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Review on Clustering, Coverage and Connectivity in Underwater Wireless Sensor Networks: A Communication Techniques Perspective

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ABSTRACT With a wide scope to explore and harness the oceanic sources of interest, the field of underwater wireless sensor networks (UWSNs) is attracting a growing interest of researchers. Owing to the real-time remote data monitoring requirements, underwater acoustic sensor networks (UASNs) emerged as a preferred network to a great extent. In UASN, the limited availability and non-rechargeability of energy resources along with the relative inaccessibility of deployed sensor nodes for energy replenishments necessitated the evolution of several energy optimization techniques. Clustering is one such technique that increases system scalability and reduces energy consumption. Besides clustering, coverage and connectivity are two significant properties that decide the proper detection and communication of events of interest in UWSN due to unstable underwater environment. Underwater communication is also possible with non-acoustic communication techniques like radio frequency, magnetic induction, and underwater free-space optics. In this paper, we surveyed clustering, coverage, and connectivity issues of UASN and qualitatively compared their performance. Particularly, the impact of these non-conventional communication techniques on clustering, coverage, and connectivity aspects is demonstrated. Additionally, we highlighted some key open issues related to the UWSN. This paper provides a broad view of existing algorithms of clustering, coverage, and connectivity based on acoustic communication. It also provides a useful guidance to the researchers in UWSN from various other communication techniques' perspective.

INDEX TERMS Clustering, connectivity, coverage, RF, MI, UWFSO, acoustic, underwater wireless sensor networks.

LIST OF ABBREVIATIONS

ACO	Ant Colony Optimization
ADVWT	Advertisement Waiting Time
AN	Actor Node
ANOVA	Analysis of Variance
AUV	Autonomous Underwater Vehicles
BGAF	Based on 3D GAF
BS	Base Station
BSN	Buoys based Sensor Network
CBKU	Clustered routing Based on improved K-means algorithm for UWSN
CDMA	Code Division Multiple Access
CDS	Connected Dominating Set
CHADV	Cluster Head Advertisement
C-LEACH	Controlled LEACH
Cl-ID	Cluster Identity
CM	Cluster Member
CVBF	Clustering Vector Based Forwarding
DABECS	Data Aggregation Based Efficient Clustering Scheme
DCP	Dependable Clustering Protocol
DUCS	Distributed Underwater Clustering Scheme
EKACASA	Enhanced K-means ANOVA-based Clustering Approach for Similarity Aggregation
EM	Electro Magnetic
FBCA	Time Matrix Clustering Algorithm
FCM	Fuzzy C-Means
GAF	Geographic Adaptive Fidelity
GPS	Global Positioning System

Gr-ID	Group Identity
HEED	Hybrid, Energy-Efficient Distributed
IBGCA	Information Based Grid Clustering
ICH	Inform to Cluster Head
JOINWT	Joining Waiting Time
LCAD	Location-based Clustering Algorithm for Data Gathering
LEACH	Low Energy Adaptive Clustering Hierarchy
LQI	Link Quality Indicator
LUM-HEED	Location Unaware Multi-hop HEED
MCCP	Minimum Cost Clustering Protocol
MHFEER	Multi-Hop Fuzzy based Energy Efficient Routing
MI	Magnetic Induction
NCH	Non Cluster Head
NURBS	Non-Uniform Rational B-Spline
QoS	Quality of Service
RF	Radio Frequency
RSSI	Received Signal Strength Indicator
SBTB	Spline Based TaBu
SG	Surface Gateway
SHCHSA	Self-Healing CH Selection Algorithm
S-LEACH	Slotted LEACH
SHFEER	Single-Hop Fuzzy based Energy Efficient Routing
SN	Sensor Node
TCBR	Temporary Cluster Based Routing
TDMA	Time Division Multiple Access
TMCA	Time Matrix Clustering Algorithm
TTCB	Two-Tier routing for Cluster-Based
TWSN	Terrestrial Wireless Sensor Networks
UASN	Underwater Acoustic Sensor Networks
UCFIA	Unequal Clustering for WSN based on Fuzzy logic and Improved ACO
UWC	Underwater Wireless Communication
UWDBCSN	Under Water Density Based Clustered Sensor Network
UWFSO	Under Water Free-Space Optics
UWSN	Underwater Wireless Sensor Network

I. INTRODUCTION

Two out of three parts of the earth is covered by water and it implies a great proportionate possibility of underwater exploration. This encompasses a wide variety of military and non-military applications like enemy vehicle surveillance, navigation assistance with autonomous underwater vehicles (AUV), threat detection at ship ports, underwater telemetry, oceanographic data gathering, water quality monitoring, tsunami detection, habitat and pollution monitoring etc. [1]–[3]. Hence underwater sensor networks became a vigorously growing field of oceanic research.

In contrast to the terrestrial wireless communication, radio frequency (RF) signals exhibit a different underwater behavior. In the underwater environment, the channel is very dynamic in nature and its behavior depends on various water depths. The communication medium is sometimes turbid and the water is majorly saline in nature. Due to these extreme characteristics, the high frequency RF signals experience a high attenuation [4]. In order to provide electromagnetic (EM) communication with low frequency signals, it requires a large sized antenna, which is impractical in underwater environments. So, an underwater wireless communication (UWC) technique that functions at low frequencies and which can provide acceptable signal attenuation is necessary. The above requirements fulfilled by acoustic technique. Thus, the typical UWC is made possible by underwater acoustic sensor networks (UASN) [5]–[7].

The current executable underwater acoustic technique typically involves wireless sensor nodes, a floating base station (BS) (In this paper, BS and sink are interchangeably used as per need) and an onshore control station. The BS has acoustic technique for UWC and RF technique for BS-shore communication. As compared with the terrestrial counterpart, in UASN, acoustic waves have a less underwater conduction velocity, the sensor nodes are expensive, bigger in size and have small memory. As the nodes are situated in deep waters; the energy resources of nodes can neither be replenished using sunlight, nor be recharged manually. Moreover, the underwater acoustic nodes consume ten times more energy compared to terrestrial sensor nodes. Thus, the available energy became a limited resource in UASN. Therefore, a lot of techniques have been developed for minimizing energy consumption and to enhance the overall system performance.

A. MOTIVATION AND CONTRIBUTIONS

One such energy saving technique is clustering wherein; nodes are grouped into a nearly non-interfering subsets called clusters. Each of the members of a cluster has localized interactions. Clustering leads to efficient utilization of resources like frequency, bandwidth and energy by allowing them to be used multiple times by non-interfering clusters. Thus, it increases system scalability and network longevity. In any sensor network, some event of interest is to be sensed, and that should be conveyed to a pre-specified destination. In this course, the degree of sensing ability and data transferability is expressed in terms of sensing coverage and connectivity respectively.

Clustering performs data aggregation by means of which it reduces data redundancy saving a lot of energy. This data redundancy results due to different nodes sensing the same event. Clustering can be either centralized or distributed. In the centralized scheme, a single BS acts as a receiver of all nodes, whereas in distributed schemes, there will be various clusters and each cluster head (CH) acts as a gateway between nodes and BS. Besides, clustering can be both dynamic and static which refer to the periodic formation of new clusters and one-time permanent formation of clusters respectively. Low energy adaptive clustering hierarchy (LEACH) protocol is one of the best examples of dynamic and distributed clustering protocol for terrestrial wireless sensor networks (TWSN). However, this protocol assumes a static nature of the medium, but the underwater nodes are often advected by

TABLE 1. Comparison and contrast between TWSN and UASN.

QoS aspects	Attributes	Comparison and Contrast		Challenges involved in UWSN
		TWSN	UASN	
Clustering	Communication technique	Electro-magnetic waves	Acoustic waves	- Limited bandwidth availability - Limited battery reserve and sunlight can not be replenished -Refer [8]–[15] for terrestrial clustering literature.
	Location awareness	GPS supportive	GPS -non supportive	
	Signal speed	Speed of light	1500m/s	
	Sensor data	Correlated	Majorly non-correlated	
	Recharge-ability	Possible	Not possible	
Coverage	Coverage radius	Upto a few meters	Upto a mile	- Pollution and corrosion renders failure of node - Manual node deployment is not possible at deeper depths
	Preferred node deployment	Manual and Random dropping	Random dropping	
	Final node position	Depends on surface terrain	Depends on water buoyancy	
	Terrain modelling technique	Delaunay triangulation	Spline function based techniques.	
	Node density	Dense	Sparse	
	Node mobility	Depends on the application	Mobile in general	
	Coverage hole recovery	Not possible	By using AUV	
Connectivity	Communication link	Stable	Unsteady	- Propagation delay underwater is 5 times that in conventional RF channel - The channel experiences fading and multi-path problems
	Communication radius	$\leq$ 150 mtr	$\leq$ 10 Km	
	Operating frequency	(908-928) MHz	(10 Hz-1 MHz)	
	Propagation delay	Low	High	
	Bit error rate	Moderate	High	
	Node deployment	Mostly 2D	2D on seabed, 3D at any depth	

oceanic currents. So, this technique is unsuitable for underwater scenarios. Moreover, global positioning system (GPS) is not supported inside water, and nodes generally are deployed sparsely in order to cover longer distances. These characteristics are quite contrary to that of TWSN. Therefore, exclusive underwater compatible clustering techniques are needed.

Coverage means how well the sensor nodes determine the presence of target in the deployed space. Coverage in UWSN differs from that of TWSN. For TWSN, techniques like Delaunay triangulation and Voronoi diagrams illustrate and model the terrain and node deployment strategies. However, due to dynamic medium of water, these cannot be directly used in UWSN. In TWSN, the final position of nodes is determined by the shape of the deployed surface. But in the underwater environment, due to drift of nodes, the final position of nodes cannot be exactly determined. The quality of coverage depends on the kind of coverage (2D/3D), the type of sensing model used and dynamics of the nodes. Achieving a 3D underwater coverage is more challenging than that of 2D. The kind of sensing model used, decides the accuracy of coverage. In UWSN, generally binary coverage models are used, but in order to have realistic information on the points of interest, a probabilistic coverage modelling has to be incorporated.

Node connectivity is defined as a ratio of the number of nodes that can communicate with the BS to the total number of nodes. Connectivity is a factor that always accompanies coverage. A guaranteed connectivity with a sound coverage is needed for effective detection of any event. Connectivity depends on various factors like node deployment, transmission power, the medium of signal propagation, signal propagation loss, the internodal distances etc. Unlike TWSN, in UASN, the communication links are unsteady, a relatively low propagation speed results in a high delay and it is followed by bit errors. Thus, UASN differs from TWSN as listed down in Table 1.

Over the last decade, apart from underwater acoustics, other techniques are also developed to facilitate UWC. Firstly, the conventional RF technique is tested for UWC, and its performance is not substantial. This is due to the saline nature of water, which causes severe RF signal attenuation. However, further research revealed that RF is favorable for fresh water scenarios. Similarly, magneto-inductive (MI) communication is another UWC technique wherein, message signals are carried forward by induction of magnetic signals. These waves propagate at high speed, but sustain for shorter distances. This limits MI waves for short range applications. The ability to propagate in turbid waters, not having an adverse effect on the marine life is some advantageous features of MI waves. This makes MI to function even in harsh environments. Underwater free space optical communication (UWFSO) is another wireless technique with a transceiver system made up of visible or IR diodes. These signals are susceptible to scattering and diffraction. But these

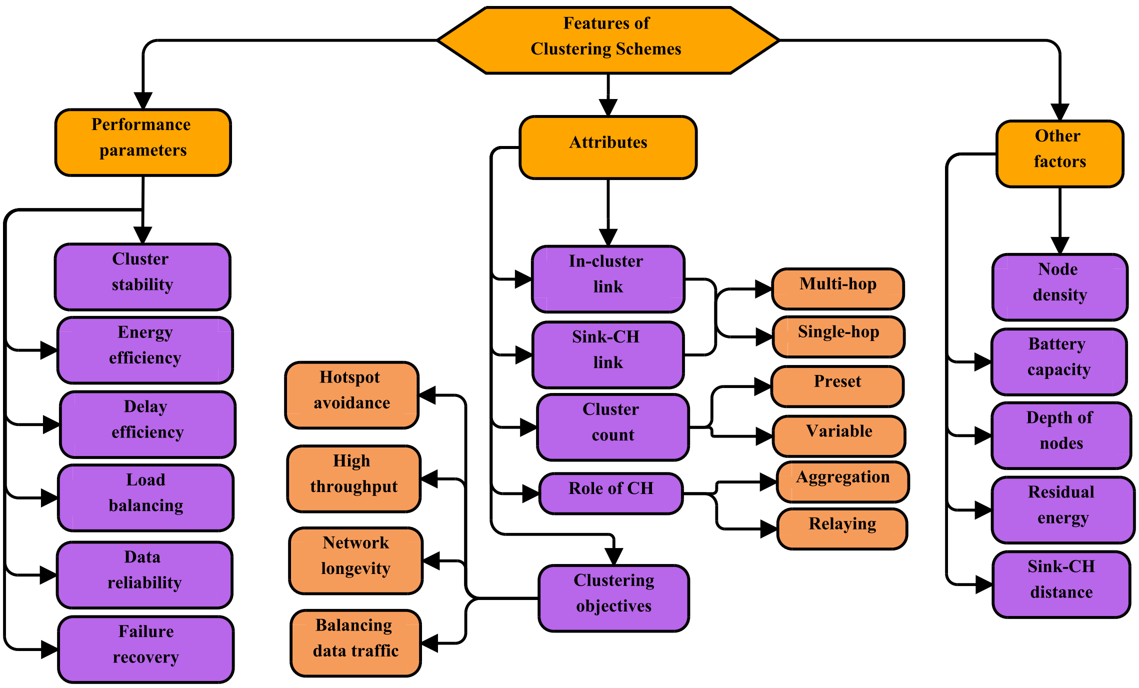

FIGURE 1. Features of clustering schemes.

are capable of providing high underwater data rates. Similar to the UASN, the other techniques also have their own pros and cons. It is a well known fact that the performance of any WSN can be controlled and reasonably enhanced by optimizing clustering and achieving significant coverage and connectivity. So, by properly understanding the coverage and communication issues, a suitable communication technique can be chosen as per the application. Motivated by the above observations, in this paper, we enumerated various factors affecting clustering, coverage and connectivity for all possible UWC techniques.

The objectives of this paper are to summarize the existing issues of clustering, coverage and connectivity in UWSN from various communication techniques perspective. Our main contributions are enlisted herein:

1) We reviewed the existing clustering techniques in UASN. The effect of various attributes affecting the underwater clustering performance is explained in detail and is qualitatively compared.
2) We reviewed the latest coverage techniques in UASN and qualitatively compared them. In addition to that, we comprehensively described the factors affecting underwater wireless connectivity.
3) We also compared communication techniques like acoustics, RF, UWFSO and MI for UWSN. For the first time, we tried to enumerate the effect of these communication techniques with respect to underwater clustering, coverage and connectivity. This gives the reader a new perspective towards UWC techniques.
4) To the best of our understanding, some new open issues and challenges for future research are mentioned, which will help in furthering the underwater wireless communication techniques.

In Section II, the process of underwater clustering, its determining factors and current clustering algorithms are explained. Section III presents a similar parametric performance study on underwater coverage. In Section IV, the factors affecting underwater connectivity are explained in detail. In the subsequent section, a logical explanation of the effect of various non-traditional UWC techniques on clustering, coverage and connectivity is presented. A scope for research and open issues is presented in Section VI. Finally, Section VII concludes the paper.

II. CLUSTERING IN UWSN

Clustering is a mechanism of gathering sensor nodes into non-intersecting groups. The objective of this mechanism is to bring about energy efficiency at large because energy is a non-replenish-able source, especially in underwater environments. Centered around this objective, clustering schemes achieve some secondary objectives like reducing data redundancy, balancing the network load, achieving a high throughput etc. The functional relation of these features is summarized in Fig. 1 categorically

A. FEATURES OF UNDERWATER CLUSTERING

1) CLUSTERING ATTRIBUTES

Various clustering algorithms in the literature differ from one another based on some of the following architectural and topological attributes. The choice of clustering scheme for a required application can be easily chosen by scrutinizing these attributes.

- *Cluster count*: Based on the kind of application the number of clusters is determined. In grid based dense node deployment techniques, there is a possibility of having a dynamic cluster head (CH) selection, but with sparse deployments, due to energy constraints the number of clusters in general is pre-determined or preset.
- *In-cluster link*: In some applications, where the sensor nodes are deployed sparsely (like in pollution monitoring applications), when clustering topology is followed, due to the energy constraints the nodes may not directly transmit to the associated CH (single-hop) but via intermediate nodes (multi-hop). In dense node deployed scenarios, both single-hop and multi-hop transmissions are possible.
- *Sink-CH links*: In some system architecture, the nodes are deployed on the seabed and from there, the sensed data is to be transferred to the base station (BS). In such cases, either an empowered heterogeneous node is used or a series of intermediate relay nodes are used. The former one has a long range communication capability, and so the communication takes place in single-hop, whereas in the latter case multi-hop signal relays take place. However, the kind of architecture chosen depends on both application and budget.
- *Role of CH*: In some algorithms, if the application is simply to detect some event and convey about it, then it requires a CH with simple relaying capabilities. On the other hand, if it is a monitoring or surveillance application, where a lot of data has to be processed, the CH fuses the data first and then relays it to the next stage.
- *Clustering objective*: As energy renewal is a limiting issue, most of the clustering algorithms focus on energy saving. Along with this, every clustering algorithm has a secondary focus on one the following objectives such as, improving network longevity, avoiding hotspots, reducing packet collision, achieving high throughput, balancing network traffic, optimizing the number of CHs and minimizing packet.

2) PERFORMANCE PARAMETERS

The efficacy of any clustering algorithms can be estimated based on the following parameters.

- *Cluster stability*: It refers to the membership status of a node. If a node is a member of any particular cluster indefinitely, then the cluster stability is said to be fixed otherwise it is said to be adaptive.
- *Delay efficiency*: In UASN, the involved delays are due to the medium characteristics which limit the propagation velocity as shown in Table 1. In addition to that, the delays are also due to the kind of communication links involved. If there is multi-hop architecture, for every hop there will be a delay associated with it. Thus, the system produces high aggregate delays. This condition is not favorable for delay-intolerant applications.
- *Load balancing*: The data aggregation and relay burden of a CH node is usually referred to as load. CH dissipates energy in due course of time. In case of homogeneous networks, where all nodes have equal energy, a node might get completely exhausted on perpetual operation as CH. So, it is needed for a node to switch its CH role with other nodes. For heterogeneous networks, one special node is highly empowered to function as a CH. So, there is no need to load balancing. In case of buoy based acoustic sensor networks (BSN), where nodes are deployed using vertical chain load balancing is not applicable as the required energy can be applied externally. Load on nodes is said to be balanced in scenarios where the nodes are spatially uniformly deployed. On the other hand, non-uniform distribution of nodes renders uneven energy exertion of nodes that is said to be unbalanced. The same behavior is observed even if RF, MI techniques are used underwater.
- *Data reliability*: Data reliability or data dependability relies on the losses of the transmitted signal; which in turn is affected by factors like turbidity, salinity of the water medium. For data critical applications like seismic detection and defense, data reliability should be high. This is possible when either when the nodes transmission power is more or when the nodes are densely deployed or when less attenuation medium is chosen or by a combination of these factors. In case of RF underwater technique, water salinity severely cuts down data reliability. In case of underwater MI, the data reliability is high, but for only shorter distances. For UWFSO communications, the data reliability depends on the line of sight signal propagation.
- *Failure recovery*: Some of the published algorithms summarised in Table 3, provide a backup CH node in order to substitute the primary CH when it expires. Otherwise, the sensed data of the NCH nodes cannot be processed further. Such schemes are said to be equipped with CH failure recovery. Providing this facility is an expensive task in acoustic communication as nodes are high-priced. This feature is very important in case of data critical applications.
- *Energy efficiency*: In UWSN, this is a very crucial parameter because it decides the network longevity; especially using acoustic technique. This is affected due to most of the above given factors. It majorly depends on the distribution of nodes; which is the average distance of all the nodes from the corresponding CH. The kind of topology being used also affects the overall energy dissipation. In case of MI communication, energy efficiency is relatively high; as the attenuation of MI signals is less. RF communication is energy efficient if it is used in freshwater scenarios.

3) OPTIMAL CLUSTERING

This feature decides the optimal number of clusters in a given scenario. A large number of clusters reduce the average node-CH distance. As a result, the average power required by a node to transmit to a CH reduces. Therefore, the aggregate

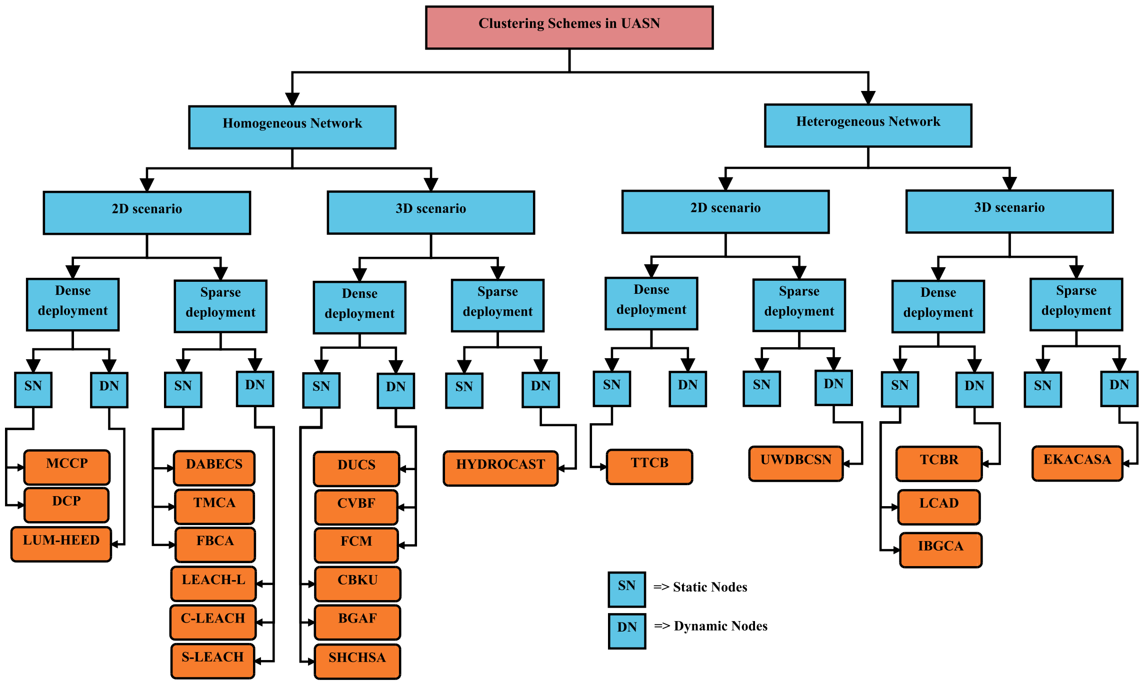

FIGURE 2. Taxonomy of underwater clustering schemes based on acoustic communications.

energy consumed gets reduced. Also, if there are a large number of clusters, there will be an increase in the number of CH-CH hops. Consequently, it increases the overall energy consumption. On the other side, decreasing the cluster count will increase the average energy consumption of each CH per round and it eventually increases the overall consumed energy. So, to bring a balancing point between having a large number of clusters and smaller number of clusters, an optimal number of clusters must be chosen [16], [17].

B. CLUSTERING SCHEMES IN UASN

The existing literature provides a several underwater clustering algorithms and each of which is suitable for a particular environment. Some of them are designed exclusively for 2D (or 3D) environments, and some of them assume a static node (SN) (or dynamic node (DN)) scenario, and some assume that the nodes have homogeneous (or heterogeneous) capabilities. On this basis, a classification of underwater clustering protocols is provided in Fig. 2. A few selected algorithms are thoroughly explained below and all of the underwater clustering algorithms are summarised with respect to various attributes and parameters in Table 3.

1) INFORMATION BASED GRID CLUSTERING ALGORITHM

This centralized, 3D GRID architecture based clustering algorithm is proposed by Priyadarsini *et al.* in [18]. Herein, nodes are deployed in the 3D grid spaces, and each grid acts as a cluster with multiple CHs located approximately at the grid center. These CHs can be selected by periodic sleep, wake cycles. Intra-cluster communication within a grid does not need any transfer of control messages. CHs gather data from non-cluster head (NCH) nodes and transfer it to the BS via multiple CHs. In inter CH routing, the data packet itself contains the control packet to establish the route. Thus, it is very energy efficient. This clustering is done in three phases namely

1) Set-up phase, wherein a CH is chosen. To this end, a potential CH sends a cluster head advertisement (CHADV) message to all NCH nodes. This message carries its own node ID and an integer count. NCHs receive it and wait for a time duration of advertisement waiting time (ADVWT), and meanwhile they may receive some different CHADV messages from other capable CHs. Based on a minimum node ID and a minimum integer count, an NCH node selects a CH and sends this decision to the chosen CH within a joining wait time (JOINWT).
2) Data gathering phase, where NCHs send data to the CHs. This is achieved simply by direct data transfer to CH and it does not need any control information also.
3) Data transmission phase, wherein, the gathered data are transmitted to the BS via different CHs. This requires route discovery and maintenance. If there is no existing route with a node, then the node sends a packet to the destination, later the destination node confirms it by sending an acknowledgement message. The route is thus established and it remains valid till a TIMEOUT period. Owing to the presence of multiple CHs this technique caters for failure recovery.

2) BGAF CLUSTERING ALGORITHM

Addressing the issues related to geographic adaptive fidelity (GAF), an improvised algorithm named based on

GAF (BGAF) is proposed by Liu *et al.* [19], which is a three-dimensional (3D), static and distributed clustering algorithm. GAF suffers from the problems like having to send continuous messages by CH, network segmenting (this is due to the death of a closer node to the BS), random choice of CHs without considering residual energy. These problems lead to a greater energy depletion and therefore, overcoming these problems is indispensable for enhancing the network survivability.

To this end, BGAF considers residual energy and node-BS distance in cluster formation. In each cycle, CH is not chosen randomly, rather the node with more residual energy and less node-BS distance is chosen as CH and thus a reasonable CH is chosen.

In addition to that, the possible network segmenting is avoided by introducing a *transit node mechanism* at a location very close to the BS. Herein, the nodes convey their energy level information to the CHs. Then, the one which has more residual energy and with less node-BS distance is chosen by the CH as a transit node. Then all the messages coming from other CHs will be passed through this transit node. As this operation is performed in regular cycles, and each cycle has a different transit node, too much energy draining of a single node near BS gets eliminated. Hence this algorithm outperforms GAF in terms of energy consumption and network lifetime.

3) CBKU CLUSTERING ALGORITHM

This is a 3D, homogeneous and static clustering technique. In order to overcome the shortcomings pertaining to K-means clustering technique Ying Zhang *et al.* introduced a protocol which is based on improved K-means algorithm for UWSN (CBKU) [20], [21]. K-means is a partition and distance based algorithm which generally begins with selecting some random initial cluster centers. Eventually, it calculates a new and final number of CHs based on a variance convergence condition, which is a repetitive process. The author claims that it is needed because, if the total number of clusters is less, then nodes will have to transmit long distances and CHs will have to fuse a lot of data. On the other hand, a large number of clusters will not produce the intended effect of clustering. However, due to random selection of initial clusters, it suffers clustering instability, greater consumption of time that results due to a large number of iterations.

To overcome the above limitations, an improved K-means based clustering algorithm is presented in literature, which applies a modified LEACH protocol by considering the parameters of node density, depth of nodes. Thus, it achieves a balanced energy consumption across the network. The threshold in LEACH is modified as follows

$$T(r) = \frac{P}{1 - P(r \times mod\frac{1}{P})} \times (\rho + (\frac{D}{D_{max}})) \quad (1)$$

where, P is the probability of a node to become CH, ρ is the node density (defined as the ratio of number of nodes in a given radius to the total number of deployed nodes), D_{max} is the distance between the bottom most node and the surface of water.

CBKU contributes in the following way:

- It introduces the concept of an aided CH and primary CH. The former is selected by considering node's residual energy and node-BS distance, whereas the latter is selected by considering the residual energy of a node and node-CH distance. While a primary CH simply performs data fusion and aggregation, the aided CH performs the operation of multi-hop data transmission to the BS. As communicational energy is more than computational energy, using aided CHs results in proper distribution of energy consumption. Considering the random deployment of nodes, CBKU considers the depth of the nodes in the initial selection of cluster centers and thus facilitates even distribution of nodes per cluster.
- Moreover, these cluster centers are chosen in such a way that there will be more clusters in the proximity of BS than that at a distance of BS. In this way, it avoids the early death caused to the nodes due to over transmission load around BS (hotspots). Thus, this algorithm outperforms previous K-means algorithm in the aspect of extending the network longevity.

4) FUZZY BASED CLUSTERING ALGORITHM

A homogeneous 2D fuzzy based clustering technique (FBCA) is proposed by Nitin *et al.* [22]. The algorithm considers some local information estimates like residual energy, node-BS distance, node density etc. Thus, it forms a good CH selection criterion. The unique contribution of this work is that, it considers two new parameters of *load on node, link quality estimation* to enhance the optimality of CH selection. These five parameters are taken as input to a fuzzy module and the output of the module is used to make a proper choice of CH.

These five parameters are estimated by different means. The residual energy is the left out energy in a node after every transmission and reception. The node-BS distance is estimated by using the Friis transmission equation. Node density represents the total number of nodes connected to a given CH which are in its transmission range. The load on a given node is a function of the number of packets in the nodes queue, the number of retransmissions, the packets dropped during retransmissions and the node quality of a node is estimated based on the number of successful data packet transmissions to the neighbor nodes.

The author claims that the proposed algorithm outperforms UCFIA clustering algorithm [23] with respect to the selection parameters of throughput, average energy consumption, packet delivery ratio and end-to-end delay.

5) TIME MATRIX CLUSTERING ALGORITHM

This is based on LEACH protocol, which by considering the NCH node-CH communication energy, CH-BS communication energy, the position of CH, defined a new standard of selecting CH. This is proposed by Xia Li *et al.* [24].

In order to overcome the lack in LEACH protocol as discussed before, this algorithm introduces two new improvements.

- Firstly, in order to spread out the CHs in the network, an initial number of CHs are chosen, which are at some uniformly distributed spatial points across the network. Then, a new CH is chosen on the basis of having maximum residual energy. This new CH should be near to the initially selected CH points. Owing to this, CH spread becomes uniform; across the network. The nodes even at the cluster edge do not have to dissipate more energy (which generally happens to LEACH).
- Secondly, it defines a new standard for selecting CH. As per this, two matrices are formed. In the first matrix, rows correspond to different CHs and columns correspond to all NCH nodes. Each element corresponds to the ratio of the residual energy of CH to NCH-CH communication energy. Obviously, this value needs to be high. In the second one, which is a row matrix where each element corresponds to the ratio of residual energy of CH to the CH-BS communication energy. Based on a weighting factor that balances NCH-CH energy and CH-BS energy, a third matrix is formed which is named as a Time matrix (not related to time), each element of which is a combined measure of CH residual energy, communication energy of CH with NCH node and BS as well. Depending on the value of each element, an NCH node in a column will select any one of CHs represented in one of the rows.

Finally, the algorithm achieves evenly spaced uniform distribution of CHs. Due to this algorithm, all nodes are approximately at uniform distances from their respective CHs. Thus TMCA outperforms the LEACH protocol by saving a significant amount of energy.

6) DATA AGGREGATION BASED ENERGY EFFICIENT CLUSTERING

This is an energy economical, 2D, static and homogeneous clustering scheme proposed by Khoa Thi-Minh *et al*. [25], which aims to perform data aggregation for effective energy utilization. This is achieved by splitting the process into rounds and each round has four phases: Initial phase, CH selection phase, clustering phase, data aggregation phase.

- In the initial phase, sink node broadcasts timestamp (the time instance, when an operation begins), span of each round and maximum node-sink distance. For effective energy usage, sink alone works in this phase. Due to this, each of the nodes knows when a round expires.
- In the next phase, each node broadcasts a HELLO message that comprises timestamp, its own residual energy, node-sink distance. Herein, the possible message collisions (that arise due to simultaneous broadcasting) are avoided by using a broadcast delaying random timer. Upon receiving HELLO messages, each node frames a priority table and finally decides one own self as CH, if it has a maximum residual energy and minimum node-sink distance. Thus CHs are selected.
- In the following phase, the actual formation of clusters takes place. To this end, INVITE message is sent from the thus self-elected CHs to all the neighboring nodes. By using the timestamp value in INVITE message, each node calculates its distance (Distance = Speed × Time) to the inviting CHs and chooses the nearest CH.
- In the last phase, the CH filters the redundant arrived messages from NCH nodes (which result due to the continuous transmission of the sensed data and sensing coverage overlaps). This is achieved by using a similarity function which compares each pair of received data for similarity. Thus, it is verified that clustering accompanied by data aggregation saves more energy as compared with clustering without data aggregation. Nevertheless, the performance sometimes gets poor at those instances when message collisions occur. This happens when the randomly generated delay timer values of any two CHs are identical.

7) LEACH-L CLUSTERING TECHNIQUE

LEACH is a 2D clustering algorithm designed for TWSN. This aims to extend the network lifetime by distributing the energy consumption of the node. To this end, it provides all nodes with an equal probability of becoming CH. However, in each round a new CH is chosen so random, that sometimes the selected CH and its members get wider apart. Then, it requires more energy by the members to transmit sensed data to CH. Obviously, the distant nodes get exhausted earlier and thus there is an energy imbalance in the network. Besides, in LEACH protocol, CH sends the aggregated data to BS directly in a single hop, which demands a greater energy of CH. Due to these characteristics, if LEACH protocol is applied in UASN there will be an early draining of node energies as they are energy hunger, non-rechargeable and deployed at wider distances. Moreover, LEACH protocol assumes a static node scenario, but in UWSN the nodes get transported by water currents and thus it is not static. Hence, LEACH is not suitable for UWSN [26].

In order to overcome some of these problems in UWSN, Xia Li *et al*. Came up with LEACH-L [27] protocol, which is an improvised version of LEACH. It works in two phases, viz initial phase and update phase. In the former, it forms an optimal number of initial clusters using conventional LEACH. In the latter, in contrast to LEACH where all the nodes get updated for every round, only a few nodes are updated locally, that enters and leaves the coverage of new CH. Here, the probability of the node to become a CH is made zero if it has already acted as a CH before. In this technique, CH position changes gradually. The current CH simply estimates the residual energies of the neighboring nodes and whichever node has the maximum energy, which is chosen as the subsequent CH. In LEACH, the relative distances between CH and its members for every round can vary widely, but in this algorithm the relative distances remain almost same. Thus, it minimizes the energy which a member requires to send to CH node. In this way, in terms of energy efficiency this protocol outperforms LEACH and is suitable for UWSN.

8) S-LEACH AND C-LEACH PROTOCOLS

In [28], Yongcui *et al*. achieves network longevity, reduction in the advertisement (ADV) packet collision probability and a large reduction in energy consumption, by introducing improved LEACH algorithms called S-LEACH and C-LEACH.

Unlike LEACH-L, a different problem associated with LEACH is highlighted in these protocols. In LEACH protocol, during its clustering phase, there is a broadcast interval during which, different self-selected CHs send advertisement messages to the NCH nodes at different random time instances. Consequently, if the time difference between two different broadcast processes is less than the cycle duration of one message transmission and reception, a collision occurs at the receiver node. Because of some reason or another, if the node is not connected to any cluster, then it needs to transmit data directly to BS, which is high energy consuming. So, this technique focusses on reducing the ADV packet collision probability.

S-LEACH or slotted LEACH completely avoids this collision by splitting the broadcast time into slots. It assumes that every node is a CH and assigns one slot to every node beforehand and that slot can be used, only if the node is a CH. As the length of each slot is equal to the maximum transmission delay needed, the collision probability is completely avoided. However, this consumes more energy, as the slots are used only by CHs which are limited in number, and NCH nodes keep listening during those unused time slots. This becomes a greater problem when there a large number of nodes (which causes longer set-up time and increased energy consumption, which has no productive usage), and when the topology is increased (which increases each slot length).

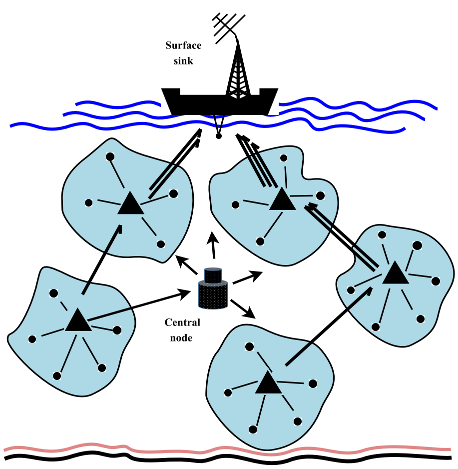

FIGURE 3. Topology of C-LEACH protocol.

In order to overcome the shortcomings of S-LEACH, C-LEACH or controlled LEACH is introduced, which uses a control node that is placed at the center of the topology as shown in Fig. 3. This node avoids the collision between two ADV messages and broadcasts the same on behalf of CHs. It consists of three phases as discussed below:

TABLE 2. Variants of LEACH protocol in UASN.

Evolution of LEACH Protocol in UWSN	Year	Comments
LEACH-L	2007	It forms a cluster head in each new round not by random selection, but based on a Local update of suitable new CH within the vicinity of older CH. Thus, it is energy efficient.
S-LEACH	2014	Avoids the collision of randomly generated advertisement messages by using a slotted broadcast time mechanism. Thus, it increases network longevity. But this cannot be used in a high spatial node distribution scenario
C-LEACH	2014	It solves the problem of long set up time duration that arises due to the slotted time mechanism. It is done by introducing a control node at the center of the scenario. Also, it avoids the need of a cluster member to send data directly to the sink.

1) In the first phase of cluster-heads informing, all CHs instead of broadcasting to all nodes send a message called ICH (Inform to CH) packet to control node (at different appropriate time intervals). The packet comprises sender node ID and position. Then, by using the IDs control node makes a cluster list.
2) In the second phase, the control node broadcasts the thus made cluster list to all the nodes in a message called C-ICH (Control node ICH) packet. Until C-ICH message is broadcasted, all the ordinary nodes remain in the sleep state and the control node alone works.
   It is assumed that the control node as shown in Fig. 3, has an extra energy reserve to perform all these operations.
3) In the last phase, the nodes upon receiving C-ICH packets, select which CH they want to belong to; on the basis of which CH is nearer to it. C-LEACH protocol, thus evades the energy wastage that occurs in S-LEACH due to unused slots. But, the collisions of ADV messages are not completely avoided. However, the overall performance of C-LEACH is more energy economical as compared to LEACH and S-LEACH. Table 2 highlights the key differences between each of the protocols.

9) DISTRIBUTED UNDERWATER CLUSTERING SCHEME

Domingo *et al*. [29] proposes this clustering scheme (DUCS) that is especially designed for long-run time-independent habitat monitoring applications. It considers all real-time characteristics of UWSN, that is random mobility of nodes under 3D scenario. DUCS incorporates a distributed way of clustering nodes. Clusters operate in rounds, and in each round cluster formation and network operation are the two phases involved.

TABLE 3. Classification and comparison of clustering algorithms in UASN.

		Attributes of clustering scheme					Performance parameters							Factors considered for clustering				
Clustering Techniques	Ref	Cluster count	In-cluster link	Sink-cluster link	Role of CH	Objective of CH selection	cluster stability	Location awareness	Energy efficiency	Delay efficiency	Load balancing	Data reliability	Failure recovery	Node density	Residual energy	Battery capacity	Depth nodes	Sink-CH distance
IBGCA	[18]	Constant	Single-hop	Multi-hop	Relaying	Improving Lifetime	Fixed	Yes	Low	Low	NA	High	Equipped	No	No	No	No	No
BGAF	[19]	Constant	Single-hop	Multi-hop	Relaying	Avoiding Hotspots	Adaptive	Yes	Moderate	Enhanced	High	Good	Not-catered	No	Yes	No	No	Yes
CBKU	[20], [21]	Variable	Single-hop	Multi-hop	Aggregating, relaying	Avoiding hotspots	Adaptive	Yes	High	Low	High	Moderate	Not-catered	Yes	Yes	No	No	Yes
C-LEACH	[28]	Constant	Single-hop	Single-hop	Aggregating, relaying	Reducing packet collision	Adaptive	Yes	High	Enhanced	Good	Good	Not-catered	No	Yes	No	–	No
CVBF	[32]	Constant	Single-hop	Single-hop	Aggregating, relaying	Improving total performance	Fixed	Yes	Moderate	Enhanced	NA	High	Equipped	Yes	Yes	No	Yes	No
DABECS	[25]	Variable	Single-hop	Multi-hop	Aggregating, relaying	Achieving high throughput	Adaptive	No	Low	Poor	Good	Moderate	Not-catered	No	Yes	No	–	Yes
DCP	[33]	Variable	Multi-hop	Multi-hop	Relaying	Improving network longevity	Adaptive	No	Moderate	Enhanced	Good	High	Equipped	No	Yes	Yes	–	Yes
DUCS	[29], [34]	Variable	Single-hop	Multi-hop	Aggregating, relaying	Improving scalability throughput	Adaptive	No	High	Enhanced	Good	High	Not-equipped	Yes	Yes	Yes	No	Yes
TMCA	[24]	Variable	Single-hop	Single-hop	Aggregating, relaying	Increasing energy efficiency	Adaptive	No	Low	Poor	Enhanced	Moderate	Not-equipped	No	Yes	No	Yes	Yes
FBCA	[31]	Variable	Single-hop	Multi-hop	Aggregating, relaying	Balancing node power consumption	Adaptive	No	Moderate	Enhanced	Good	High	Not-equipped	Yes	Yes	Yes	–	Yes
FCM	[31]	Variable	Single-hop	Multi-hop	Aggregating, relaying	Improving network longevity	Adaptive	No	Medium	Low	Moderate	High	Not-equipped	Yes	Yes	Yes	No	Yes
Hydrocast	[35]	Constant	Single-hop	Multi-hop	Relaying	Minimizing packet transmissions	Fixed	No	High	Enhanced	Good	Moderate	Equipped	Yes	No	No	Yes	Yes
LCAD	[36]	Constant	Single-hop	Multi-hop	Aggregating, relaying	Enhancing Network lifetime	Fixed	Yes	High	Low	High	High	Not-equipped	Yes	Yes	No	Yes	Yes
LEACH-L	[27]	Variable	Single-hop	Single-hop	Relaying	Improving network lifetime	Adaptive	Yes	Low	Less	Good	Low	Not-equipped	No	Yes	No	–	Yes
LUM-HEED	[37]	Variable	Multi-hop	Multi-hop	Aggregating, relaying	Balancing network traffic	Adaptive	No	Moderate	Low	High	Moderate	Not-equipped	No	Yes	Yes	No	Yes
MCCP	[38]	Variable	Multi-hop	Multi-hop	Relaying	Improving network longevity	Adaptive	No	Low	Moderate	Good	Moderate	Not-equipped	No	Yes	No	–	Yes
SHCHSA	[39], [40]	Variable	Single-hop	Multi-hop	Aggregating, relaying	Provisioning protection	Adaptive	Yes	High	Moderate	High	Moderate	Equipped	No	Yes	No	No	Yes
S-LEACH	[28]	Constant	Single-hop	Single-hop	Aggregating, relaying	Reducing packet collision	Adaptive	Yes	Moderate	Poor	Good	Good	Not-equipped	No	Yes	No	–	No
TCBR	[41]	Constant	Multi-hop	Multi-hop	Relaying	Improving energy efficiency	Assumed	No	Low	Moderate	NA	Moderate	Not-equipped	Yes	No	No	Yes	No
TTCB	[30]	Variable	Single-hop	Multi-hop	aggregating, relaying	Improving network longevity	Adaptive	Yes	Moderate	Moderate	NA	Moderate	Not-equipped	No	Yes	Yes	–	No
UWDBCSN	[42]	Variable	Multi-hop	Multi-hop	Aggregating, relaying	Minimising number of CHs	Adaptive	No	Moderate	–	NA	–	Not-equipped	Yes	Yes	No	–	Yes
EKACASA	[43]	NA	Single-hop	Multi-hop	Aggregting, relaying	Reducing data redundancy	Adaptive	No	Moderate	Enhanced	Good	High	-	-	-	-	-	-

In Phase-I, by considering residual energy and nodes initial energy; every node calculates a threshold, which gives a CH probability. Then a probable CH sends an advertisement to the neighboring NCH nodes. Now, by using acoustic time of arrival (ToA) approaches each node calculates its distance to the advertising CH and if the CH is nearer, then it accepts that node as CH by sending a join-request. However, a node which does not receive any advertisement opts to send to BS directly.

In phase-II, CH coordinates cluster members (CMs) and CH sends frames containing various time slots, each of which is assigned to different CMs. Initially, once after the formation of clusters, CH sends an acoustic signal to its CMs so as to measure the round trip time (which is the propagation delay suffered by each CM) Accordingly, it sets up a TDMA schedule for medium access, and sends it to the CMs using CDMA. TDMA is set up in such a way that all CMs will have their slot starting time, according to increasing units of propagation delay (First slot goes to CM with the least delay and last slot goes to CM with maximum delay). This adjustment made by CH is called timing advance, due to which high propagation delays are compensated. Consequently, the CH while receiving data packets from CMs experiences only the least unavoidable delay, and all other data packets are received uninterruptedly. Moreover, random mobility of nodes causes a change in the nodes respective locations and it follows a change of propagation delays. Due to this two or more CMs may simultaneously reach the CH and causes a packet collision, and hence there will be a data loss. To avoid this, a guard time is introduced between slots, that as such reduces or avoids the possible interference. Remarkably, due to timing advance; the guard time length is very less (it is a maximum of one tenth of slot).

After completion of each round, the cluster structure changes and accordingly the frame structure also changes. Meanwhile, if nodes get displaced, then the predefined slot structure may not accommodate the changed propagation delay, thus there is a possibility of packet collisions. With these efficient features the author claims that, the protocol achieves a high packet delivery ratio, a reduced network overhead and an increased throughput.

10) TWO-TIER CLUSTERING BASED ROUTING PROTOCOL

It is a clustering based routing protocol proposed by DiWu *et al.* [30] that finds application in 2D shallow underwater monitoring. The protocol comprises clustering and routing phases. It considers an architecture consisting of heterogeneous underwater nodes and a BS. There are first level sensor nodes having both CHs and CMs and upper level sensor nodes having only CHs. The latter ones possess more energy reserves.

The protocol operates in rounds. At the start of a round, the first-level CH node is elected. In order to have a reasonable distribution of CHs, two regulatory factors based on cluster interval and node energy are considered. Using these factors, a CH eligibility threshold is set, which depends on the residual energy and initial energy of a node. It also depends on the amount of energy consumed by the CH in the previous round. Any node that crosses this threshold; self-elects as CH and broadcasts it using strong acoustic signals. Then, the member nodes based on the residual energy and distance to the competing CH; select a CH. Later the member nodes send a JOIN REQUEST which gets accepted by the CH. In response, the CH sends a confirmation along with the assigned schedule of time slots; during which CMs can communicate with their respective CH.

In a similar way, first-level CHs send a request to the second level nodes by using flooding technique. Then, the second-level nodes send a response message. Now, the first-level CHs by considering 1) the time when the message is reached and 2) the received signal strength, elects a second-level CH. Later, a join request is sent by the first-level CHs and the elected CHs assign the time schedule of first-level CHs. The protocol uses an improved ant colony algorithm (ACO) in establishing an optimum path between these two level CHs. In the steady state phase, data transmission takes place between first-level CH and second-level CH which subsequently sends the received data to BS. After a little while, the BS makes a re-election command, that is where another round begins. The authors claim that the proposed protocol enhances the network survivability and it is especially of appreciable use when there are a large number of nodes.

11) FUZZY C-MEANS CLUSTERING ALGORITHM

It is a 3D, homogeneous cluster based technique proposed by Souiki *et al*. [31], wherein the clustering is performed using Fuzzy C-Means algorithm. The author proposes two routing protocols named as single-hop fuzzy based energy efficient routing (SHFEER) and multi-hop fuzzy based energy efficient routing (MHFEER) in which both the protocols use the same clustering method. But in transmission phase, the CH to BS transmission is performed through single-hop and multi-hop respectively. The adopted clustering is a fuzzy based initialization sensitive local optimization algorithm. As such, the algorithm needs an initial value and then, it quickly converges to a local minimum value. In this clustering algorithm, initially, the node that is closer to the center is chosen as CH, and in the subsequent stages the node with maximum residual energy is chosen as CH. MHFEER outperforms SHFEER in efficient use of overall energy.

12) LUM-HEED PROTOCOL

In [37], Ce Wang *et al*. proposed a homogeneous multi-hop clustering based routing protocol. This is adaptive to mobile node topology, and this can cater real-time industrial application needs. With a slight modification, it uses HEED protocol for underwater clustering. HEED is a clustering protocol in TWSN with location awareness and with a single-hop node-BS communication. However, performing the same in UWSN will cause an early energy drain of the nodes.

In order to incorporate HEED in UWSN, the author introduces an improvised protocol called Location Unaware Multi-hop HEED (LUM-HEED). This is a node location-unaware protocol and it adopts multi-hop communication. It assumes a homogeneous and random distribution of nodes. It operates in three phases named initialization, clustering, multi-hop routing.

- The first phase, which makes the current protocol suitable for underwater scenarios wherein, the sink assigns a degree of each node. At the outset, the degree of all nodes is initialized to zero. Then, using a single-hop, the BS sends a message with a broadcast radius of 'Rb_1' informing that your node degree is 1. Those nodes whose degree is less than 1 replace it with 1. Later, the updated nodes send a similar message with a broadcast radius of 'Rb_2' ($Rb_1 < Rb_2 < \cdots < Rb_n$). Thus, by the end of initialization the nearer nodes are given a higher degree and the farther nodes are given a lower degree. Interestingly, the higher the node degree the lesser the transmission power needed to relay the data packet. Consequently, although the nearer nodes to the BS are heavily taxed due to multi-hop, there will not be a problem of hotspot. This is because; the high degree node's transmission power is very less. Besides, the node degree remains almost same in a long time duration because, the node's advection due to ocean current is very little in comparison with the node radius. Thus, it is suitable for real-time applications.
- In the second phase, it incorporates the HEED protocol [44] for forming clusters, which is based on two parameters, namely residual energy and intra-cluster communication cost.
- In the last phase, by using route discovery messages, the nodes with lower degree chooses the nodes with a higher degree as a next-hop node and thus the multi-hop routing is performed.

13) ENHANCED K-MEANS ANOVA BASED CLUSTERING APPROACH

Hassan *et al*. [43] proposes this clustering technique along with a two-tier data aggregation method wherein, at first, each NCH node preliminarily performs an elimination of redundant data by considering the spatial resemblance of the node readings. Then, the NCH node periodically sends that distinct data to CH. Here is a possibility that any two different nodes can send the same data. Therefore, each CH by using an enhanced K-means algorithm based on ANOVA model fuses the identical data sent by two or more different nodes into non-redundant data. Thus, it reduces the data redundancy.

III. COVERAGE IN UWSN

Coverage refers to the field monitoring capability of the sensor network [45]. The better the coverage the better the response to the detection of any event. There are various kinds of coverage requirements based upon application specifications. In whichever case, coverage is affected by the initial spatial status of the nodes; that in turn depends on the deployment strategy being incorporated. Proper node deployment along with a proper choice of transmission power can ensure 100% coverage. Various features governing the underwater coverage are mentioned in this section and various existing coverage algorithms are summarised in Table 6.

A. FEATURES OF UNDERWATER COVERAGE

Coverage Attributes: There are several attributes that affect the achievable coverage of any algorithm as summarized in Fig. 9. Some of them are explained below.

1) ALGORITHM TYPE

In centralized algorithms, a central node is there with which every node directly interacts. Generally in underwater communications the nodes are wide apart. The centralized algorithm requires more energy on nodes for communication and thus the overall lifetime of the system reduces. But this mechanism is simple to operate. However, in distributed networks, there is no central node and the nodes form a mutual network among themselves. These algorithms save energy resource; as the node can interact with any neighboring nodes for any data exchange. However, as the distributed network involves coordinating a lot of nodes, it is less complex, which in turn depends on the cardinality of nodes.

2) SENSING MODEL

Broadly, two types of sensing models can be named. The first is a boolean model wherein, after a particular distance a node's sensing ability will be absent. In 2D underwater scenarios, the locus of sensing radius takes a disk shape and in 3D counterpart, a spherical shape. The second is a probabilistic model which approximates the realistic node's sensing behavior wherein, sensing is certain till some point and it exponentially reduces for a further little span. In the analytical coverage modelling, the model being used has a significant impact on the estimate of the amount of data overlapped.

3) NODE MOBILITY

In underwater communications, node mobility can be discussed in two ways. One is a mobile node and the other is a static node, but this gets moved by the mobile medium. If node has the movability, then coverage can be enhanced, coverage overlaps can be minimized, and coverage holes can be brought under sensing coverage. But if somehow the node gets moved by the medium, then one of the above things can happen involuntarily. Mobility due to the advection of water body eventually changes the 2D network topology (shrinks or stretches) and subsequently alters the 3D coverage. Nodes equipped with movability are a desired feature.

4) NODE TYPES

Two types of nodes based on the directionality are there. Nodes with scalar sensors (these sense ambient parameters like temperature, pressure etc.). These have omnidirectionality due to which the sensing locus forms a disk (2D) or a sphere (3D). The other kind of nodes are multimedia sensors (with an inbuilt directional camera). These have unidirectionality, which gives a conical sensing locus. But the latter has a more sensing range as compared with the former due to directing the entire energy towards a particular direction.

5) COVERAGE RECOVERY

Random node deployment leads to non-uniform spatial distribution of nodes in the monitoring area. This leaves some of the spaces uncovered, and that results in the formation of coverage hole. These coverage holes can be prevented by two ways. One is by increasing the node density. The other is by using a mobile node. The mobile node by moving to the coverage hole area offers sensing coverage. Thus, the mobility of nodes can provide coverage hole recovery. Algorithms that are equipped with such mobile nodes are very suitable for coverage critical intrusion applications.

6) ENERGY CONSUMPTION

The energy of the node is the central factor that affects all other performance parameters. Due to complete energy draining if a node dies, it results in the formation of coverage holes which makes the system less efficient in offering the coverage.

7) DEPLOYMENT TECHNIQUES

Underwater sensor deployment is a very crucial process as it decides the achievable sensing and communication coverage [46], [47]. The underwater node deployment is unlike that on terrestrial terrains. In underwater scenarios, for a 2D coverage application, nodes are deployed either on the water surface or on the seabed. But the former is prone to manipulation by human intervention, because herein, the nodes are prominently visible. Consequently, the latter is the usual choice for 2D node deployment. On the other hand, for a 3D coverage application, the nodes are deployed in underwater 3D spaces.

In doing so, the nodes are initially deployed on the water surface, which eventually sink into the water. After reaching the bottom of the sea, the nodes get anchored to the seabed. Then, by means of a winch-based node setup (which has a vertical movement-adjustable mechanism) as shown in Fig. 8, the nodes lift themselves up and reposition themselves at some pre-calculated depths [1], [48]. But in this kind of deployment, the mobility of water-bed causes the sinking nodes to drift [49]. This makes it difficult to estimate the final positions of 3D deployed nodes [50]. Various deployment techniques are shown in Fig. 7

Deployment method ensues different kinds of coverage as shown in Table 4. Deploying sensor nodes at different strategic positions, namely on the vertices of an equilateral triangle/ on a square lattice with different sensor radii ensues different kinds of coverage (for example: - 1-coverage, 2-coverage etc.). It can be observed from Fig. 4. However, the choice of various sensing models in coverage algorithm has a significant impact on the overall network longevity. This is because, in achieving 100% coverage disk model of sensing coverage results in more sensing overlap as compared with

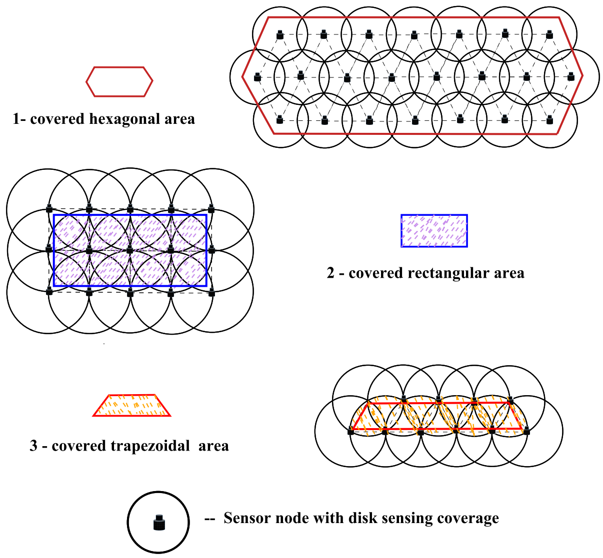

FIGURE 4. Deployment ensuing various kinds of coverage.

TABLE 4. Ways of deployment to ensue different kinds of K-coverage.

K-coverage	Suitable node positions	Sensing model	Comments
1-coverage (See Fig. 4)	On hexagonal grid lattice	Deterministic	Any node failure breaks 1-coverage and it is a sensitive configuration. 21% of the overlap is redundant [51].
2-coverage	On square grid lattice	Deterministic	It provides an efficient solution for multi point relay problem in WSN [52]
3-coverage	On both square and hexagonal lattice	Deterministic	Applied in triangulation-based tracking, 3D hull building [53]

that by using a probabilistic model. That is to say, the disk model results in relatively a higher sensed data redundancy. So, for energy critical applications, the probabilistic sensing model can be chosen.

One more factor that affects the underwater coverage is the mobility of nodes. Mobility is due to the advection of the water body. This results in a change of network topology in 2D plane (shrinks or stretches), which subsequently alters the coverage in 3D volume [54].

B. COVERAGE SCHEMES IN UASN

1) DISTRIBUTED SCHEME FOR 3D COVERAGE

A distributed and adaptive 3D space coverage algorithm is proposed by Hakan *et al.* [55] that estimates the appropriate depth to which the sensor nodes can be lowered into water from sea surface buoys. This achieves 90% of 3D space coverage with a minimal acceptable level of control traffic load. In this scheme, the average distance between a pair of nodes is increased in such a way that, there are no corridors (corridors are uncovered spaces through which intruders can enter) in the monitored space. This feature makes the scheme suitable for applying specifically for intrusion detection applications.

2) CDS BASED COVERAGE CONTROL ALGORITHM

Cai Wen-Yu *et al.* proposes a novel 3D oceanological facility, which is a part of UASN called BSN, buoys based sensor network [56]. This comprises a mass of buoy-based vertical detection chains otherwise called surface buoy node. This node can float offshore and data acquiring sensors are suspended down in water by means of this buoy node. This uses a novel coverage control algorithm based on connected dominating set (CDS). Those nodes having more residual energy are opted to be members of CDS. This is done by using a centralized Wu algorithm. The nodes of CDS are programmed to remain awake till the subsequent new round, whereas, the nodes that are not from CDS go to sleep state. Data sensing is done by means of the vertical detection chains, and the transmission uses RF communication. Thus, it increases the data transmission rate. Keeping the members of CDS to a minimal, is conducive for energy saving, but it is an NP-hard issue. As the algorithm assumes a sparse distribution of buoy nodes, the coverage is not guaranteed. So, providing unfailing coverage in BSNs is a research issue.

3) SELF DEPLOYMENT SCHEMES

Scheme 1: Fatih Senel *et al.* [54] proposed a self deployment node mechanism, which primarily focusses on enhancing the 3D coverage along with guaranteeing 1-connectivity. Herein, the nodes are assumed to be simply dropped on the water surface and eventually they sink themselves down to some calculated depths. This algorithm uses a CDS based approach for computing the depth of the nodes.

Initially, all the nodes are supposed to be dropped on the water surface. It is assumed that the nodes are initially connected in 2D and the mobility of nodes in 2D is exploited by making use of meandering current mobility model [57]. Now a few nodes are selected as leader nodes or dominating nodes which have subordinate nodes called dominees. In cyclic turns, the dominator nodes calculate the depths of their dominees by trying to minimize the coverage overlaps in vertical direction. The dominator nodes are always kept connected. The dominees are linked with that dominator having less sensing overlap. This group of dominators is called CDS, which works like a backbone of the network. Thus the algorithm tries to enhance the 3D coverage by exploiting the 2D movement of nodes. It can be seen from Fig. 5 that nodes N2, N9, N6 are chosen as dominating nodes and the dominee nodes are connected to one of these nodes with a single-hop link.

This algorithm achieves a coverage which is only 10% lesser or very close to the standard coverage achieved by using cluster based graph coloring technique, which is a baseline approach. The novelty in this algorithm lies in achieving

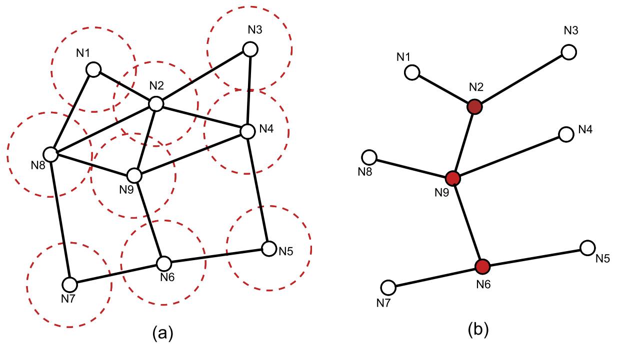

FIGURE 5. Formation of network backbone by choosing dominator and dominee nodes. (a) Node's 1-hop communication radius is more than its coverage radius. (b) Dominator node is chosen based on less coverage overlap.

1-connectivity besides providing a maximized 3D coverage. Moreover, the achieved connectivity is independent of the ratio of transmission range and sensing range.

Scheme 2: A self deployment technique offering a 3D connected coverage, is proposed by Akkaya et.al [58]. This self deployment technique is very much needed in the context, where the nodes cannot be manually deployed due to some security issues. It is a distributed scheme, and especially it can work well in less node density scenarios, both in terms of coverage and connectivity. In this algorithm, the nodes are initially assumed to be deployed at the sea bottom and are allowed to move only in vertical direction. The 2D sensing overlap of the nodes is reduced by this vertical movement of nodes, and the 3D overlaps are overcome by using a graph coloring technique.

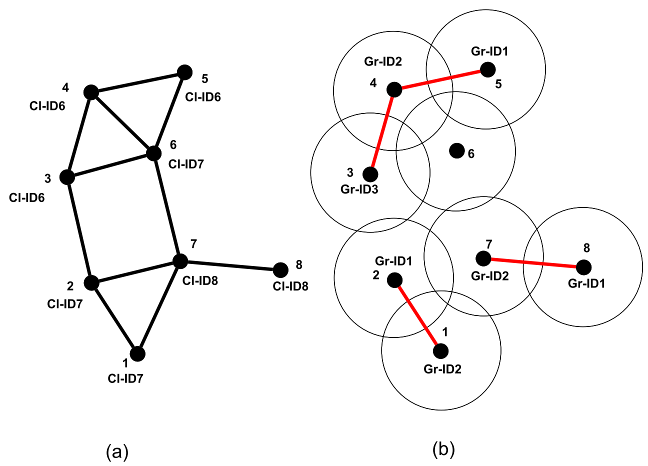

FIGURE 6. Clustering and grouping phases (redrawn from [58]).

This algorithm works in four phases

1) Clustering phase, wherein, each node stores the node IDs of its 1-hop neighbors. The one having highest node ID is chosen as the cluster leader. For example, in Fig. 6, Node 3, Node 4, Node 5 is having Node 6 as their 1-hop neighbors. As Node 6 is the neighbor having the highest Node ID, the nodes (3, 4, 5) are categorized under cluster ID 6 (Cl-ID6).
2) Grouping phase, herein, the nodes of the same cluster having coverage overlaps are grouped. This is done by using a graph coloring technique. Overlap sharing nodes are to be sent to different depths in order to eliminate or reduce overlap. The nodes in the same cluster having sensing overlaps are assigned different group IDs (Gr-IDs) using graph coloring.
3) Depth assignment, herein, a new and different depths are allotted to nodes of different Gr-IDs in such a way that the nodes without any coverage overlap remain at the same level of depth.
4) Additional rounds are needed after the initial round. This is because of possible overlap between nodes, which are at new depths. The nodes in the same layer having coverage overlap repel themselves, such that overlap reduces. This process terminates as soon as the number of rounds touches a threshold limit of rounds or when no further improvement is found in reducing sensing coverage. Thus, this algorithm achieves maximum 3D coverage along with connectivity.

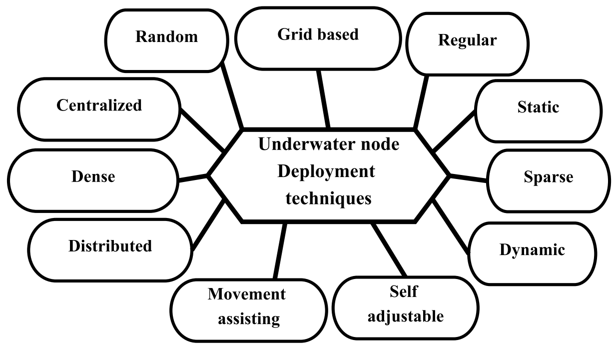

FIGURE 7. Classification of underwater node deployment techniques.

TABLE 5. Sensor node architecture in UWSN.

Characteristics	SN + AN	SN + AUV
Size	Light weighted	Bulky
Coverage recovery time	High ;due to slow displacement of ANs	Low ; due to faster displacement of AUVs
Application	Providing dynamic coverage	Coverage hole recovery and aiding in navigation

4) DYNAMIC COVERAGE ALGORITHM

Xiaoyuan Luo *et al.* [59] developed this technique which uses a blend of mobile actor nodes (AN) and static nodes to achieve 3D connected dynamic coverage. Herein, by using multiple actor nodes, not only is the data sensed but also the received data based action is taken. This method cuts down the construction cost of the underwater networking system. Also, it achieves dynamic coverage even without using AUVs, which are generally used in mobile sensor networks.

This algorithm works as follows. Initially, the connecting links are optimized and energy dissipation is reduced.

This is done by topology optimization, which is based on min-weighted rigid graph based approach. Then it is followed by achieving dynamic coverage task. In performing coverage task, firstly, a local message exchange takes place. Secondly, based on the received information from the neighbors, ANs spatially moves toward an isolated node and situate them near it, so that the isolated node has a neighbor. This is called feeding movement. Apart from this, when the AN within its purview, finds a node having more than one neighbor, it performs clustering action and simultaneously avoids over-crowding of nodes. The above operations are performed till the required coverage is achieved. The advantage of an actor node and AUV is comparatively described in Table 5.

5) SPLINE FUNCTION BASED COVERAGE SCHEME

Hsin-Hung Cho *et al.* [60] proposed a novel spline based tabu (SBTB) coverage algorithm based on non-uniform rational B-spline (NURBS). It defines the underwater field of interest (FoI) that uses convex hull feature of Spline function so as to tolerate uncertainty in mobility. It solves the problem of dynamic coverage very well. Herein, the network contact pattern is classified into four scenarios based on the sensor node distribution behaviour such as fixed contact, predicted contact, schedule based contact and opportunity contact. The last scenario is found to be the most suitable and robust environment to extend coverage. In this deployment model, the problem of finding the approximate node location underwater is addressed and full coverage is assured by using the convex hull feature of Spline function. SBTB outperforms the baseline greedy based coverage mechanism.

6) COVERAGE ALGORITHM BASED ON 3D VORONOI CELLS

A robust 3D underwater sensor node deployment mechanism for providing maximal sensing coverage, is proposed by Zhongsi Wang *et al.* [61]. This introduces a two-stage node selection and sinking scheme. Firstly, an optimal number of nodes are found and then a few selected randomly deployed surface anchor nodes are sunk in water. This is done by using an effective minimum-cost perfect matching of the complete bipartite graph algorithm. After this, some coverage holes will be left, which are covered by using a clustering and a 3D Voronoi diagram based algorithm. This algorithm addresses repairing of coverage holes and is capable of producing a greater coverage ratio as compared with the existing peer algorithms.

7) COVERAGE HOLE AND ENERGY HOLE AVOIDANCE SCHEME

As energy hole and coverage hole are potential degraders of network performance, these two issues were resolved in the paper by Kamran Latif *et al.* [62]. Herein, the solution for the energy hole problem was improved by scrutinizing the power dissipation in depth based routing techniques. For repairing the coverage holes, the existing coverage overlap areas are found. Then, the redundancy causing nodes move to appropriate places and thus the coverage ratio is increased.

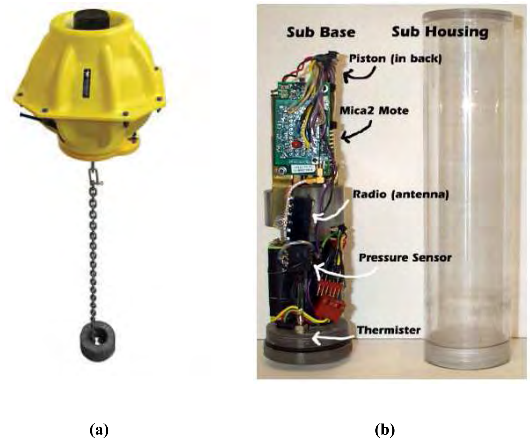

FIGURE 8. Underwater node (a) Vertical movement adjustable mechanism with a winch based node set-up (b) Cylindrical node with an adjustable piston [48].

The algorithm achieves three goals. The first is maximizing network lifetime. This is done by reducing routing overhead in the first stage of depth based routing. A technique called '*pick a back*' is used for this purpose. By means of this, the energy consumption is reduced. Simultaneously, nodes are updated about the points where too much energy is spent. The other two achieved goals are packet loss minimization and avoidance of multipath fading. This is achieved by a coverage hole repair algorithm called SHORT (spherical hole repair technique). SHORT works in three phases

1) In the knowledge sharing phase (KSP), the nodes are updated about the residual energy, their depths and location information by using Motetrack Identification schemes.
2) In the network operation phase (NoP), each node performs three functions of data aggregation, holding time calculation (By introducing this, packet losses are minimized at the receiver) and data forwarding.
3) Lastly, in hole repairing phase (HRP), nodes are moved to the places where coverage holes are formed. The holes might be formed either due to non-uniform node distribution or death of node. This phase gets activated upon the received announcement of the death status of the node.

The algorithm produces an improved throughput and energy efficiency by using varying transmission power but, at the expense of large delay. As the proposed methodology is based on availing the dense deployment, this coverage hole repairing algorithm cannot be applied to sparse sensor node deployed scenarios.

8) COVERAGE AND CONNECTIVITY ENHANCING DEPLOYMENT SCHEME

A novel 3D deployment scheme is proposed by Manjula *et al.* [63] that can achieve greater coverage, connectivity, and efficient resource utility all together. For the first time the parameter of 'attenuation factor' is considered in node deployment algorithm, due to which the coverage achieved outmatches the approach of connected dominated set based depth computation (CDA).

This algorithm achieves two major goals. Firstly, coverage is enhanced by incorporating an efficient node deployment scheme. Secondly, connectivity is improved, by the proper route planning of AUVs and proper placement of surface gateways (SG). Proper placement of SG is performed in two phases. Firstly, an optimal number of needed SGs is found, and secondly the approximate coordinates of placement of SGs are determined. The end-to-end delay, node overall energy consumption is reduced by deploying more SGs. Moreover, the algorithm defines four kinds of path plans for AUVs and it can be chosen as per the need of complexity, network cost, tolerable delay etc. This algorithm is expensive to realize in practice as it involves a lot of AUVs to be deployed.

9) DEPLOYMENT SCHEME WITH NODE REUSE

Son Le *et al*. [66] came up with a deployment framework with the node reuse scheme. As per this, the entire network works in a fixed region of interest and each node works in a fixed area of deployment. As soon as the node is advected beyond its boundaries, it is brought back and restored with a linguistic delay. The idea is that, node reuse stabilizes the network metrics. Based on the coverage and connectivity algebraic models which they constructed, without performing simulations the number of nodes required for a given percentage of coverage and given probability of connectivity can be found out. This is very useful for the network designers. However, this proposition does not consider the vertical or 3D advection of sensor nodes.

10) PADP SCHEME

PADP refers to prediction assisted dynamic surface gateway scheme [64], with four prime targets: maximizing the overall coverage, controlling the power consumed for redeployment, guaranteeing the connectivity, and meeting the budget requirements. This scheme uses the technique of incorporating multiple SGs which act as receivers sensor node data. By means of this, the associated long propagation delays and concomitant energy consumption of the nodes is reduced.

PADP increases the overall coverage in the following way. As the node's position gradually changes with node advection, deploying the SG based on the current position of sensor nodes reduces coverage. In order to maximize coverage and minimize the error probability, SGs are deployed based on the prediction of current and future node positions. Apart from that, in order to provide proper connectivity, this scheme integrates 'Interacting multiple model' named sensor position tracking scheme, branch-and-cut technique and disjoint set data structure clustering method. With this dynamic SG deployment method, coverage is more considerably maintained as compared with static SG deployment.

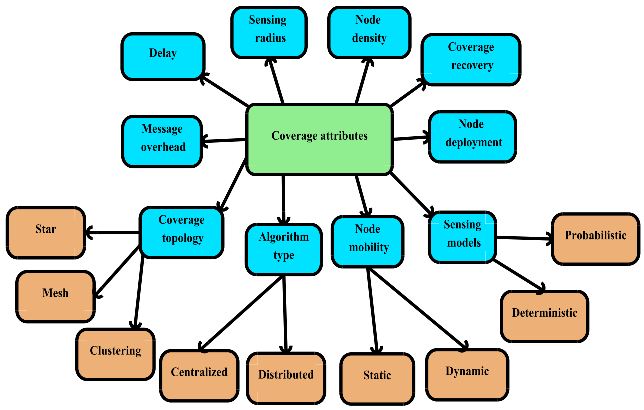

FIGURE 9. Attributes of underwater coverage schemes.

11) DEPLOYMENT SCHEME FOR 2D COVERAGE

Zhang *et al*. [65] proposed a deployment strategy for both sensors and gateways over a two-dimensional surface. This involves deploying nodes along coastline in two parallel lines which are of full connectivity, coverage and there is availability of localization and scalability. It is found that it exceeds the performance of random deployment strategy. This is validated by the increased throughput, decreased end-to-end delay and energy consumption.

IV. CONNECTIVITY IN UWSN

Connectivity is the probability that the given network graph forms a single connected component. Also, connectivity is a metric that defines the ease with which the nodes can connect to the surface station. Connectivity is required to ensure that the detected event is conveyed to BS [67], [68]. There are quite a few parameters which significantly affect the quality of connectivity in UWSN.

A. FACTORS AFFECTING UNDERWATER CONNECTIVITY

There are several factors that affect the connectivity in any network. These factors are summarized in Fig. 10. Some of which are vividly explained in this section.

1) SINK ARCHITECTURE

If there are multiple sinks, then the nodes will have an alternative path to connect to the sink [68]. Further, the probability of loosing connectivity due to failure of any intermediate node in the connection link gets reduced. Thus, the connectivity gets enhanced. In Underwater communication, when the distance of coverage is very large, the multi sink architecture can provide very reliable connectivity.

2) TOPOLOGY

Proper choice of topology makes the connectivity more reliable. For example, in case star topology, there is only single hop communication, in case of mesh topology, multi-hop is possible and clustering topology is a combination of multi-mesh networks [69]. The first two can be considered in case

TABLE 6. Classification and comparison of coverage schemes in UASN.

Ref	Sensing model	Coverage algorithm	Communication technique	Node deployment	Cost	Coverage recovery	Node mobility	Arena	Delay	Coverage achieved	Message overhead	Energy efficiency	Applications
[55]	Binary	Distributed	Wired+RF	Random	High	N/A	Static	3D	Moderate	90%	Acceptable	Less	Detection of intruders
[56]	Boolean	Distributed	Wired+RF	Sparse	High	N/A	Static	3D	Less	Poor	Acceptable	More	Time-critical applications
[54]	Spherical	Distributed	Acoustic+RF	Autonomous	Moderate	Good	Mobile	3D	Moderate	High	Acceptable	More	For pollution and habitat monitoring
[58]	Spherical	Distributed	Acoustic+RF	Autonomous	High	Less	Mobile	3D	High	100%	Acceptable	Less	Tactical surveillance
[59]	Binary	Distributed	Acoustic+RF	Min-weighted dynamic cover	Less	Poor	Static and mobile	3D	Moderate	High	Less	More	Instrument monitoring
[60]	Probabilistic	Distributed	Acoustic+RF	Random	High	Poor	Mobile	3D	Moderate	Outmatches baseline	Acceptable	More	Non-specific
[61]	Binary	Centralized	Acoustic+RF	Random	Less	Good	Static	3D	Less	High	Moderate	More	Non-specific
[62]	Probabilistic	Distributed	Acoustic+RF	Random and dense	High	Good	Mobile	3D	High	High	Less	More	In Coverage critical apps
[63]	Probabilistic	Distributed	Acoustic+RF	Manual	High	Good	Static and Mobile	3D	High	Outmatches	Moderate	More	Non-specific
[64]	Binary	Centralized	Acoustic+RF	Random	Moderate	Poor	Mobile	3D	Less	Close to baseline	Acceptable	More	Non-specific
[65]	Binary	Centralized	Acoustic+RF	Manual	Less	Poor	Mobile	2D	Less	100%	Acceptable	Less	Coastline applications

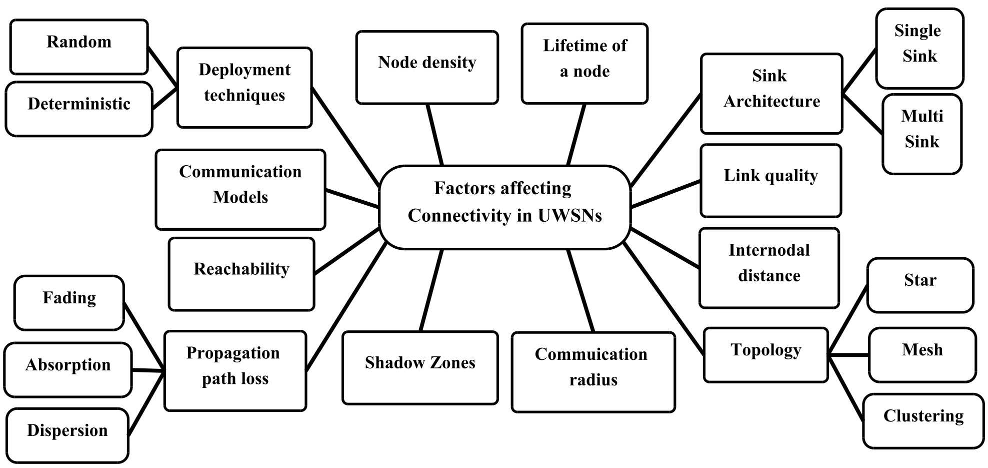

FIGURE 10. Factors affecting underwater wireless connectivity.

of having a single main node, and in case if there are multiple main nodes (CHs), clustering topology can be used and it can provide maximal connectivity.

3) SIGNAL PROPAGATION LOSS

The loss of connectivity is proportional to the loss of signal. The signal loss is due to signal traversing a significant distance, or due to absorption of particles or molecules in the medium, or due to weather conditions.

4) REACHABILITY

It is a sensitive metric that quantifies the ability of the network to communicate (especially in sparse networks) [68], [69]. It is the fraction of node pairs in the total number of nodes. Less reachability refers to a situation where the number of node pairs to form a link are less; consequently the connectivity is poor.

5) SHADOW ZONES

These are the spatial locations where communication signal is practically void. These zones are quite common, especially when the area of coverage is very large and it can be expected in areas where there is a high signal attenuation [70], [71]. Underwater is the medium where shadow zones can be expected because of having a wide area to cover.

6) INTERNODAL DISTANCE

In UASN, nodes after initial deployment are lowered to a calculated depths. However, in doing so, increasing the distance between nodes reduces connectivity, whereas decreasing the node distance enhances the coverage overlap. Thus, there is a tradeoff between coverage and connectivity. However, a balance of both can be achieved by keeping communication radius more than sensing radius. So, a suitable Internode distance has to be maintained [67].

7) OTHER FACTORS

There are several other factors that affect the connectivity of nodes in the network. One of which is the *communication radius*, which in other words refer to the transmitter node's signal power. Nodes can form connected components or loop only when the communication radius is large enough to link up with at least one neighboring node. This signal power in turn depends on the *energy resource* the nodes do have and on the kind of application. Besides, *Node density* also affects connectivity. There is a trade off between the required node density and the available communication radius. In security applications, however, both communication radius and node density may have to be high. Further, the communication *link quality* decides the quality of communication that can happen and various link quality measures like RSSI, link quality indicator (LQI) define the degree of link quality as per the application. Moreover, in underwater scenarios, nodes establish an optimal connection among themselves by spatial self adjustment in vertical direction. This mechanical adjustment to give rise to a better node connectivity, naturally depends on the initial position of nodes before depth adjustment, in other words it depends on *node deployment*. So, the deterministic node deployment and the random node deployment schemes provide a high and moderate node connectivities respectively. Apart from that, the *lifetime of the node* leads to the formation of two or more disconnected components in the network graph. Thus, the node with high longevity provides long term connectivity.

V. IMPACT OF COMMUNICATION TECHNIQUES ON CLUSTERING, COVERAGE AND CONNECTIVITY

In this section, we tried to elaborate on the effect of non-acoustic communication techniques like MI, RF and UWFSO for underwater clustering, coverage and connectivity aspects.

A. MI FOR UNDERWATER COMMUNICATION

For wireless underwater communications, the suitable frequency range of MI communications is from 0.5 KHz to 3 KHz. MI waves are tolerant to wave turbulence, obstructing segments and also are immune to acoustical noise. Besides, the MI waves do not have any adverse effect on the aquatic life. As air and water have same magnetic permeability [72]; the underwater generated waves will have a smooth transition at the air-water boundary.

In MI communications, the coils generally have the capability to relay the induced signals. If provided with sensing circuitry and some required memory, future MI nodes can be used for data aggregation as well as for relay otherwise MI coils can only relay. Depending upon the type of application, the range of MI coils can be chosen. The range increases with the increased size of coils. The MI signal absorption by the underwater channel is less because, the MI underwater transmission distance is less than the signal wavelength [73], [74]. So, a suitable frequency can be chosen for a required communication range. Owing to these favorable factors, clustering can be performed successfully using MI technique. Also, the transmitted data is reliable as the signals are not affected by the turbidity of water.

For MI communication, the coils have to be driven by an electrical signal and in underwater communications that signal will be given by any underwater vehicle or robot carrying the MI coil. However, the vehicles that power MI coils inside water can move in random directions [72], [75]. In order to provide unbreakable connectivity it is not possible with unidirectional coil antennas. So, an MI transmitter and receiver must be equipped with three dimensional signal propagation capability as shown in the Fig. 11.

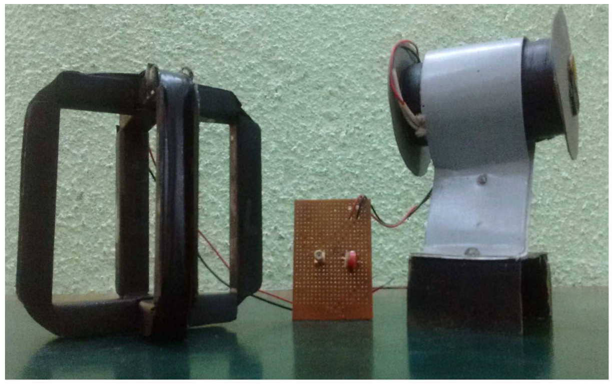

FIGURE 11. MI coils (2D (left) and 1D (right)) designed in VNIT lab.

Using the MI wave guide technique, bit error rate and path loss can be tremendously reduced, especially for all varieties of freshwater applications. Therefore, MI communication can be used for the habitat monitoring of the freshwater lakes [76], [77]. For saline water environments, MI can be applied to overcoming the limitations of acoustic underwater technique. In defense applications, existence of the shadow regions in the coverage area causes security threat. MI can overcome all shadow zones [78]. So, it can offer a maximum coverage. Therefore, for a maximal coverage requirement in shallow water short range applications MI gives better service.

B. OPTICAL UNDERWATER COMMUNICATION

Underwater optical communication operates in four possible modes: a) Point-to-point line of sight mode b) Retroreflector based LoS mode c) Diffused LoS mode d) Non-Line of Sight mode. UWFSO communications has the advantage of being able to provide high data rates of up to Gbps, very high immunity For latency of transmission and low cost or inexpensive, non-bulky small volume transceivers [79]. These advantages make UWFSO; suitable for a wide variety of applications.

Underwater applications include homogeneous, heterogeneous, static, dynamic and a combination of the above scenarios. In the first two modes, where LoS is a prominent feature, dispersion and scattering can reduce the efficacy of the LoS communication [80]. Therefore, there must be a scenario, wherein nodes are relatively stationary and there must be an

TABLE 7. Behaviour of various communication techniques in underwater environment.

Factors affecting clustering, coverage and connectivity underwater	**MI**	**Acoustic**	**RF**	**Free space optics**
Conduction velocity	$3 \times 10^8 m/s$	1500m/s	$\approx 3 \times 10^8 m/s$	$\approx 3 \times 10^8 m/s$
Communication range	$\leq 10mtr$	$\leq 10km$	a few meters	a few 100 meters
Recharge-ability	Yes	No	No	Yes
Propagation path loss	very less	25-30 db/km/100MHz	High	Turbidity dependant
Transmission power	Moderate	Moderate	High	Moderate
Data rate	A few Mbps	$\leq 100Kbps$	$\leq 10Mbps$	$\leq 1Gbps$
Directionality	Omni	Omni	Omni	Uni
Preferred area of application	Shallow waters	Long haul communication	Shallow waters, Short distance local underwater communication	Deep fresh waters
Usable frequency band	In MHz	$\leq 100KHz$	30-300 Hz	$10^{14} - 10^{15} Hz$

empowered node to which the rest of the nodes can send data. Here the nodes need not change their direction and thus LoS condition is satisfied. Due to the above features, wireless underwater optical communication can be used for real-time video transmission, intrusion and earthquake detection.

Moreover, in the last two modes as there is diffused LOS or non-line of sight source of light, this can be used for dynamic and homogeneous node clustering scenarios. This kind of setting can be used for underwater habitat monitoring, pollution and marine life monitoring kind of applications. UWFSO communication is an economical choice than acoustic in this case. Further, there is a trade-off between the attenuation of diffused light rays and the coverage achieved. With respect to connectivity, there is not much difficulty in deep waters, but in shallow waters, due to the frequent tidal phenomenon there are serious connectivity issues.

C. RF UNDERWATER COMMUNICATION

RF technique complements acoustic technique as they hardly overlap in any of their operating conditions. So, RF technique can be used for those applications for which acoustic technique fails to comply with. For example, RF signals do not adversely affect the marine life, can sustain even through turbid regions and work well in shallow water conditions, can smoothly transit the water-air interface etc. On the other hand, RF signals suffer electromagnetic interference and attenuation due to the conductivity of saline water, and air limited to short ranges. These are exactly opposite to that of underwater acoustic signal capabilities [81].

In addition to that, the range of RF signals is limited to a few meters or even less. So, RF communication may be used in applications that comprise fresh water, in a confined area with some time critical security applications. Further, a swift transportability at the air - water boundary makes the RF system less complex and more economical. In air, RF signals attenuate very less, so there must be a proper spatial separation for usage of frequencies. On the contrary, RF signal attenuates highly underwater [82]. Therefore, it is very much suitable for communication in a multi-user localized environment. Apart from that, it can be used for very short range, high speed, physical touchless data transfer applications [83].

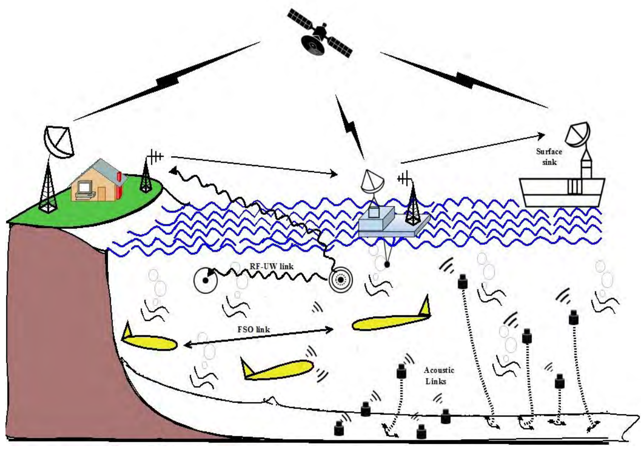

FIGURE 12. Working of various underwater wireless communication techniques.

It is a fact that when a signal travels from a denser medium to a rarer medium, signal moves away from the normal of the medium boundary. As per this, any RF signal travelling from water to air refracts at the boundary in such a way that the signal becomes nearly parallel to the water surface. It is shown in Fig. 12. On account of this, when the RF signal is used for shallow water applications, a minor portion of the signal is used underwater and a major portion of it can be propagated through the air, thus it is quite possible to monitor shallow water regions using RF technique even without using a surface buoy. This makes the RF underwater system economical as compared with UASN. Table 7 gives a glimpse of the typical characteristics and behavior of all the above underwater communication techniques.

VI. OPEN ISSUES AND CHALLENGES

In this section, a few research problems, some key challenges and scope for further technical improvements related to coverage, clustering and connectivity is mentioned. These issues are summarized in Table 8 for quick reference.

TABLE 8. Summary of open issues and challenges in UWSN.

QoS aspects	Attributes	Challenges and open issues
Clustering	Network longevity	Designing control information optimization algorithm
	Novel clustering	Designing clustering technique for sparsely deployed 3D homogeneous network
	Retransmission reduction	Design of mechanism with a least number of data retransmissions
	Shallow water clustering	Need a cluster technique that works in shallow waters
	Payload reduction	Need to design an energy efficient data fusion technique
	Effective clustering	Need to consider distance optimization in CH selection
	Realistic energy dissipation model	Need to estimate the accurate network lifetime
	Cross layer optimization	Finding an optimal cluster count considering energy dissipation in various layers
Coverage	Fault tolerance	Need a robust coverage hole repair algorithm
	Energy conservation	Need an overlap sensing mechanism with a least control traffic overhead.
	Realistic sensing model	Needed to estimate accurate coverage overlap
	Horizontal coverage	A laterally movable sensor nodes can be designed
Connectivity	Economical network	Design of a low-cost acoustic modem technology
	3D K-connectivity	Design of a suitable node deployment strategy.
	Re-connectivity	Need a mechanism to reconnect nodes after forming partitions
	Reduced delay	Need a delay optimized connectivity mechanism
	Multi-BS architecture	To achieve time critical connectivity, useful for defence applications
	Cooperative transmissions	To achieve adaptive connectivity based on residual energy awareness
	Directional antenna	To achieve application specific energy efficient connectivity

A. CLUSTERING

- *Network longevity:* It is needed to design a clustering algorithm that is focussed on reducing the control information. Reducing control message signals will reduce the overall energy consumption. It eventually enhances the network longevity. This can be done at intra-cluster level, inter-cluster level and in between BS and CHs.
- *Novel clustering:* Clustering techniques have been developed for many application specific requirements. Clustering techniques do exist for underwater 2D/3D, static/dynamic, homogeneous/heterogeneous scenarios. But there is one specific underwater scenario for which there is no clustering technique developed so far. To bridge the gap, a robust clustering technique needs to be designed for a sparsely deployed 3D homogeneous network. To the best of our knowledge, as per our survey, this type of underwater clustering is not yet addressed in existing literature.
- *Energy consumption:* Retransmission of signals is required due to some failures in data packet delivery. This consumes additional energy. So, it is very much productive working upon reducing the data retransmissions. This reduces the overall energy consumption.
- *Shallow water clustering:* Clustering performed in deep water is not so much affected by the dynamics of underwater because, despite the movement of underwater, relative positions of members of cluster remain almost same. But in shallow waters, due to so much turbulence, sometimes CMs may go out of their cluster. So, a clustering technique, especially for shallow water applications is required that addresses this issue.
- *Reducing payload:* It is very much desirable to design a robust data aggregation or data compression technique within a CH, so that the payload of transmitting signals and thus reduces overall energy consumption reduces.
- *Effective clustering:* Generally, CH is chosen randomly. It implies that sometimes the chosen CH may be far away from its CMs, so the CMs require more energy in transmitting signal to CH. Therefore, in choosing CH, it should be seen that the CH is approximately equidistant to all the CMs. This further saves energy consumption and balances load on CH. So, a distance optimized CH selection technique makes the clustering more effective.
- *Cross layer optimization:* An increase in cluster count decreases the total energy consumed as a result of reduced inter-CH distance (PHY layer perspective). It increases the total energy consumed as the total number of hop counts increase (Network layer perspective). Similarly, in MAC layer perspective, the total energy increases due to an increase in the probability of becoming CH. Therefore, in order to have a minimum consumption of energy, an optimal number of clusters are needed to be chosen. So, a cross-layer optimized clustering is needed to be done. The same can be applied for all underwater techniques [84].
- *Realistic energy dissipation:* In any clustering process, the network lifetime is measured based on the rate of energy dissipation of nodes. If the estimated lifetime is lesser than the actual lifetime, then the system resources are underused and if the estimated lifetime is greater than the actual lifetime, the system performance said to be poor in terms of network longevity. So, a realistic energy dissipation model needs to be used in the design of the clustering process.

B. COVERAGE

- *Fault tolerance:* In defense applications, it is needed to detect the entry of intruders. To achieve this, the deployed sensor nodes aim to cover the entire field of observation. But, when a node fails to function, it causes a coverage hole that becomes a loop hole for the intruder to enter. Therefore a robust coverage hole repair mechanism has to be developed which considers the dynamic underwater channel characteristics and it must be fault tolerant.

- *Energy conservation:* In executing a coverage algorithm, sensing overlaps are detected and then the nodes are moved to some suitable locations. It is to be noted that, attaining a required coverage involves some control messages, which do not constitute the actual data needed. So, an energy efficient coverage technique needs to be designed with a least amount of control traffic overhead.
- *Horizontal coverage:* So far, in achieving required coverage, the available nodes can be moved only in vertical direction only. But the sensor nodes also have to enhance the coverage to their maximum extent in horizontal direction. Therefore, sensor nodes are needed to be suitably designed to move in horizontal direction also. This optimizes sensing coverage in all directions.
- *Realistic sensing model:* Sensor homogeneity, spherical model of sensing radius and communication radius are some of the commonly made assumptions for underwater sensors [85]. It is needed to develop a realistic sensing and communication model for the coverage algorithms. By using realistic coverage models, a lot of sensing data overlap can be reduced.

C. CONNECTIVITY

- *Economical network:* In UASN, inter-node communication is possible despite having the node positions at a few miles away. This is due to a high acoustic transmission range. But the same feature makes the system expensive also. Thus, it is needed to design a low-cost acoustic modem for long-range communication so that it allows for more spatial sensor node distribution. Having a high node density naturally assures connectivity as well as coverage [86].
- *3D k-connectivity:* For some coverage critical applications, it is challenging to find out what is the minimum required spatial node density in order to achieve k-coverage and k-connectivity [87], [88]. The relative positions of underwater sensor nodes depend upon the kind of deployment strategy being used. Therefore, it is needed to design a node deployment strategy that can achieve 3D k-coverage and connectivity.
- *Re-connectivity:* Owing to the dynamic nature of the underwater environment, the nodes may sometimes loose connectivity and form partitions. Once the partition is formed, the node again needs to reconnect to the network, otherwise the connectivity becomes poor. To avoid this, there needs to be some standby mechanism to re-establish the lost connection.
- *Reduced delay:* Delay sensitive applications like earthquake and Tsunami detection requires least delay networks. In UWSN there is an unavoidable delay due to the propagation speed of the signals [89]. So, there is a need to have a delay optimized connectivity mechanism.
- *Multi-BS architecture:* Generally in a UASN, a single sink is used for collecting data from the underwater CHs. Underwater acoustic signals experience a high delay due to less propagation velocity. For some time critical applications, data needs to be conveyed with least possible delays. Suppose there are multiple BSs, then it will reduce the total number of hops required to convey the message signal to the onshore sink. Thus, the multi-BS architecture reduces the overall delay. So, it is needed to incorporate multi-BS architecture for delay-insensitive underwater applications.
- *Cooperative transmissions:* In some underwater clustering techniques, a CH is chosen very randomly. Sometimes the distance between CH and BS becomes so wide that the node has to drain a lot of energy. If the residual energy of CH is not sufficient enough to reach BS, then there is a loss of connectivity. In such cases, cooperative transmission can be performed. By means of cooperative transmission, the CH aggregates energy from the surrounding nodes and transmits high energy signals [90], [91]. In this way, an adaptive connectivity mechanism with residual energy awareness needs to be developed.
- *Directional antenna:* In a typical underwater application, nodes are randomly deployed with the omni directionality of the radio transmitting antenna. But in some specific applications where the target object of observation is decided, then the orientation of the deployed nodes will be unidirectional. In such cases, a unidirectional antenna will suffice. Moreover, for a given power, the nodes with directional antennas can send signals to larger distances than that with omnidirectional antennas [92], [93]. So, directional antennas can be incorporated for achieving low cost application specific connectivity.

VII. CONCLUSION

In this paper, the latest underwater acoustic clustering techniques have been studied and a comparative analysis has been done with respect to various performance parameters. Various schemes by which coverage can be maximized and simultaneously maintaining an ensured connectivity either by adjusting the depth of the nodes or by using autonomous underwater vehicles has been studied and summarised. In addition to that the feasibility and impact of non-conventional communication techniques like MI, UWFSO, RF for underwater communication has been objectively discussed. Various applications for which these three communication techniques can outperform acoustic communication technique are explained. The constraints of all the communication techniques are objectively compared which makes it possible to choose a viable communication technique for a given application.

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