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OFDM-based spectrum-aware routing in underwater cognitive acoustic networks

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Abstract: With the long propagation delay of an acoustic signal in underwater communications systems, relay node selection is one of the key design factors, because it significantly improves end-to-end delay, thereby improving overall network performance. To this end, the authors propose orthogonal frequency division multiplexing-based spectrum-aware routing (OSAR), a scheme in which spectrum sensing is done by an energy detector, and each sensor node broadcasts its local sensing results to all one-hop nodes via an extended beacon message. Each sensor node then selects nodes that agree on an idle channel, consequentially forming a set of neighbouring nodes. The selection of a relay node is determined by calculating the transmission delay – the source/relay node selected is the one that has the minimum transmission delay from among all nodes in the neighbouring set. To evaluate OSAR, the authors perform extensive simulations via ns-MIRACLE for different numbers of channels using a BELLHOP model, and evaluate the average delay for different sensor nodes within the considered network. The results show a substantial decrease in delay as the number of sensor nodes increases in the network. In addition, the authors verify that the packet delivery ratio increases with increases in the number of sensor nodes, and prove better performance in the overhead ratio. The authors' simulation results verify that OSAR outperforms existing solutions.

1 Introduction

Underwater acoustic communications systems have been attracting significant interest in the last decade in order to deal with various applications for scenarios ranging from the depths of the ocean to the surface of the ocean. These applications include underwater resource exploration, environmental monitoring, target tracking, oceanography data collection, ship navigation, ship traffic management, and marine animal study [1–4]. Unique challenges in the underwater environment (e.g. severe path loss, limited bandwidth, long propagation delays, etc.) and co-location of diverse acoustic communication systems in the ocean increase the demand for safe and stable communications in this new research venue. The communication systems include both natural acoustic systems (e.g. marine mammals) and artificial acoustic systems (e.g. sonar systems). They both rely on acoustic waves for communication. Luo *et al*. [5] showed that the spectrum band from 1 to 40 kHz is heavily shared among different acoustic users, triggering high competition to utilise the spectrum resource efficiently. Like the terrestrial radio spectrum [6], maritime communication systems [7] have also undergone spectrum scarcity due to the emerging demands of underwater applications.

To alleviate the spectrum scarcity in underwater networks, cognitive acoustic (CA) is a viable solution as it can utilise a spectrum in an environmental-friendly manner (i.e. avoiding harmful interference with natural acoustic systems) and in an efficient manner (i.e. high spectrum utilisation) [8]. Underwater cognitive acoustic network (UCAN) systems perform the same task of allocating an idle channel to CA users while protecting primary user (PU) activity. A stable acoustic link is essential for communicating with different acoustic users in order to meet the increasing demands of underwater applications. A link is formed only when two communicating users have consensus about a common idle channel. Therefore, a new cognitive routing protocol is required to ensure cooperation among acoustic users; thereby retaining a stable link for underwater communications.

Routing is a process that helps acoustic users to establish a stable route to forward messages to the whole network. Due to harsh underwater environments, implementing a routing protocol under water is a challenging task, especially when utilising the idle spectrum while keeping PU activity undisturbed. Moreover, the sound signal in underwater acoustic channels is attenuated by multipath interference or fading, developing an acoustic system that is truly wideband [9]. To overcome these drawbacks of underwater acoustic channels, multicarrier modulation seems to be a solution. Orthogonal frequency division multiplexing (OFDM) has been widely studied as a popular method for both terrestrial and underwater communications in order to decrease inter-symbol interference and overcome the long delay spread. Therefore, a novel cognitive routing protocol based on an OFDM modulation scheme is an essential requirement for underwater networks.

However, in order to maintain a stable link to reach the destination while avoiding interference with diverse acoustic systems and keeping the activity of licensed users undisturbed and cope with the shortcomings of long propagation delay, selection of a relay node is one of the key design factors in underwater sensor networks. Therefore, selecting a relay node that incurs minimum transmission delay to send packets to the destination improves the overall network performance. Consequently, forming an underwater cognitive sensor network that guarantees scalability and sustainability while co-existing with multiple acoustic systems is a primary aim of this study.

Our main objective is to combine cognitive capability with a routing technique in order to overcome the problems of spectrum scarcity and high latency in underwater cognitive networks. OFDM-based spectrum-aware routing (OSAR) performs spectrum sensing to evaluate the surrounding environment, and then finds the best relay node to deliver packets to the destination. Spectrum sensing is performed with an OFDM-based energy detection scheme. The querying node first finds a common idle channel by comparing its local sensing results with all the neighbours within the transmission range, and then selects a relay node for the next hop that has the minimum transmission delay. Two sensor nodes can only communicate while protecting the activity of both 'natural acoustic users' and 'artificial acoustic users' if they find a common free channel.

The rest of this paper is organised as follows. We begin with a discussion of conventional routing protocols in Section 2, and introduce the framework of OSAR in Section 3, with a detailed description of channel- and relay-selection mechanisms. Section 4 demonstrates the simulation results of the proposed solution. Finally, we conclude this paper in Section 5, and point out some future directions for our work.

2 Related work

Routing in UCANs is more challenging, compared with conventional routing protocols in underwater sensor networks. Conventional routing protocols proposed for terrestrial communications have been modified for underwater communications by considering the characteristics of underwater channels. Yan *et al*. [10] proposed depth-based routing (DBR) for underwater sensor networks to provide scalable and efficient services for dense networks. DBR is based on a greedy algorithm in which each sensor node takes a decision by comparing its own depth with the depth of the previous node. The protocol achieved a 95% packet delivery ratio without considering recovery algorithms to avoid the void.

Pressure routing for underwater sensor networks [11] addressed the local maxima by maintaining a recovery route. In this algorithm, a route discovery method was proposed that implements hop-limited two-dimensional (2D) flooding. To select a set of forwarding nodes that maximises greedy progress and limits co-channel interference, an opportunistic routing mechanism and a dead end recovery method were used. Pompili *et al*. [12] proposed two distributed geographic routing algorithms for delay-insensitive and delay-sensitive applications in underwater environments. They investigated the problem of data gathering by achieving high acoustic channel efficiency and limiting the packet error rate. Their objective was to minimise energy consumption by jointly selecting the best next hop, the optimal transmit power, and the best forward error correction rate for each packet.

Noh *et al*. [13] proposed void aware pressure routing (VAPR) for underwater sensor networks. VAPR is a soft-state protocol that uses *enhanced beaconing* to propagate the data from sonobuoys to sensor nodes, and *opportunistic directional data forwarding* then builds a directional trail to the closest sonobuoy. The algorithm is robust to network dynamics and ensures loop-freedom for mobile networks. Coutinho *et al*. [14] recently presented detailed guidelines for opportunistic routing protocols in underwater networks and discussed the advantages and disadvantages of candidate set selection for sender-side-based, receiver-side-based, and hybrid procedures. Carlson *et al*. [15] designed a reactive, link-state mobile ad hoc network routing protocol – a location-aware source routing (LASR) protocol that considers the characteristics of underwater acoustic networks. LASR uses the key idea of the dynamic source routing (DSR) protocol by considering source routes for communication between autonomous underwater vehicles (AUV), maintaining only those routes that are in use. Their results achieved greater reliability over both DSR and blind-flooding routing protocols. Ali *et al*. [16] proposed the diagonal and vertical routing protocol (DVRP) for underwater wireless sensor networks in order to reduce the network load and improve throughput by calculating a flooding zone. The purpose of this flooding zone is to prevent flooding the whole network, thereby increasing the reliability of the network. The authors demonstrated improvement over DBR in simulated results.

All of these existing routing protocols for underwater sensor networks do not consider spectrum scarcity issues caused by limited communication frequencies. To meet the increasing demands of underwater acoustic users, it is essential to propose a cognitive routing protocol that takes the spectrum scarcity issue into account. Luo *et al*. [17] proposed a receiver-initiated spectrum management system for UCANs. They allowed acoustic users to utilise the spectrum with both ‘natural acoustic systems’ and ‘artificial acoustic systems’ efficiently and courteously. They increased the overall data transmission rate by combining a collision avoidance mechanism with joint power and channel allocation. Their results showed better performance for both the tree topology and the partially connected mesh topology by integrating spectrum sensing on the physical layer with spectrum sharing on the medium access control layer.

To the best of our knowledge, combining cognitive principles with routing schemes for underwater sensor networks has not yet been considered. This is the first work implementing a cognitive routing protocol in UCANs that simultaneously considers spectrum sensing and routing for underwater sensor networks. To enhance route stability, we try to overcome both spectrum scarcity and path stability issues side by side. Our goal is to provide a stable route for communications between sensor nodes and surface buoys in underwater environments by jointly selecting channel and relay.

3 Proposed scheme

We propose the OSAR protocol for underwater cognitive acoustic networks. The objective of this proposed scheme is to ensure cognitive routing in underwater sensor networks by considering both natural acoustic systems and artificial acoustic systems as primary users. We consider an underwater cognitive sensor network with N sensor nodes and L primary users. The purpose of using cognitive principles in underwater sensor networks is to increase the spectrum opportunities for different users communicating with each other in the ocean. OSAR is a spectrum-aware routing scheme in which each node first senses its surrounding environment to make sure that the channel is free from both natural acoustic systems and artificial acoustic systems, and then choose the best relay node as the next forwarder to reach the destination. The two CA nodes can only communicate with each other when they have consensus on a common idle channel. Our goal is to minimise the transmission delay by selecting the best relay nodes between the source and destination. Likewise [11], we consider one-dimensional (1D) geographic routing in a single upward direction to sea level.

Sensor nodes are assumed to be equipped with acoustic modems and depth sensors in order to configure their depths and measure the distance to the surface of the ocean. All nodes periodically update the depths of their neighbouring nodes. This helps the querying node to find the best relay node that incurs the minimum transmission delay. We divide the acoustic spectrum into M channels. CA users perform spectrum sensing to find an acoustic spectrum not utilised by the PUs. Spectrum sensing is a challenging problem in underwater networks because both types of primary users in the underwater environment are mobile, and we cannot predict the position of natural acoustic systems. Moreover, another critical issue in underwater acoustic networks is time delay. For that reason, we use an energy detection scheme to detect the presence of a PU, because it is the simplest technique that has a short sensing time, and it is useful when little or no information about PU signals is available. One distinguishing issue with an acoustic signal is that it is attenuated by fading or multipath interference due to sound absorption and rough sea surfaces. To overcome fading or multipath interference, we use OFDM as a modulation technique. OFDM simultaneously uses multiple sub-bands to transmit the packets between two communicating sensor nodes. As this is a cognitive routing scheme, cognitive users need to sense the spectrum continuously to find a number of free subcarriers for communications among different users. This means that a link between two communicating acoustic nodes has a set of sub-channels/subcarriers free from PU activity. Therefore, to improve the data rate, a packet can be transmitted over a number of free subcarriers. Accordingly, we assume that the primary signal is an acoustic OFDM signal. Before going into a more in-depth description of OSAR, we first discuss how sound signals from marine mammals can be detected and how the spectrum can be utilised in the presence of marine mammals.

3.1 Discussion

One might think about how a sound signal from marine mammals is detected by the CA users. Here, we briefly discuss the assumptions we make for sound signals produced by marine mammals. Marine bioacoustics [18] is used by researchers and marine scientists to record the sounds produced by marine animals in order to study their behaviour and relationships with the marine environment. Various studies have been carried out to measure and detect different sound patterns produced by different marine mammals [19, 20]. Researchers have placed various hydrophones on the sea floor to detect the sound signals. Like these studies, we assume that the patterns of sound signals are known and each CA user can detect this signal frequency by using an energy detector. The methods marine scientists used to measure animal sounds are not part of this work. Our motive is to protect the signal produced by either marine mammals or SONAR systems from interfering with CA users. We will further explore this problem in the near future. Additionally, the sound patterns of marine animals like whales, dolphins, etc., have pauses of a few seconds, and multipath arrivals of sound with echoes are considered noise. Moreover, mammals can hear each other at up to six miles apart [20]; beyond that distance, the sound signal is also considered noise. Therefore, the spectrum can be utilised even when marine mammals are communicating with each other, either during pauses or when CA users are far enough from legitimate users to keep PUs safe. For that reason, we model PU activity as an exponential on/off activity pattern. In SONAR systems as a PU, we assume that both transmitters and receivers are equipped with transducers. However, for natural acoustic systems, receivers only are equipped with transducers.

3.2 Spectrum sensing and the channel model

In this section, we perform spectrum sensing to detect the presence of a PU signal on an underwater acoustic channel. The significant aspect of the underwater acoustic channel is the dependence between bandwidth and frequency and the distance between the communicating sensor nodes [21]. Spectrum sensing is done with an energy detection scheme. We consider an OFDM-based cognitive acoustic system in which the PU-OFDM system consists of P subcarriers. The CA system performs sensing operations to detect which subcarriers are free from PU activity.

In an OFDM modulation scheme [22–24], the symbols of the PU first pass through a serial-to-parallel converter to generate parallel streams, and they then enter the P-point inverse fast Fourier transform block, which generates transmit samples. Then, multiplexing is done to generate serial streams of PU symbols, after which a cyclic prefix is added to the original samples. Finally, the OFDM-based PU samples are transmitted through an underwater acoustic channel. On the receiver side, CA users receive samples from the acoustic channel, remove the cyclic prefix, and allow these samples to pass through a serial-to-parallel converter to enter the P-point FFT block. The receiver detects the total number of subcarriers that can be used by CA users for communicating with each other. Hence, the received signal after the FFT operation is defined as

$$y_{q,i}(n) = s_{q,i}(n) + w_{q,i}(n), \tag{1}$$

where $q = 1, \dots, P-1$ is the subcarrier index.The received signal is then modelled as a binary hypothesis test in order to detect the presence or absence of a PU signal on the underwater acoustic channel. The two hypotheses are defined as follows:

$$y_{q,i}(n) = \begin{cases} w_{q,i}(n), & H_0 \\ s_{q,i}(n) + w_{q,i}(n), & H_1 \end{cases} \tag{2}$$

where $i = 1, \dots, N, s_{q,i}(n)$ is a complex PU signal at subcarrier q, and $w_q, i(n)$ is noise. The energy-based test statistic in discrete domain is given as follows:

$$y_{E_{q,i}} = \sum_{n=1}^{W} y_{q,i}[n]\widetilde{y_{q,i}}[n], \tag{3}$$

where W is the time-bandwidth product and $\widetilde{y_{q,i}}[n]$ is the conjugate signal of $y_{q,i}[n]$.

The key parameter in the underwater realm is the acoustic propagation speed, which is assumed to be 1500 m/s in most of the literature. However, the propagation speed in acoustic theory is mainly affected by depth, temperature, and salinity, and can be modelled in metres per second as follows [12]:

$$\begin{aligned} q(z, s, T) = {} & 1449.05 + 45.7\,T - 5.21T^2 + 0.23T^3 \\ & + (1.333 - 0.126\,T + 0.009T^2)(s - 35) \\ & + 16.3z + 0.18z^2, \end{aligned} \tag{4}$$

where z is the depth in kilometres, s is the salinity in parts per trillion, and $T = (\text{temperature in }^\circ\text{C})/10$.

Another peculiar property of an underwater acoustic channel is the dependence of path loss $A(d, f)$ on the signal frequency, f. This path loss while travelling over distance d affects the received signal power, which in turn changes the signal-to-noise-ratio (SNR) for each user transmitting at f. Therefore, each sensor node experiences a different SNR, which is calculated as follows [21, 25]:

$$\text{SNR}(d, f) = \frac{P_\text{T}}{A(d, f)N(f)\triangle f}, \tag{5}$$

where P_T is the transmitted power, $\triangle f$ is the width of frequencies, and $N(f)$ is the noise power spectral density, which is calculated as

$$N(f) = N_\text{t}(f) + N_\text{s}(f) + N_\text{w}(f) + N_\text{th}(f) \tag{6}$$

The right-hand side of (6) refers to the superposition of four components: turbulence (t), shipping and other human activities (s), wind and waves (w), and thermal noise (th). These four components are calculated as follows [26]:

$$\begin{aligned} N_\text{t}(f) &= 17 - 30\log_{10}(f) \\ N_\text{s}(f) &= 40 + 20(s - 0.5) + 26\log_{10}(f) \\ &\quad -60\log_{10}(f + 0.03) \\ N_\text{w}(f) &= 50 + 7.5\sqrt{\text{w}} + 20\log_{10}(f) \\ &\quad -40\log_{10}(f + 0.4) \\ N_\text{th}(f) &= -15 + 20\log_{10}(f) \end{aligned} \tag{7}$$

$A(d, f)$ in (5) is defined as $A(d, f) = d^k a(f)^d$, where k is the path loss exponent that models the geometry (spherical and cylindrical) of propagation, and $a(f)$ is the absorption coefficient, which can be obtained by Thorp 's formula [27]

$$A(f) = \frac{0.11f^2}{1 + f^2} + \frac{44f^2}{4100 + f^2} + 2.75 \times 10^{-4}f^2 + 0.003, \tag{8}$$

where $A(f) = 10\log_{10} a(f)$.

Acoustic communications in underwater systems present various challenges due to environmental conditions that are primarily related to accurate modelling of the channel behaviour [28]. To propose an appropriate algorithm for underwater cognitive routing networks on both the physical link layer and the network layer, an introductory requirement is to design a relatively accurate channel model. Guerra *et al.* [29] showed the significant difference in using a ray tracing tool over empirical propagation formulae. The empirical equations cannot model complex phenomena, such as sound speed profile, bathymetry, and sound propagation in bottom sediments, whereas a Bellhop ray tracing tool provides an accurate emulation of sound propagation and a relatively accurate channel model. However, the authors also claimed that accuracy provided by a Bellhop simulator is only limited to channel attenuation. For modelling noise in an underwater channel environment, empirical equations are still used in simulations. Also, Qarabaqi and Stojanovic [30] claimed that ray theory seems to be a viable solution for providing an accurate picture of an underwater acoustic channel. We second them, therefore, like Toso *et al.* [31] and Bahrami *et al.* [32], and in this study, we use beam tracing tools, such as the Bellhop [33], to compute the channel attenuation to take into account ineluctable channel variations.

In our proposed scheme, each sensor node first senses the spectrum individually by using (2), and then exchanges its local

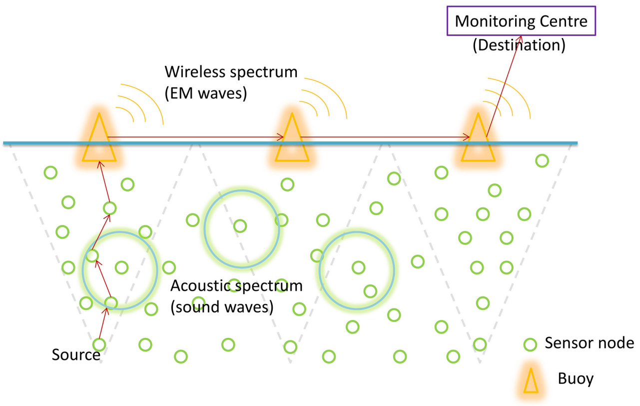


Fig. 1 *Underwater cognitive acoustic network*

sensing results with all the nodes within the acoustic transmission range to find the next forwarder in its vicinity. The querying node then selects the forwarder with a shallower depth if and only if they both have consensus about the common idle channel and they both meet the other constraints (explained in the next subsection) to establish a routing path to the surface. The following section explains how routing is done in underwater communications systems using the channel state.

3.3 Relay selection

To select the best relay node in order to make a stable route between the source and destination, we propose an efficient routing scheme by using the sensing results obtained as described in the previous subsection. To initiate routing, the source node first broadcasts a beacon message to all its neighbouring nodes. The beacon packet includes the sender's ID, depth, channel state, and speed. The channel state and speed are calculated from (2) and (4), respectively. The channel state is defined as the state that represents either the channel under observation is idle or busy. Each sensor node updates its table by receiving the beacon messages from neighbouring nodes. Each node compares its depth with the source/querying node. The nodes at the same and greater depth to the querying node will drop the packet (i.e. they will not participate in the routing protocol). The nodes making a positive advance toward the destination will be added to P_i^D. The nodes in P_i^D compare their local sensing results, and if they find a common idle channel between two of them (i.e. querying node and relay node), they will be added to N_i (the neighbour set of node i with common idle channels). It is noteworthy that two sensor nodes can only communicate with each other in order to form a path between the source and destination if they have consensus about a common idle channel. The selected relay nodes now jointly calculate the packet size, capacity, propagation delay, and estimated number of hops to the destination. These parameters are jointly calculated as transmission delay, which is defined as

$$\mathrm{TD}_{ij}^{\mathrm{ch}} = \left(\frac{L_{\mathrm{P}}}{r_{ij}^{\mathrm{ch}}} + \mathrm{PD}_{ij}\right)\widehat{N}_{ij}^{\mathrm{Hop}}, \tag{9}$$

where ch is one of the M channels; L_{P} is the packet size; r_{ij}^{ch} is the data rate of link (i,j), defined as $r_{ij}^{\mathrm{ch}} = C_{ij}^{\mathrm{ch}} = \int_{f_{\mathrm{l}}^{\mathrm{ch}}}^{f_{\mathrm{h}}^{\mathrm{ch}}} \log_2(1 + (S(f)/N(f)))\,\mathrm{d}f$. The capacity of the common idle channel between the two communicating nodes is as assumed elsewhere [21, 34], where f_{h} and f_{l} are upper and lower frequencies of each channel, respectively, and $S(f)$ is the power spectral density of the transmitted signal. If there is more than one common channel between two communicating nodes, then the querying node randomly selects a channel. PD_{ij} is the propagation delay, defined as $\mathrm{PD}_{ij} = D_{ij}/q(z,s,T)$; $D_{ij} = \mathrm{Depth}_i - \mathrm{Depth}_j$; $\widehat{N}_{ij}^{\mathrm{Hop}} = \max\left((D_{iD}/\langle D_{ij}\rangle_{iD}), 1\right)$, in which D is the destination node, and $\langle D_{ij}\rangle_{iD}$ is the projection of distance D_{ij} on the line connecting source to destination.

Our algorithm allows each node to select its best next hop with the objective of minimising the transmission delay while taking the condition of the common idle channel between the two communicating nodes into account. The key idea behind OSAR is similar to greedy routing, which is to select a node that is farthest from the source node (closest to the destination). However, the selection of the next hop node by considering only the propagation delay seems like an unjustifiable issue in underwater cognitive acoustic networks. This is because the acoustic speed is very small in comparison with the speed of light used in terrestrial communications and finding a common idle channel is an elementary step for sensor nodes to communicate. Therefore, in our scheme, we modify the greedy routing algorithm by considering transmission delay. Our algorithm selects the farthest node based on (9), which not only considers the estimated number of hops but also considers the propagation delay along with the data rate and packet size. The selection is defined in terms of an optimisation problem, as follows:

$$\begin{aligned} &\text{Find:} \quad j = \arg \min_{j \in N_i \subset P_i^D} \mathrm{TD}_{ij}^{\mathrm{ch}} \\ &\text{Minimise} \quad \mathrm{TD}_{ij}^{\mathrm{ch}} = \left(\frac{L_{\mathrm{P}}}{r_{ij}^{\mathrm{ch}}} + \mathrm{PD}_{ij}\right)\widehat{N}_{ij}^{\mathrm{Hop}}, \end{aligned} \tag{10}$$

where N_i is the set of nodes within i's transmission range that has a common idle channel with node i and P_i^D is the set of nodes making positive advance towards D.

To summarise the whole idea, let us assume some sensor nodes are distributed in the target area, as shown in Fig. 1. The destination in this study is any surface buoy located at the sea level. Basically, the original destination is the monitoring centre on land, but this final route from the sensor node (source) in the ocean to a monitoring centre on land will be our future work by jointly handling wireless and acoustic communications. Here, we assume that all the surface buoys are at the same depth, and each sensor node in the network recorded the depths of the surface buoys. We assume marine mammals are one kind of PU in this study. When a source node, as shown in Fig. 1, wants to communicate with a surface buoy, it starts looking for the best relay node for establishing a stable path from itself to the surface of the ocean. The very first task of the querying node is to find a common idle channel. Therefore, each sensor node first performs spectrum sensing to detect the number of subcarriers free from PU activity. The sensor nodes then exchange their local sensing results with the neighbouring set of all nodes present in P_i^D. The nodes having common idle channels form another set: N_i. From this set, the querying node selects the node that has the minimum transmission delay among those relay nodes that have an idle channel in common with the querying node. Thus, the process is repeated by each relay sensor node until the packet reaches the destination. The flowchart for selection of the next hop node in OSAR is represented by Fig. 2.

4 Simulations

We simulated OSAR in ns-MIRACLE [35] connected to a Bellhop channel simulator [33] via the World Ocean Simulation System (WOSS) [29] interface. WOSS is basically a powerful tool that provides a connection between ns-MIRACLE and the Bellhop channel simulator. It takes the scenario information (geographic location of all the sensor nodes) from the network simulator and provides the environmental data queried from the oceanographic databases to the channel simulator. As mentioned before, the Bellhop channel simulator uses ray theory to model relatively accurate channel characteristics by employing the information about the sound speed profile, bathymetry, and types of bottom sediments. After some post-processing [28], WOSS finally returns the channel attenuation and interference to the ns-MIRACLE network simulator.

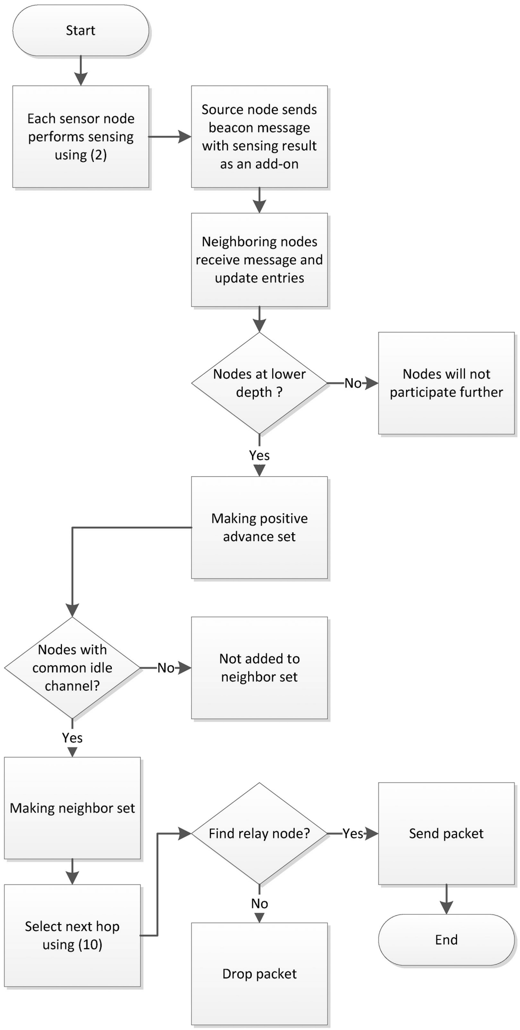


Fig. 2 *Flowchart representing OSAR protocol*

In our scheme, randomly placed sensor nodes are distributed in a target area of 500 m × 500 m × 500 m, each having a transmission range of 250 m. Packet size L_P is assumed to be fixed (i.e. 64 bytes). The number of CA users, N, varies between 10 and 30, and the acoustic spectrum band (10–40 kHz) is divided into M= 5 channels. Each channel can be occupied by a licensed PU. The bandwidth of each channel is 6 kHz with carrier frequencies of {13, 19, 25, 31, 37} kHz. This means that a band of frequencies is free for use by legitimate users in order to transmit data packets over a number of free subcarriers. The total number of subcarriers, $P = 128$, each have carrier spacing of 46.875 Hz. As we know that channel sensing is affected by sensing time in any cognitive radio network, we therefore use fewer subcarriers to make it reasonable for underwater cognitive acoustic networks. For the same reason, we use the length of cyclic prefix, $T_{\text{CP}} = 12.4$ ms with symbol duration, $T_s = 21.33$ ms which is greater than the typical value of delay spread in underwater networks, i.e. ∼ 11 ms [25]. The PU is $L = 1$ in this study, and it can move up to a distance of 1000 m from the target area of CA users, because marine mammals can listen to each other at up to six miles apart [20]. Beyond this distance, their signals are considered noise. The PU is moving randomly in the network. The transmission power, P_{T}=150 dB re μ Pa, which is within the range of the power value for acoustic signals of dolphins [19].

We evaluated DBR [10] and DVRP [16], each in combination with an energy detector-based spectrum sensing scheme [36] for underwater cognitive sensor networks just for reference. For simplicity, we denote these schemes as Cog-DBR and Cog-DVRP, respectively. DBR is a depth-based routing protocol proposed for underwater sensor networks that selects its next forwarder in a single upward direction. Cog-DBR modifies the DBR protocol such that each sensor node first senses the spectrum. Then each node exchanges its local sensing results with all the sensor nodes in its neighbourhood to select a common idle channel from among the set of forwarding neighbours. Finally, it implements the key idea of DBR to choose the final appropriate relay node. Another modification in DBR is that if the source/relay nodes do not find the next hop with a common channel at the maximum distance, Cog-DBR selects one at a greater depth within the transmission range. DVRP is a flood-based routing protocol for underwater sensor networks that forwards data packets (based on the flooding zone angle) from the sender nodes towards the surface of the ocean. It selects the next-hop node within the defined flooding zone. Like Cog-DBR, Cog-DVRP modifies the DVRP protocol, such that each sensor node exchanges the spectrum sensing results within its defined zone in order to find a common idle channel. The two communicating nodes, having consensus about a common idle channel, then exchange data packets to make a stable route between source and destination.

Fig. 3 shows the performance of average delay as a function of the number of sensor nodes with the number of channels as a parameter. Average delay is defined as the average time required by a packet sent from the source node to reach the surface buoy. The average delay decreases with an increase in the number of sensor nodes. The reason for the decrease is the greater connectivity in the network due to the increase in the number of sensor nodes. With fewer sensor nodes, the packet usually has to wait longer than normal. However, in addition to this reason, finding a common idle channel in cognitive communication scenarios is another cause of packet delay. As our goal is to minimise the transmission delay, we therefore select the next relay node that needs a relatively minimum time to deliver the packet to the next hop. Also, this relay selection continues until the packet reaches any buoy at the surface of the ocean. On the other hand, Cog-DBR makes the next-hop decision based on greedy routing after finding a common idle channel between two communicating nodes. Hence, OSAR outperforms Cog-DBR because it selects the next relay node based on transmission delay in order to make a stable path between the source and destination. Also, both OSAR and Cog-DBR outperformed Cog-DVRP. It can be seen from Fig. 3 that the delay for Cog-DVRP is even higher than Cog-DBR. This is because Cog-DVRP restricts the neighbouring set for the querying node. The querying node is bound to select a relay node within the flooding zone. As this is a cognitive routing scheme, the elementary step of selecting a common idle channel between two communicating nodes further degrades the performance of this reference scheme. As a result, finding a relay node within a flooding zone decreases network performance by reducing the number of sensor nodes. Fig. 3 also shows that increasing the number of channels increases the chance for the sensor nodes to have even more common idle subcarriers. When there is only a single channel in the network, the number of idle subcarriers is also fewer; hence, the CA users face difficulty in accessing subcarriers free from a PU. Increasing the number of channels allows CA users to opportunistically access the common idle sub-bands, and increases the chances for more sensor nodes to participate in the network. In this regard, the average delay under OSAR is the lowest compared with other scenarios when the number of channels is $M = 5$, as shown in Fig. 3*c*.

Fig. 4 shows the packet delivery ratio of OSAR, Cog-DBR, and Cog-DVRP. Packet delivery ratio is defined as the ratio of the number of packets delivered to any surface buoy to the number of packets generated by the source node. The delivery ratio increases with an increase in the number of sensor nodes. We achieve 93% packet delivery under OSAR when there are more sensor nodes in the network, compared with both of the other reference schemes. The reason is the difference in the selection of the relay node. When the selection is based on the DBR protocol, the querying node may select a relay node that does not make a stable link due to greater delay, resulting in link failures and a low packet delivery ratio. In a cognitive underwater environment, in addition to underwater environmental challenges, another factor that affects the packet delivery ratio is the selection of a common idle channel. However, when OSAR is the cognitive routing scheme, the packet

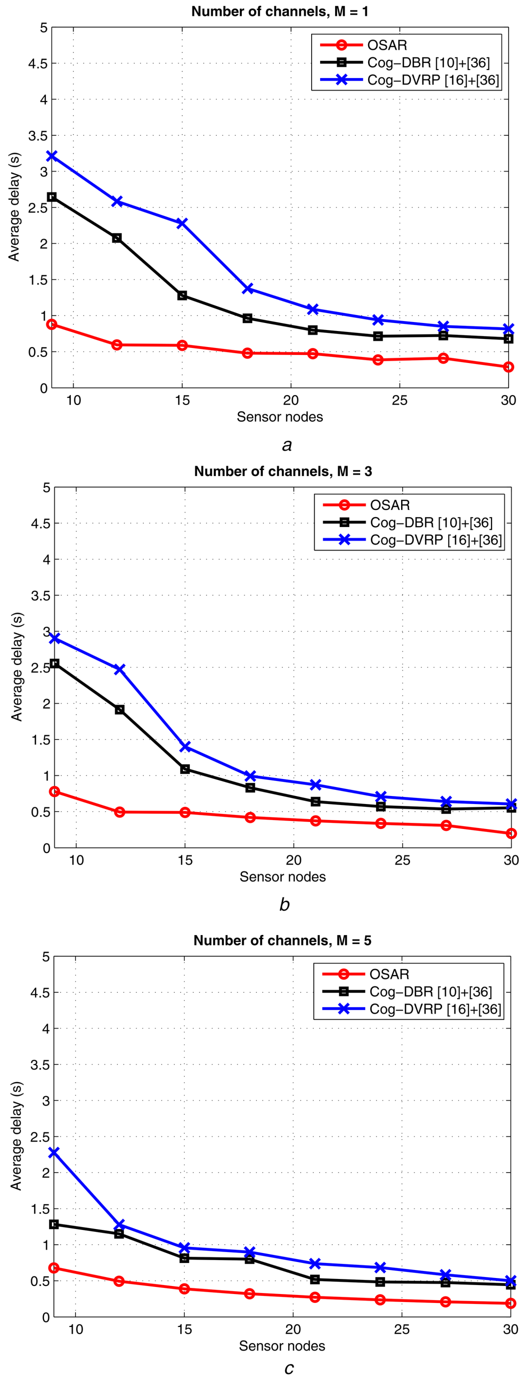


Fig. 3 *Performance comparison between OSAR, Cog-DBR, and Cog-DVRP for average delay as a function of the number of sensor nodes with different numbers of channels, M*

(a) Average delay when $M = 1$, ***(b)*** Average delay when $M = 3$, ***(c)*** Average delay when $M = 5$

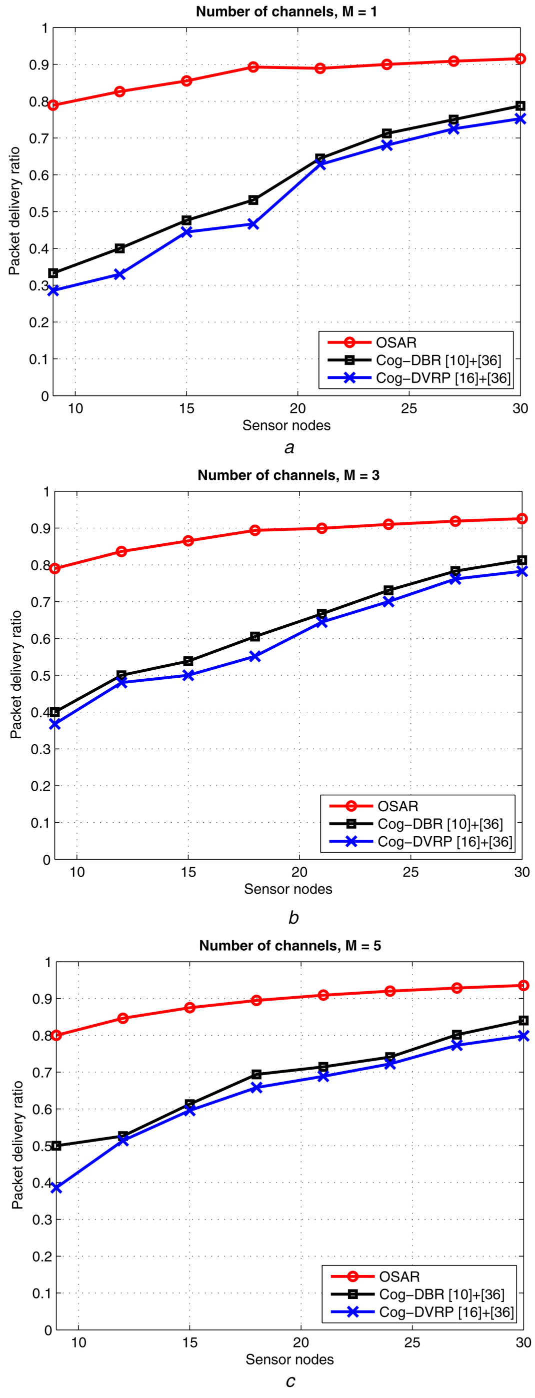
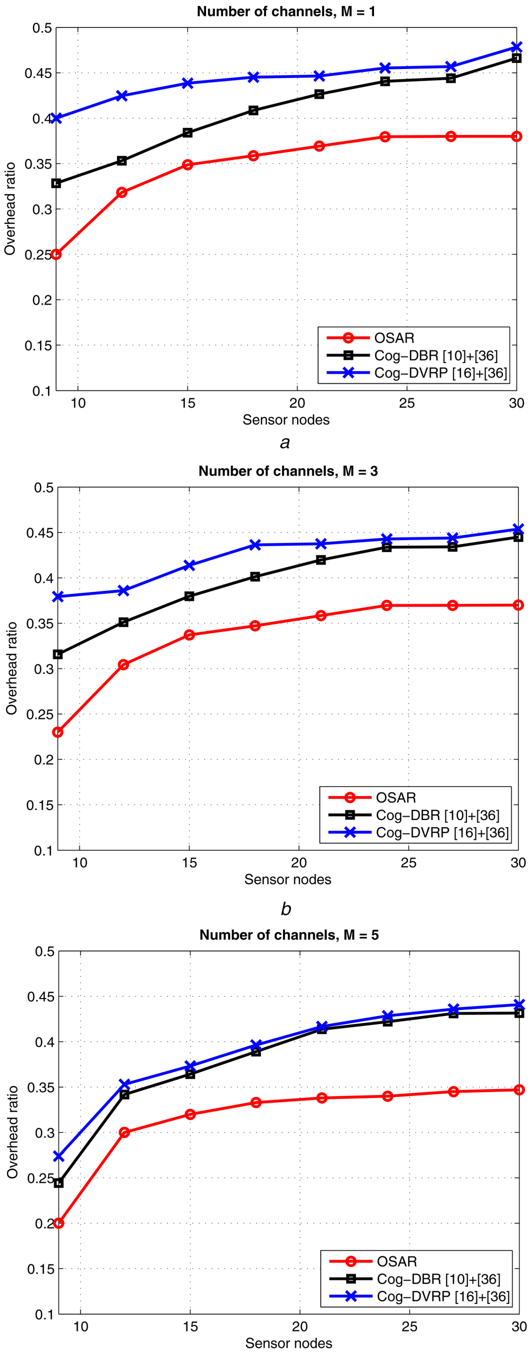


Fig. 4 *Performance comparison between OSAR, Cog-DBR, and Cog-DVRP for a packet delivery ratio as a function of the number of sensor nodes with different numbers of channels, M*

(a) Packet delivery ratio when $M = 1$, ***(b)*** Packet delivery ratio when $M = 3$, ***(c)*** Packet delivery ratio when $M = 5$

delivery ratio is higher for different numbers of channels, in comparison with the other two reference schemes. The reason is the selection of the relay node based on minimum transmission delay. OSAR only selects a node that delivers the packet quickly, hence, reducing delay and increasing the packet delivery ratio. Furthermore, we achieve almost the same packet delivery ratio from OSAR with varying numbers of channels. This is because OSAR selects a relay node from the set of nodes with an idle channel in common with the querying node. Once the querying node finds a relay node with minimum delay, it will deliver the packet to its next relay node. The relay selection continues in this pattern until the packet finally reaches the destination. It is the value of (9) that changes at every next selection of a relay node, making changes in the average delay. For that reason, the number of packets delivered to the destination for different numbers of channels in OSAR is almost the same; hence, the delivery ratio is almost the same. Fig. 4 also shows that the performance of Cog-DVRP is poorer than the other two schemes. This is because the selection of relay nodes in Cog-DVRP is restricted by the flooding zone, and therefore, its delivery ratio is lower than the other two schemes. Like Cog-DBR, Cog-DVRP also makes the next-hop decision based on the distance from the querying node. Hence, this cognitive routing scheme, finding a common idle channel within the flooding zone, reduces the chances of successful delivery of packets. Therefore, OSAR outperforms both cog-DBR and Cog-DVRP.

Fig. 5 shows the overhead ratio of OSAR, Cog-DBR, and Cog-DVRP as a function of the number of sensor nodes, with the number of channels as a parameter. Overhead ratio is defined as the ratio of the number of control packets to the total number of



a

b

c

Fig. 5 *Performance comparison between OSAR, Cog-DBR, and Cog-DVRP for the overhead ratio as a function of the number of sensor nodes with different numbers of channels, M*

(a) Overhead ratio when $M = 1$, ***(b)*** Overhead ratio when $M = 3$, ***(c)*** Overhead ratio when $M = 5$

packets in the network. The routing overhead for both the proposed and reference schemes increases with an increasing number of sensor nodes in the network. We observed a similarity in all the schemes in terms of an increase in the overhead ratio when the number of sensor nodes increases and the number of channels decreases. The more sensor nodes, the higher the message update rate. However, OSAR outperforms both reference schemes. The reason for the better performance is our selection criterion that reduces unnecessary control messages by picking the next-hop node based on transmission delay, and by not restricting the size of the neighbouring set. The overhead ratio for both Cog-DBR and Cog-DVRP is higher than OSAR. In both these schemes, the querying node may select a relay node that does not make a stable path due to greater delay; hence, resulting in link failure that incurs large overhead. Also, calculating the flooding zone further reduces the chances of successful delivery of packets. This is because sensor nodes may not find a common idle channel for communication, which therefore increases the overhead ratio. It can be seen in Fig. 5 that the maximum overhead ratio of our proposed scheme is almost 38%, whereas for the reference schemes, it is more than 45%. Fig. 5 also shows that for fewer channels, M, the subcarriers are mostly occupied by a PU. Increasing the number of channels increases the free subcarriers in the network, and thereby decreases overhead by providing a large number of unused subcarriers to the sensor nodes for stable communications. In this regard, it decreases the overhead of control messages used to find an idle channel. A complete analysis of our simulated results shows that for an underwater cognitive routing scheme, the selection of a relay node based on transmission delay makes the network more stable than distance-based schemes. Another observation from these results is that a restriction of the selection zone is not suitable for underwater cognitive routing schemes, as this result in poor network performance. This is because nodes must reach consensus about a common idle channel between the two communicating sensor nodes. Also, we determined that using an OFDM-based energy detection scheme in this band-limited cognitive underwater environment increases the chances of finding more idle subcarriers for sensor nodes. In so doing, it provides multiple sub-bands simultaneously to transmit the packets between two communicating sensor nodes.

5 Conclusion

We proposed a novel routing scheme for underwater cognitive sensor networks. The combination of both channel selection and relay selection in underwater communication systems makes this method unique. Both natural acoustic systems and artificial acoustic systems are considered PUs in this scheme. When a source node located somewhere in the deep ocean wants to send data packets to any surface buoy located at the sea level, it selects the best relay to make a stable path between itself and the destination. A set of neighbouring nodes having consensus about a common idle channel is formed after exchanging local sensing results. Then, a node that has the minimum transmission delay is selected as the next relay node. An OFDM-based energy detection scheme is used for spectrum sensing. Our results show better performance for average delay, packet delivery ratio, and overhead ratio. This work is valid only for underwater acoustic communications. In the future, we will extend this work to hybrid communications to reach a monitoring centre on land.

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