and attenuation problem in underwater environment improves the performance of the overall network	i. Noise attenuation needs proper methodology
		ii. The next-hop and IP multicast mechanism enhances the packets delivery ratio	ii. Data forwarding mechanism is needs improvement
			iii. Distance factor may be increases due to node movement and will affect the overall network performance
	LAFR	i. 3-D node deployment mechanism is better	i. Ordinary sensor nodes have the extra burden for calculating routing path and obviously this extra burden will reduce the battery life of the ordinary sensor nodes and in resultant the overall network performance will be reduced
		ii. Beam width mechanism reduces the end-to-end delay	ii. Routing discovery through link detection is not possible in underwater environment due to continuous movement of water
	MRP	i. Use of super node enhances the battery life of the ordinary sensor node	i. Nodes deployment is considered as 2D but in real sense the underwater environment supports the 3-D deployment
		ii. Use of powerful super node also increases the packets delivery ratio	ii. Packets holding time algorithm is not properly defined
			iii. Due to the water current the sensor nodes can move throughout the water and can away from the super node and in resultant the sensor nodes will drop the packets; obviously the overall network performance can also be affected

Table 3 Comparison of data forwarding routing protocols through characteristics

Classification	Protocol	Single or multi-sink	Hop-by -hop/end-to -end	Single or multiple copies	Cross-layer/ non-cross layer	Hello message	Localization needed
FAB routing protocols	H2-DAB	Multi-sink	Hop-by-hop	Single	Non-cross-layer	√	×
	TCBR	Multi-sink	Hop-by-hop	Single	Non-cross-layer	√	×
FDB routing protocols	AURP	Single-sink	Both	Single	Non-cross-layer	√	√
	EEDBR	Multi-sink	Hop-by-hop	Multiple	Non-cross-layer	√	√
CBS routing protocol	HydroCast	Multi-sink	Hop-by-hop	Multiple	Non-cross-layer	×	×
PB routing protocols	PER	Single-sink	Hop-by-hop	Single	Cross-layer	×	×
	MDT	Single-sink	Hop-by-hop	Multiple	Non-cross-layer	×	×
	MPT	Multi-sink	Hop-by-hop	Multiple	Non-cross-layer	√	√
	LMPC	Single-sink	Hop-by-hop	Multiple	Non-cross-layer	×	×
	LAFR	Single-sink	Hop-by-hop	Single	Non-cross-layer	√	×
	MRP	Multi-sink	Hop-by-hop	Multiple	Non-cross-layer	√	×

Table 4 Comparison of data forwarding routing protocols through performance

Classification	Protocol	Performance	Cost efficiency	Data delivery	Delay efficiency	Energy consumption	Bandwidth efficiency	Reliability
FAB routing protocols	H2-DAB	Medium	High	High	Medium	Medium	Medium	Medium
	TCBR	Low	Low	Medium	Low	Medium	Medium	Medium
FDB routing protocols	AURP	Medium	Low	High	Medium	High	Medium	Medium
	EEDBR	Medium	N/A	High	Medium	Low	Medium	Medium
CBS routing protocol	HydroCast	High	Medium	High	High	Medium	Medium	Medium
PB routing protocols	PER	High	Medium	High	Medium	High	Low	High
	MDT	Medium	Low	Low	Low	High	Medium	Medium
	MPT	Medium	Low	High	Low	Medium	Low	Medium
	LMPC	Medium	Medium	High	Medium	Low	High	Medium
	LAFR	Low	Medium	High	Low	High	Low	Medium
	MRP	Medium	N/A	High	Low	Low	Medium	Medium

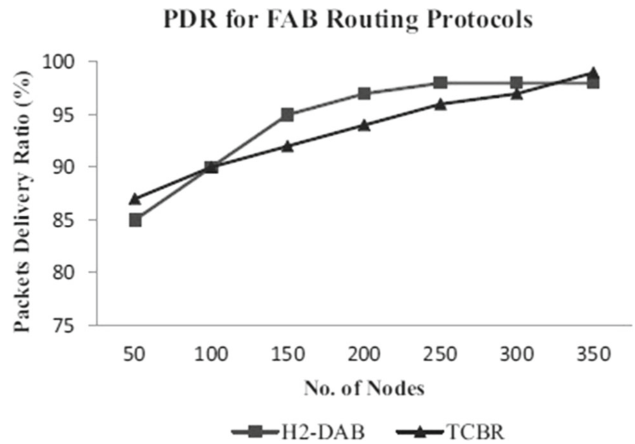

Fig. 1 FAB PDR versus number of nodes

respect to the water depth is almost the successful methodology among the data forwarding routing protocols.

3.2.2 Average energy consumption

It measures the average difference between the initial level of energy and the final level of energy that is left in each node. Let E_i is the initial energy level of a node, E_f is the final energy level of a node and n = number of nodes in the simulation [36]. Then average energy is given in Eq. 2 is:

$$E_a = \frac{\sum_{k=1}^{n} (Ei_k - Ef_k)}{n} \quad (2)$$

We compare the average energy of FAB routing protocols in Fig. 6; TCBR routing protocol consumes the less energy as compare to H2-DAB because in data forwarding mechanism the use of costly courier node and less number of hops saves the energy level of ordinary sensor nodes. H2-DAB data forwarding mechanism utilizes more energy due to increase in number of hops.

Figure 7 shows the average energy consumption of FDB routing protocols. In Fig. 7 EEDBR routing protocol consumes the less energy as compare to AURP because EEDBR uses the energy balancing mechanism in data forwarding. AURP consumes more energy due to signaling overheads.

Figure 8 focuses the average energy consumption of CBS routing protocol; if number of nodes are 50 the HydroCast consumes the 160 joules and if number of nodes are 350 HydroCast consumes the 1150 joules.

Figure 9 shows the average energy consumption of PB routing protocols. In Fig. 9 MRP consumes less energy as compare to other proposed PB routing protocols because MRP uses the powerful static super nodes which enhances the life of the ordinary sensor nodes. Secondly LMPC routing protocol consumes the less energy as compare to rest of

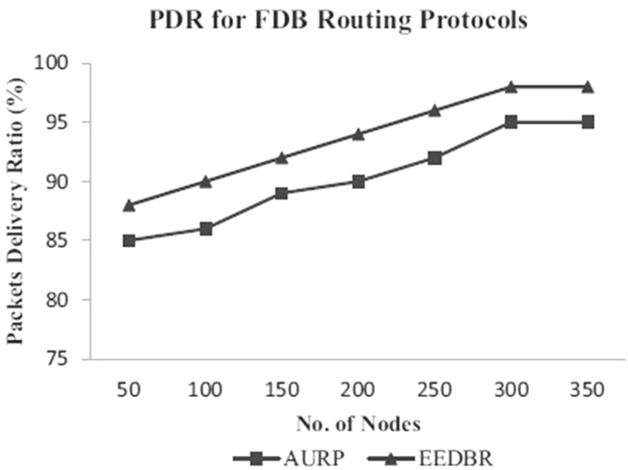

Fig. 2 PDR versus no. of nodes for FDB routing protocols

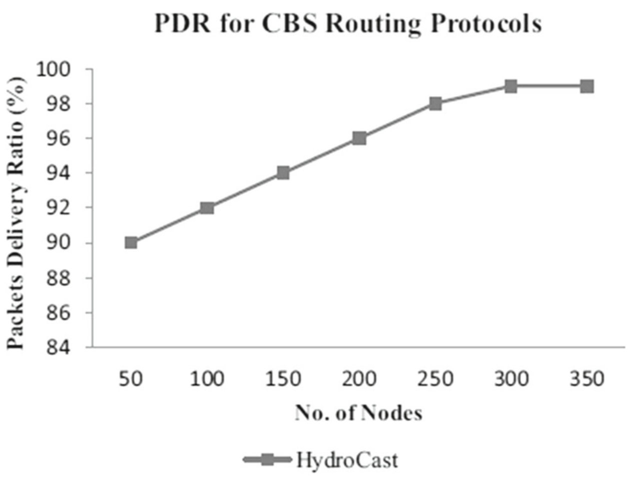

Fig. 3 PDR versus no. of nodes for CBS routing protocol

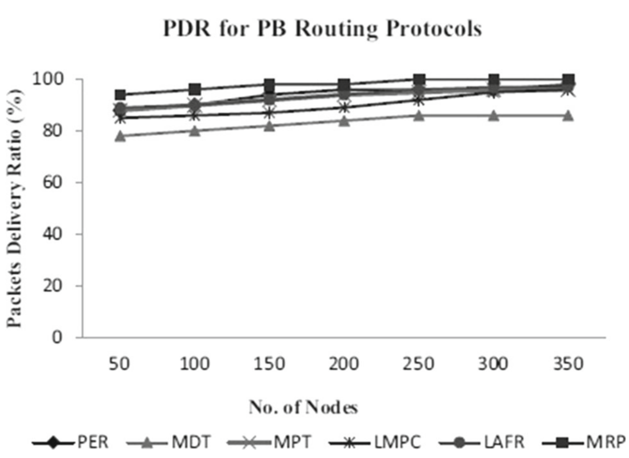

Fig. 4 PDR versus number of nodes for PB routing protocols

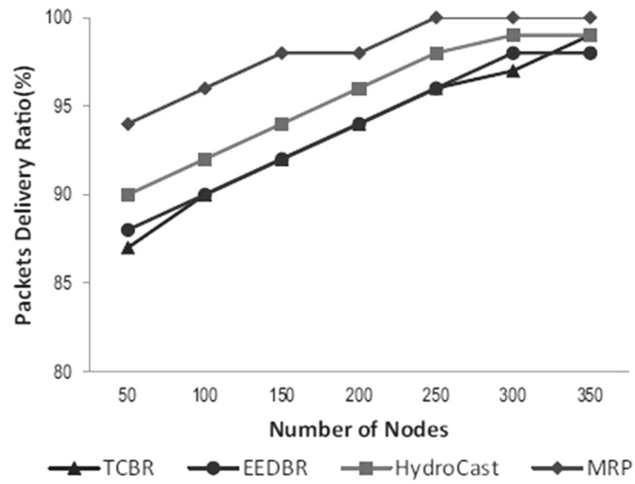

Fig. 5 PDR versus no. of nodes among high in PDR

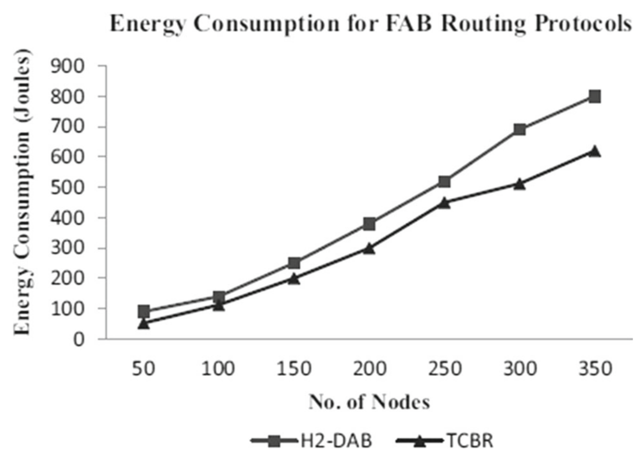

Fig. 6 Energy consumption versus number of nodes for FAB protocols

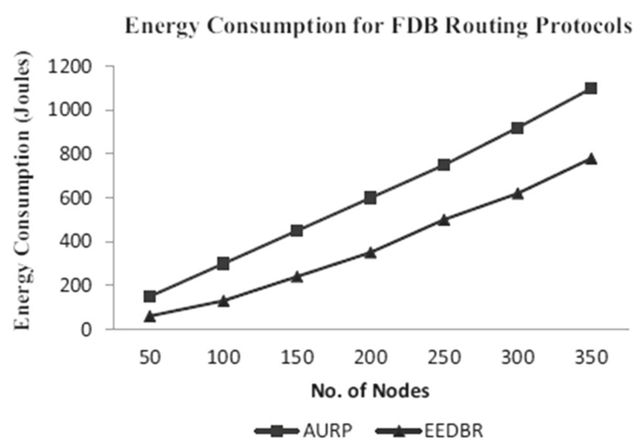

Fig. 7 Energy consumption versus number of nodes for FDB protocols

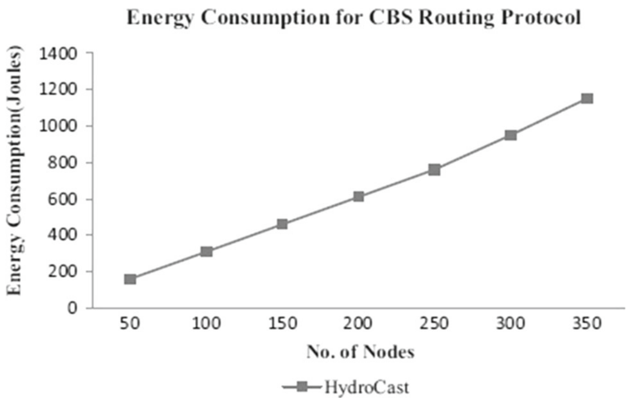

Fig. 8 Energy consumption versus number of nodes for CBS protocols

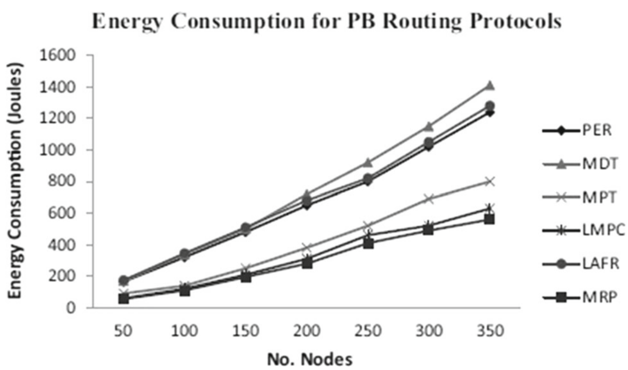

Fig. 9 Energy consumption versus number of nodes for FAB protocols

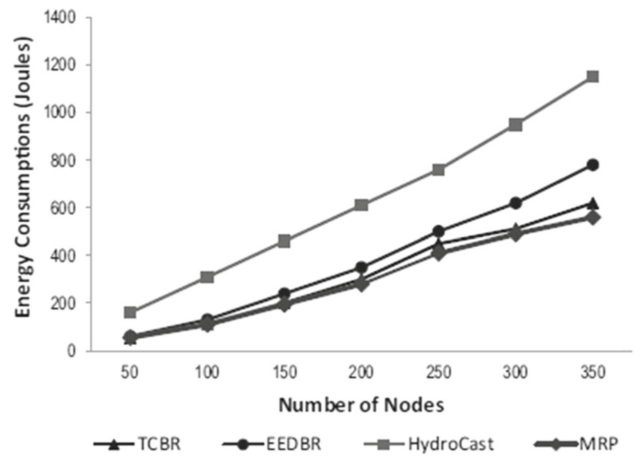

Fig. 10 Energy consumption versus no. of nodes among low in energy consumptions

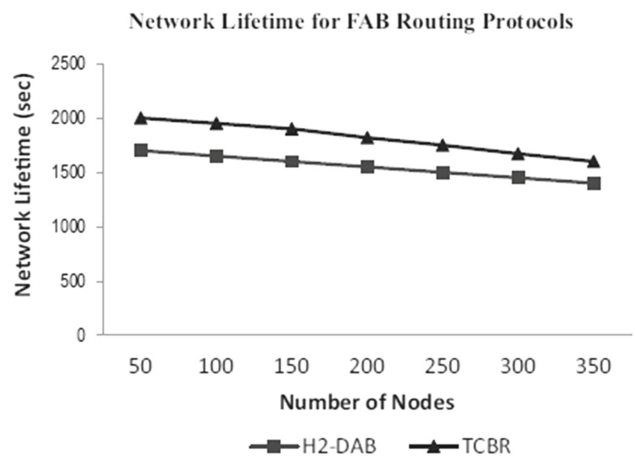

Fig. 11 Network lifetime versus number of nodes for FAB routing protocols

the PB routing protocols because LMPC reduces the routing overheads.

Figure 10 focuses the comparison among low in average energy consumption of data forwarding routing protocols. We observed that MRP routing protocol consumes low energy as compare to TCBR, EEDBR, and HydroCast because methodology adapted by authors is seem to be more efficient with usage of static super nodes and distribution of sensor nodes with different water depths.

3.2.3 Network lifetime

Network lifetime is inversely proportional to energy consumption and referred to time elapsed since the nodes deployment till the first node dies due to energy depletion.

Figure 11 focuses the network lifetime of FAB routing protocols. In Fig. 11 TCBR routing protocol is high in network lifetime as compare to H2-DAB because use of special courier nodes enhances the network lifetime of TCBR. H2-DAB uses the complicated mechanism of data forwarding with maximum number of hops which reduces the network lifetime of H2-DAB.

Figure 12 shows the network lifetime of FDB routing protocols. In Fig. 12 the network lifetime of EEDBR is higher than AURP because EEDBR is an energy efficient routing protocol which utilizes the energy balancing algorithm. The network lifetime of AURP is less than EEDBR; because the signaling overhead reduces the network lifetime of the AURP.

Figure 13 focuses the network lifetime of CBS routing protocol. In Fig. 13 when the numbers of nodes are 50 the network lifetime of HydroCast is 1220 sec and in same way the network lifetime reduces when the number of nodes are 350 the network lifetime is 1100 sec.

In Fig. 14 the network lifetime of PB routing protocols is shown. In Fig. 14 the network lifetime of MRP is higher than other proposed path based routing protocols because MRP uses the high powerful fixed super nodes on different water depths which enhances the network lifetime of MRP routing protocol. It is observed that after MRP the network lifetime of MDT and MPT is higher than rest of the PB routing protocols.

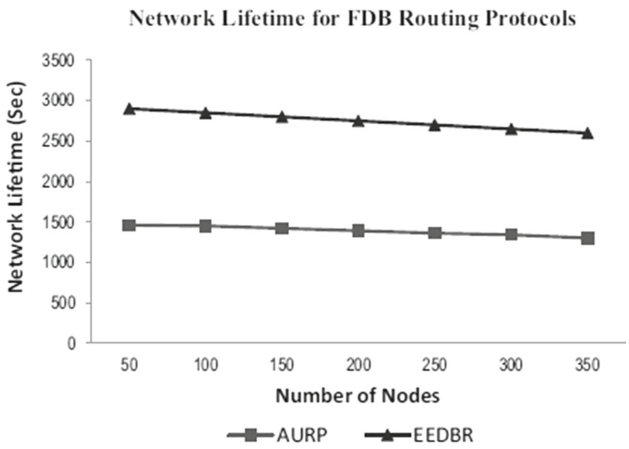

Fig. 12 Network lifetime versus number of nodes for FDB routing protocols

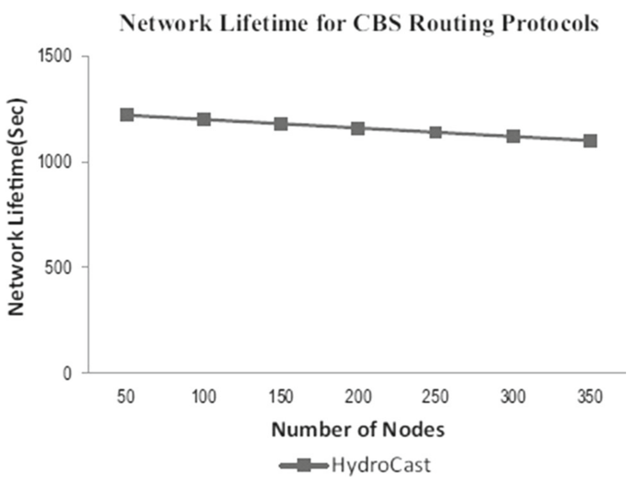

Fig. 13 Network lifetime versus number of nodes for CBS routing protocols

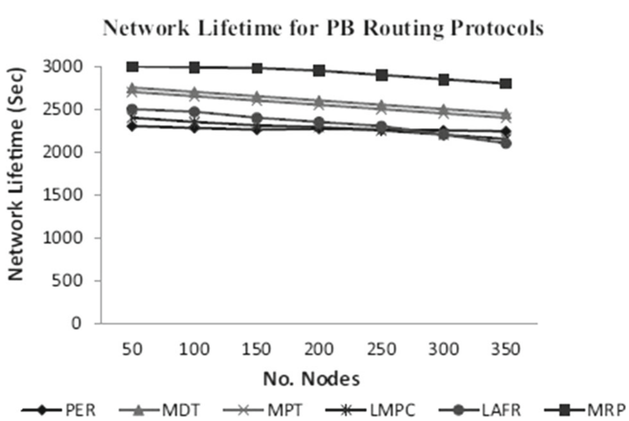

Fig. 14 Network lifetime versus number of nodes for PB routing protocols

Figure 15 shows the network lifetime of data forwarding routing protocols which are high in network lifetime of FAB, FDB, CBS, and PB routing protocols. In Fig. 15 the

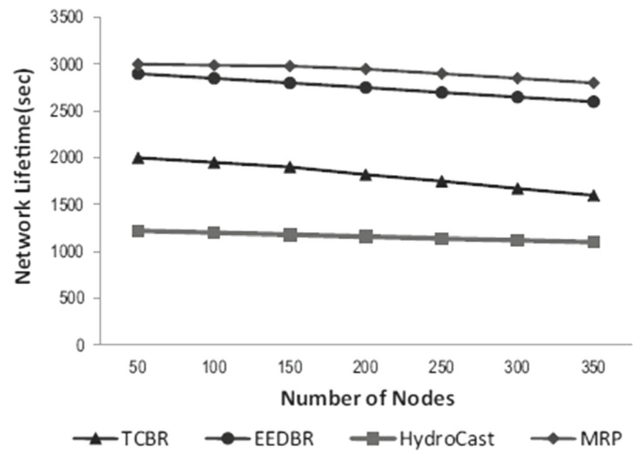

Fig. 15 Network lifetime versus number of nodes among high in network lifetime

network lifetime of MRP is higher than TCBR, EEDBR, and HydoCast.

3.3 Summary

It is observed that in data forwarding routing protocols the path based routing protocols are more efficient than FAB, FDB, and CBS routing protocols because in underwater environment due to continuous movement of water, water current and water pressure the dynamic topology is appropriate. Among the entire path based routing protocols it is observed that the MRP routing protocol has used the fixed powerful super nodes with layer formation and layer_ID in data forwarding mechanism which made the MRP more efficient, scalable, and robust among other proposed routing protocols. No doubt the methodologies adapted by H2-DAB, TCBR, and EEDBR are also efficient for data forwarding routing protocols but the simulation response of MRP is more efficient in PDR, energy consumption, and network lifetime.

4 Open research issues

In recent years; the research of UWSN has remained the major focus of researchers due to its attractive and valuable applications. Majority of the researchers have designed the famous routing protocols; but still research needs improvement in majority number of open research issues due to underwater environmental conditions. Some major research issues related to the routing protocols are listed below:

i. *Deployment of sensor nodes* Deployment of underwater sensor nodes is the major issues because the underwater environment supports the 3D deployment; so in underwater environment the 3D deployment is not an easy task due to underwater pressure and water current. Majority of the researchers have resolved this problem but still 3D deployment needs improvement.

ii. *Behaviour of acoustic channel* Underwater environment cannot support the RF and optical signalling because RF signalling keeps the low frequencies (30–300 Hz) and travels only for short distance due to high attenuation and absorption effect; whereas optical signalling requires very high precision in pointing the narrow laser beams with line of sight communication; so in underwater environment the optical signalling also cannot perform well. Acoustic signalling are only the way to communicate better between underwater sensor nodes as compare to RF and optical signalling; but acoustic signalling can reduce its power strength due to multipath propagation, Doppler shift and external noise; to control the power strength of the acoustic signal in underwater is also one of the challenging issues. The design of reliable algorithm is needed which can control the power strength of acoustic signal.

iii. *Time synchronization* Due to the sound speed and long propagation delay in underwater environment; it is complicated to maintain the time synchronization between the sensor nodes during data transmission. Majority of the researchers have introduced the time synchronization algorithms but still research is needed for time synchronization between sensor nodes.

iv. *Propagation delay* In underwater environment the propagation delay of acoustic channel is five orders of magnitude is higher than RF terrestrial channels; and is extremely variable which affects the transmission in between sensor nodes; and in resultant the packets delivery ratio may be degraded. The design of routing protocols' must take care of this serious issue.

v. *Localization* Localization means to find the location of underwater sensor nodes; localization is the major issue in underwater environment because the water current and water pressure affects the localization; majority of the researchers have designed the localization based routing algorithms but still localization problem needs improvement.

vi. *Void region problem* Void regions are basically the shadow zones or obstacles in underwater environment; the removal of void regions is also a major issue because due to the void regions the high bit error rate may be increased.

vii. *Hardware protection* Underwater sensor nodes are much more expensive and sensor nodes may be failure due to the fouling and corrosions; so the protection of sensor nodes in deep underwater environment is also one kind of major issues. Research community is also engaged to resolve this serious problem.

viii. *Battery power* Sensor nodes keeps the limited battery power because in underwater environment the battery cannot be recharged easily; majority of researchers have designed the energy efficient routing algorithms to maintain the battery power of sensor nodes with long life but still research needs improvement to design the best energy efficient algorithm(s).

ix. *Reliability* Reliable delivery of sensed data to the surface sink or water surface is a challenging task; because reliability may be affected due to the water current and water environmental conditions; there is need of the reliable algorithms which can develop the reliable communication between source nodes to sink nodes.

x. *Temporary loss* Due to the environmental conditions of water the packets sending time and packets receiving time may be affected and in resultant the loss of packets may occur. The reliable time related algorithms are needed to control the loss of packets.

5 Conclusion

In this review article we have focused the data forwarding routing protocols for UWSN with its types like FAB, FDB, CBS, and PB. We present the data forwarding methods of different routing protocols with its issues and advantages. We also present the performance analysis with analytical method and numerical simulation method with critical analysis. The simulation performance focuses the packets delivery ratio, energy consumption, and network lifetime of routing protocols based on data forwarding. We have also compared the simulation response of the routing protocols with their critical analysis and we observed that the path based routing protocols are more efficient than FAB, FDB, and CBS. It is also observed that the MRP routing protocol is more efficient among all the data forwarding routing protocols due to the usage of powerful fixed super nodes and layer formation mechanism.

References

1. Darehshoorzadeh, A., & Boukerche, A. (2015). Underwater sensor networks: A new challenge for opportunistic routing protocols. *IEEE Communications Magazine*, *53*, 98–107.
2. Akyildiz, I. F., Pompili, D., & Melodia, T. (2005). Underwater acoustic sensor networks: Research challenges. *Ad hoc networks*, *3*, 257–279.
3. Han, G., Jiang, J., Bao, N., Wan, L., & Guizani, M. (2015). Routing protocols for underwater wireless sensor networks. *IEEE Communications Magazine*, *53*, 72–78.
4. Khan, G., Gola, K.K., & Ali, W. (2015). Energy efficient routing algorithm for UWSN-A clustering approach. In *Advances in computing and communication engineering (ICACCE), 2015 sec-*

ond international conference on, *IEEE* 2015, 1–2 May 2015, (pp. 150–155). doi:10.1109/ICACCE.2015.42.

5. Carlson, E. A., Beaujean, P.-P., & An, E. (2006). Location-aware routing protocol for underwater acoustic networks. In *OCEANS, IEEE 2006*, 18–21 Sept 2006, (pp. 1–6). doi:10.1109/OCEANS.2006.306965.
6. Seah, W. K., & Tan, H.-X. (2007). Multipath virtual sink architecture for underwater sensor networks. In *OCEANS 2006-Asia Pacific*, *IEEE* 2007, 16–19 May 2007, (pp. 1–6). doi:10.1109/OCEANSAP.2006.4393933.
7. Shen, J., Tan, H., Wang, J., Wang, J., & Lee, S. (2015). A novel routing protocol providing good transmission reliability in underwater sensor networks. *Journal of Internet Technology*, *16*, 171–178.
8. Sun, P., Seah, W. K., Lee, P. W. (2007). Efficient data delivery with packet cloning for underwater sensor networks. In *Underwater technology and workshop on scientific use of submarine cables and related technologies, IEEE 2007. Symposium on*, 2007, 17–20 April 2007, (pp. 34–41). doi:10.1109/UT.2007.370944.
9. Ghoreyshi, S. M., Shahrabi, A., & Boutaleb, T. (2016). A novel cooperative opportunistic routing scheme for underwater sensor networks. *Sensors*, *16*, 297.
10. Ali, T., Jung, L. T., & Faye, I. (2014). End-to-end delay and energy efficient routing protocol for underwater wireless sensor networks. *Wireless Personal Communications*, *79*, 339–361.
11. Jafri, M. R., Sandhu, M. M., Latif, K., Khan, Z. A., Yasar, A. U. H., & Javaid, N. (2014). Towards delay-sensitive routing in underwater wireless sensor networks. In *5th International conference on emerging ubiquitous systems and pervasive networks / the 4th international conference on current and future trends of information and communication technologies in healthcare / affiliated workshops,* (Vol. 37, pp. 228–235).
12. Cai, S. B., Gao, Z. G., Yang, D. S., & Yao, N. M. (2013). A network coding based protocol for reliable data transfer in underwater acoustic sensor. *Ad Hoc Networks*, *11*, 1603–1609.
13. Zhang, S., Li, D., & Chen, J. (2013). A link-state based adaptive feedback routing for underwater acoustic sensor networks. *IEEE Sensors Journal*, *13*, 4402–4412.
14. Wang, P., Fu, D. H., Zhao, C. Q., Xing, J. C., Yang, Q. L., & Du, X. F. (2013). A reliable and efficient routing protocol for underwater acoustic sensor networks. In *2013 IEEE 3rd annual international conference on cyber technology in automation, control and intelligent systems (Cyber),* (pp. 185–190), *IEEE* 2013, 26–29 May 2013. doi:10.1109/CYBER.2013.6705443.
15. Wang, Y., Liu, Y. J., & Guo, Z. W. (2012). Three-dimensional ocean sensor networks: A survey. *Journal of Ocean University of China*, *11*, 436–450.
16. Luo, H., Guo, Z., Dong, W., Hong, F., & Zhao, Y. (2010). LDB: Localization with directional beacons for sparse 3D underwater acoustic sensor networks. *Journal of Networks*, *5*, 28–38.
17. Llor, J., & Malumbres, M. P. (2012). Underwater wireless sensor networks: How do acoustic propagation models impact the performance of higher-level protocols. *Sensors*, *12*, 1312–1335.
18. Son, J., & Byun, T.-Y. (2010). A routing scheme with limited flooding for wireless sensor networks. *International Journal of Future Generation Communication and Networking*, *3*, 33–40.
19. Wei, B., Luo, Y.-m., Jin, Z., Wei, J., & Su, Y. (2012). ES-VBF: an energy saving routing protocol. In *Proceedings of the 2012 international conference on information technology and software engineering*, *Springer-Verlag Berlin Heidelberg* 2013, 06 Nov 2012, (pp. 87–97). doi:10.1007/978-3-642-3428-9_10.
20. Hu, T. S., & Fei, Y. S. (2010). QELAR: A machine-learning-based adaptive routing protocol for energy-efficient and lifetime-extended underwater sensor networks. *IEEE Transactions on Mobile Computing*, *9*, 796–809.
21. Xie, P., Cui, J. H., & Lao, L. (2006). VBF: Vector-based forwarding protocol for underwater sensor networks. *Networking 2006: Networking Technologies, Services, and Protocols; Performance of Computer and Communication Networks Mobile and Wireless Communications Systems*, *3976*, 1216–1221.
22. Wahid, A., Lee, S., & Kim, D. (2014). A reliable and energy-efficient routing protocol for underwater wireless sensor networks. *International Journal of Communication Systems*, *27*, 2048–2062.
23. Erol, M., Vieira, L. F., & Gerla, M. (2007). Localization with Dive'N'Rise (DNR) beacons for underwater acoustic sensor networks. In *Proceedings of the second workshop on underwater networks*, *WuWNet ACM*, 2007, 14 Sep 2007, (pp. 97–1000). doi:10.1145/1287812.1287833.
24. Ayaz, M., Baig, I., Abdullah, A., & Faye, I. (2011). A survey on routing techniques in underwater wireless sensor networks. *Journal of Network and Computer Applications*, *34*, 1908–1927.
25. Namazi, B., & Faez, K. (2013). Energy-efficient multi-speed routing protocol for wireless sensor networks. *International Journal of Electrical and Computer Engineering*, *3*, 246.
26. Ayaz, M., & Abdullah, A. (2009). Hop-by-hop dynamic addressing based (H(2)-DAB) routing protocol for underwater wireless sensor networks. In *2009 International conference on information and multimedia technology, proceedings, IEEE 2009,* 16–18 Dec 2009, (pp. 436–441). doi:10.1109/ICIMT.2009.70.
27. Ayaz, M., Abdullah, A., & Jung, L. T. (2010). Temporary cluster based routing for underwater wireless sensor networks. In *Information Technology (ITSim), 2010 international symposium in*, *IEEE* 2010, (Vol. 2, pp. 1009–1014). doi:10.1109/ITSIM.2010.5561598.
28. Yoon, S., Azad, A. K., Oh, H., & Kim, S. (2012). AURP: An AUV-aided underwater routing protocol for underwater acoustic sensor networks. *Sensors*, *12*, 1827–1845.
29. Wahid, A., Lee, S., Jeong, H. J., & Kim, D. (2011). EEDBR: Energy-efficient depth-based routing protocol for underwater wireless sensor networks. *Advanced Computer Science and Information Technology*, *195*, 223–234.
30. Lee, U., Wang, P., Noh, Y., Vieira, F., Gerla, M., & Cui, J.-H. (2010). Pressure routing for underwater sensor networks. In *INFOCOM, 2010 proceedings IEEE* 2010, 14 Mar 2010, (pp. 1–9).
31. Huang, C. J., Wang, Y. W., Liao, H. H., Lin, C. F., Hu, K. W., & Chang, T. Y. (2011). A power-efficient routing protocol for underwater wireless sensor networks. *Applied Soft Computing*, *11*, 2348–2355.
32. Xu, J., Li, K., & Min, G. (2011). Multi-path division transmission for improving reliability and energy effciency in underwater acoustic networks. *Procedia Computer Science*, *4*, 86–95.
33. Zhou, Z., & Cui, J.-H. (2008). Energy efficient multi-path communication for time-critical applications in underwater sensor networks. In *Proceedings of the 9th ACM international symposium on Mobile ad hoc networking and computing*, 2008, 26 May 2008, (pp. 221–230). doi:10.1145/1374618.1374649.
34. Xu, J., Li, K., Min, G., Lin, K., & Qu, W. (2012). Energy-efficient tree-based multipath power control for underwater sensor networks. *IEEE Transactions on Parallel and Distributed Systems*, *23*, 2107–2116.
35. Wahid, A., Lee, S., Kim, D., & Lim, K. S. (2014). MRP: A localization-free multi-layered routing protocol for underwater wireless sensor networks. *Wireless Personal Communications*, *77*, 2997–3012.
36. Ahmed, A., Bakar, K. A., Channa, M. I., & Khan, A. W. (2016). A secure routing protocol with trust and energy awareness for wireless sensor network. *Mobile Networks and Applications*, *21*, 272–285.

Mukhtiar Ahmed received B.Sc and M.Sc in computer Technology from US Jamshoro Sindh Pakistan in 1995, received MS (IT), HU Sindh Pakistan, (Ph.D) CS, UTM, Malaysia, currently Research fellow in UTM, Malaysia.

Mazleena Salleh is currently working as an Associate Professor in Department of Computer Science Faculty of Computing UTM, Malaysia. She received her BS(Electrical Engineering) in 1983 from university of southern califorina, MS(EE) in 1985 from Virginia Polytechnic and State University and Ph.D in Computer Science in 2008 from UTM, Malaysia.

M. Ibrahim Channa is currently working as Professor in QUEST, Nawabshah Sindh Pakistan. He received his B.Sc and M.Sc in Computer Science from US Jamshoro Sindh Pakistan, MS(IT) NUST Pakistan, PhD from AIT Thailand.