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Challenges and Opportunities of Underwater Cognitive Acoustic Networks

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ABSTRACT In oceans, both the natural acoustic systems (such as marine mammals) and artificial acoustic systems [like underwater acoustic networks (UANs) and sonar users] use acoustic signal for communication, echolocation, sensing, and detection. This makes the channel spectrum heavily shared by various underwater acoustic systems. Nevertheless, the precious spectrum resource is still underutilized temporally and spatially in underwater environments. To efficiently utilize the spectrum while avoiding harmful interference with other acoustic systems, a smart UAN should be aware of the surrounding environment and reconfigure their operation parameters. Unfortunately, existing UAN designs have mainly focused on the single network scenario, and very few studies have considered the presence of nearby acoustic activities. In this paper, we advocate cognitive acoustic as a promising technique to develop an environment-friendly UAN with high spectrum utilization. However, underwater cognitive acoustic networks (UCANs) also pose grand challenges due to the unique features of underwater channel and acoustic systems. In this paper, we comprehensively investigate these unique characteristics and their impact on the UCAN design. Finally, possible solutions to tackle such challenges are advocated.

INDEX TERMS Underwater acoustic networks, cognitive acoustic, environment-friendly communications, efficient spectrum utilization.

I. INTRODUCTION

During the past decade, underwater acoustic networks (UANs) have attracted significant interests from both academia and industry due to a wide range of applications including underwater environment monitoring, offshore structural health monitoring (SHM), target tracking and oceanography data collection [1]–[3]. Various applications coexisting in oceans leads to multiple underwater networks sharing channel resources with each other.

To date, most research efforts on UANs have been focused on the single network scenario where all users are in the same acoustic network, tackling challenges from high channel error rates, long propagation delay and mobility [4], [5]. However, the underwater acoustic environment is complex in oceans, where multiple acoustic systems might exist in the same area using sounds for communication, echolocation, sensing and detection. Examples include not only the ‘‘artificial acoustic systems’’, like UANs and sonar users, but also the ‘‘natural acoustic systems’’, such as marine mammals.

The spectrum is a scarce resource heavily shared by underwater acoustic systems. Due to the frequency-dependent attenuation, the available communication frequencies in water are severely limited, usually from tens of hertz to hundreds of kilohertz. The majority of ‘‘artificial acoustic systems’’ and ‘‘natural acoustic systems’’ utilize the frequency band from 1 kHz to 100 kHz, making the acoustic channel crowded. Nevertheless, this precious resource is still *underutilized*. For instance, the mobility and idle listening of acoustic systems may cause the spectrum to be underutilized temporally, and the directional transmission and reception of acoustic systems may potentially cause the spectrum to be underutilized spatially.

In order to use the underwater spectrum more efficiently where multiple acoustic systems coexist, a smart UAN should be aware of the surrounding environment and dynamically reconfigure their operation parameters (e.g. frequency band, modulation scheme, and transmission power). Unfortunately, few studies have considered the presence of nearby acoustic activities and the *coexisting problem* in the UAN design.

Here, we advocate *cognitive acoustic* (CA) as a promising technique to develop an environment-friendly UAN with high spectrum utilization. Through sensing the surrounding spectrum usage, CA users in underwater cognitive acoustic network (UCAN) are able to intelligently detect whether any portion of the spectrum is occupied, and change their frequency, power or even other operation parameters to temporarily use the idle frequencies without interfering with other networks. By exploiting the sensing ability and reconfigurability, the CA users can capture and follow the *real-time spectrum variation* in oceans. All these capabilities provide CA users with abilities to efficiently, comprehensively and friendly utilize the spectrum.

Although there exist some recently developed dynamic spectrum management protocols for underwater cognitive networks, the UCAN design is still an underexplored area. To make CA technique practical, it faces grand challenges posed by the unique features of underwater channel and acoustic modems. Some of these features, like the long propagation delay, have been extensively studied in the literature. Other characteristics that are still overlooked can be itemized as follows:

- *The narrowband response of acoustic transducer* results in limited frequency bandwidth for underwater communications. The transmission opportunities of CA users are therefore considerably constrained by this hardware limitation.
- *The long preamble* embedded by acoustic modems in each packet considerably increases the overhead of short packet transmissions for message exchanging in UCANs.
- *The severe busy terminal problem of acoustic modems* causes impulsive and unpredictable delays for packet transmissions, which would futile the scheduling of medium access protocols.
- *The highly dynamic underwater channel* challenges the parameter reconfiguration. In fast-varying underwater environments, the transmission power adaptation and dynamic channel allocation may not follow the environment variation causing unexpected interferences.

The major contribution of this paper involves three parts. Firstly, we investigate the spectrum usage of acoustic systems in oceans and reveal the opportunities of UCANs in developing environment-friendly and spectrum-efficient networks. Secondly, we discuss the unique features of underwater channel and acoustic systems. Finally, we analyze the grand challenges faced in the UCAN design and advocate some simple solutions. The ultimate objective of this work is to encourage research efforts to tackle practical issues in the UCAN study.

The remainder of this paper is organized as follows. In Section II, we investigate the acoustic spectrum usage in oceans, which helps CA users to be aware of the potential channel competitors. Then we introduce the motivation on developing cognitive acoustic in Section III. The framework of UCAN is discussed in Section IV. We present the unique features of the underwater channel and acoustic modems in Section V and their impacts on the UCAN design are analyzed in Section VI. The development of cognitive technique in the radio network and underwater acoustic network is briefly introduced in Section VII. Finally, Section VIII concludes this paper.

II. ACOUSTIC SPECTRUM USAGE IN OCEANS

In this section, we investigate the spectrum usage of various underwater acoustic systems in oceans. Then, by analyzing features of these systems, we unveil that the underwater spectrum resource is heavily shared, and meanwhile it remains underutilized.

A. UNDERWATER ACOUSTIC "SYSTEMS"

Imagine an underwater world with various acoustic "systems" including both "artificial acoustic systems" and "natural acoustic systems", as illustrated in Fig. 1. A sensor network equipped with acoustic modems is employed in the oil drilling installation system to acquire real-time deflection data. In the same area, a bottom mounted data collection system might be deployed to inspect the health of subsea oil pipelines, transmiting data to autonomous underwater vehicles (AUVs). An ad hoc underwater acoustic network works close to the sea surface, to monitor and detect oil spill events. At the same time, the ships traveling around use sonar for navigation. Besides these aforementioned artificial systems, marine mammals, e.g. dolphins and whales, are playing in the neighborhood and using sound signal to communicate with each other or search for food through echolocation.

Taking a closer look at the spectrum usages of these systems we can reveal the fact that the underwater spectrum recource is heavily shared. Marine mammals use sound for orientation, communication and foraging. To name a few, toothed whales communicate on frequencies around 10 kHz; the echolocation signal of killer whales has majority power on the 12-25 kHz frequency band; the whistle signal (for communication) and click signal (for echolocation) sent by bottlenose dolphin range from 200 Hz to 24 kHz and from 200 Hz to 150 kHz, respectively. The sea lions can hear the sound with frequency up to 70 kHz, and generally vocalize within a range of 100 Hz to 10 kHz [6].

In addition, a mass of marine organisms may also occupy frequencies by creating noise. Take the snapping shrimp as an example. These invertebrates usually gather in warm shallow water area. The snapping of their huge asymmetrical pincers creates torrents of cavitation bubbles, the implosion of which generates intense broadband noises with high amplitude up to 60-90 dB re μPa/$\sqrt{\text{Hz}}$ spectrum density on the frequency

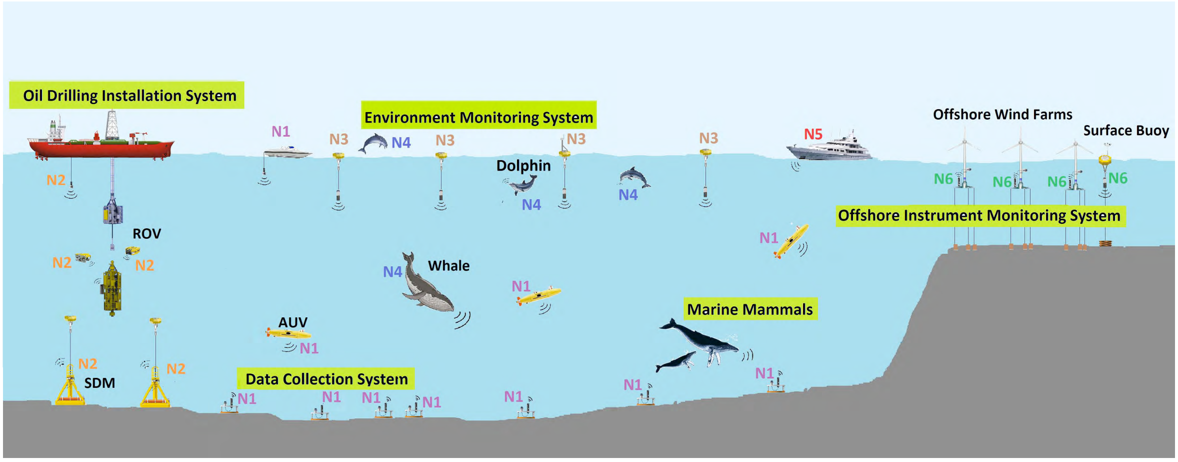

FIGURE 1. **An underwater world with various acoustic systems. *N1:* AUV based subsea data collection system; *N2:* Offshore oil drilling deflection monitoring system; *N3:* Acoustic ad hoc network for surface monitoring; *N4:* Marine mammal acoustic networks; *N5:* Ship navigation and science bathymetry sonar systems; *N6:* Offshore structural health monitoring system.**

band 1-10 kHz. The highest source level of the bubble noise can even reach 190 dB re 1 μPa [7].

The frequency usage of "artificial acoustic systems" is considerably overlapped with marine mammals as displayed in Fig. 2. Sonar systems are widely used on ships, remotely operated vehicles (ROV) and unmanned underwater vehicles (UUV) for applications like detection, navigation and bathymetry. The working frequency of sonar systems varies from hundreds of hertz to hundreds of kilohertz depending on the specific requirement in the application. For instance, the frequency band of continuous wave (CW) beacon is usually 8-16 kHz for navigation and ranges from 10 kHz to several hundreds of kHz for bathymetry (e.g. Simrad EM120 uses 12 kHz signal and EM300 operates arround 32 kHz). The fishery sonar, which is widely used to find and harvest fish, usually works on frequencies from 20 kHz to 200 kHz. These sonar systems have high source levels from 185 to 200 dB re 1 μPa. Hence, the aforementioned artificial signals can cause interference to other faraway acoustic systems.

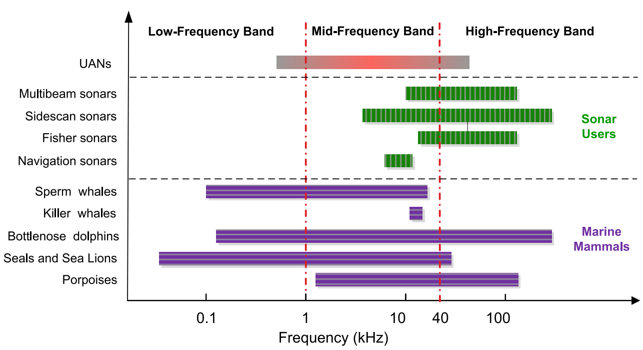

FIGURE 2. **The spectrum usages of underwater acoustic systems.**

Furthermore, underwater acoustic networks enable a widespread range of applications, including environment monitoring, target tracking and oceanography data collection. Due to the severely frequency-dependent attenuation of the acoustic signal on high frequencies [8], and the size constraint of acoustic transducer which prevents the system from using ultra low frequencies, UANs usually operate on *mid-frequencies* from 1 kHz to 40 kHz. The source level of these UANs varys around 185 dB re 1 μPa depending on the communication range.

The overlapped spectrum usage of representative underwater acoustic systems summarized in Fig. 2 indicates the fact that the underwater spectrum, especially on mid-frequencies, is heavily shared by various acoustic users. In the practical UAN design, the activities of other acoustic systems should be considered carefully to avoid interferences with each other.

B. UNDERUTILIZED ACOUSTIC SPECTRUM IN OCEANS

Although the underwater acoustic spectrum is heavily shared by various acoustic systems in oceans, it is actually underutilized from both temporal and spatial perspectives.

1) TEMPORAL SPECTRUM UNDERUTILIZATION

In an interested area of oceans, some frequency bands might be only temporally utilized but vacant most of the time. We call these frequencies as *temporally underutilized acoustic spectrum*. Temporal underutilization of acoustic spectrum might be caused by the mobility and low duty cycle of acoustic systems.

Mobility: When frequencies are occupied by marine mammals, sonars on ships or AUVs, the usage of these frequencies in a target region might be neither long nor continuous - they will be released with the movement of mobile systems. In other words, acoustic frequencies are used when mobile systems come, and become idle when they move away. In oceans, if we allocate any exclusive frequencies (frequencies that can be only used by specific users in a certain region) to mobile systems, the spectrum might be temporally underutilized.

Low duty cycle: Generally speaking, neither "natural" nor "artificial" acoustic systems would stay active all the time. The spectrum will be vacant when the users are idle causing temporal spectrum underutilization. The low duty cycle is the nature of both "natural" and "artificial" systems, since neither one can stay active all the time. In applications such as environment monitoring, offshore structure flaw detection and data collection, users only need to periodically wake up and suspend in the rest of time to save the energy. Meanwhile, the activity of artifical acoustic users are constrained by the limited power supply in oceans. Taking the UANs as an example, users in UANs are usually powered by batteries, for which replacement or recharging is difficult. Suppose underwater users are equipped with Teledyne Benthos ATM-885 modems [9] for communications. The battery pack capacity of ATM-885 is 300 Watt-hours. The power consumption of this modem in sleep mode (switched on but is inactive) and in full power transmission mode are 16.8 mW and 20 W, respectively. If a user sends one packet of 400 Bytes per hour and sleeps in rest of the time, then the energy consumption rate is as low as 0.72 Watt-hours/day. That is, the network can stay for 416 days in this low traffic mode. By contrast, the network can only work for 15 hours if users keep transmitting all the time. The duty cycle of acoustic systems varies depending on applications but is usually very low under fairly general conditions. The low duty cycle feature essentially leads to the temporally underutilized underwater spectrum.

2) SPATIAL UNDERUTILIZATION

In oceans, acoustic frequencies might be fully utilized in some crowded areas, but vacant in other regions. We call these frequencies as *spatially underutilized acoustic spectrum*. Both the nonlinear sound propagation and directional communication of acoustic systems lead to a spatially underutilized acoustic spectrum.

Nonlinear Sound Propagation: Unlike radio signals, which propagate straight in air, the actual propagation path of acoustic signals in water is modeled as a *curve*, especially in long range communication over 2 km. This nonlinear propagation feature originates from the fact that sound speed is not constant but varies with the water pressure, salinity and temperature. The acoustic signal always bends toward the medium with slower sound speed according to the law of Snell-Descartes. Fig. 3 demonstrates a schematic plot of

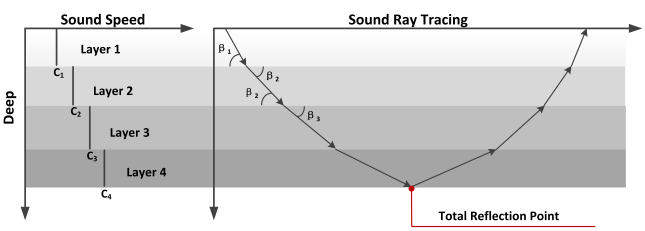

FIGURE 3. **Schematic plot of nonlinear sound propagation. Sound velocity profile (*left*) and the corresponding sound ray (*right*).**

nonlinear sound propagation, while Fig. 4 shows the sea test result of the sound profile and sound rays in the Arctic region [11].

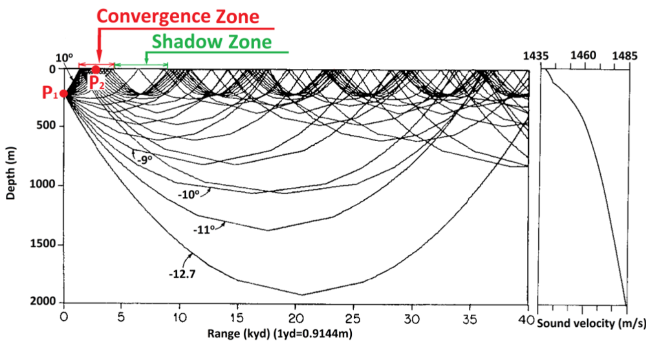

FIGURE 4. **Test result of nonlinear sound propagation in the Arctic region (Urick, 1979 [10]). Sound velocity profile (*right*) and corresponding sound rays (*left*).**

The curved propagation of acoustic rays in Fig. 4 leads to *shadow zones* and *convergence zones* in underwater communications. In shadow zones where few sound rays can reach, the signal strength is very weak. No users would be deployed in these regions for reliable communication. As depicted in Fig. 4, when deploying an UAN, the intended receiver (e.g. P2, Fig. 5) should be located in the convergence zones of the sender (e.g. P1, Fig. 5). Given a single UAN, the spectrum resource in shadow zones of this network is vacant, which we call spatially underutilized spectrum.

Directional Communication: In conventional underwater medium access control (MAC) protocol design, we usually assume omnidirectional transmissions and receptions [4]. With this assumption, the transmission range and interference area of these users can be modeled as circles. However, both the transmission and reception of acoustic systems, such as marine mammals and sonar, are highly directional in the real world. For instance, the 3 dB beamwidth of echolocation signals from bottlenose dolphins and beluga is only $10-11.7°$ and $6.5°$, respectively [6]; the 3 dB beamwidth of most sonar systems is about $10-30°$ when working on frequency band between 10 kHz and 30 kHz. In this situation, the acoustic spectrum might be spatially underutilized if we keep the omnidirectional transmission and reception assumption. Next we use an example to explain this problem in detail.

Denote two pairs of users, $\{P_1, P_2\}$ and $\{S_1, S_2\}$, from two different networks, where P_1 and S_1 are senders, and P_2 and S_2 are the corresponding receivers. The transmission ranges of P_1 and S_1 are R_p and R_s, respectively. Suppose the sensing and receiving of $\{S_1$ and $S_2\}$ are omnidirectional, but the 3 dB beamwidths of P_1 and P_2 for transmission and reception are ϕ_1 and ϕ_2, respectively. As depicted in Fig. 5(a), the two pairs of users will not interfere with each other because of the directional transmission and reception. However, if we take the transmission of P_1 as omnidirectional by mistake as shown in Fig. 5(b), S_2 has to stop working when P_1 is transmitting to avoid interference from P_1,

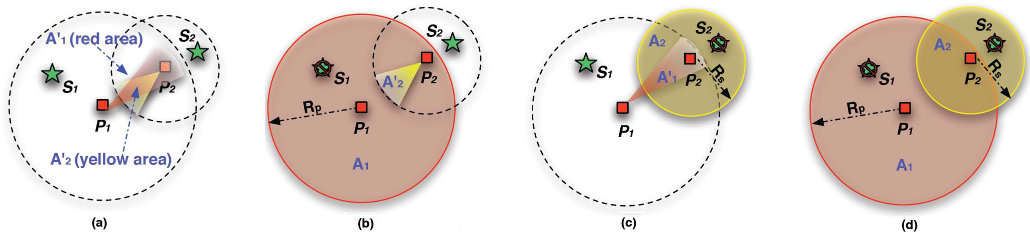

FIGURE 5. Interference area of primary users in different situations. (a). $\phi_1, \phi_2 \neq 360°$ (directional transmission and reception); (b). $\phi_2 \neq 360°$ (directional reception at P_2); (c). $\phi_1 \neq 360°$ (directional transmission at P_1); (d). $\phi_1 = \phi_2 = 360°$ (omnidirectional transmission and reception).

which resulted in spectrum underutilization. Similarly, when we consider the reception of S_2 as omnidirectional in Fig. 5(c), spectrum underutilization also occurs on S_1 when trying to abstain interference to P_2.

III. WHY COGNITIVE ACOUSTIC

In the previous section, we studied the spectrum usage in oceans. Although the spectrum resource is heavily shared by various acoustic systems, it is still underutilized temporally and spatially. To promote the environment-friendly communications and efficient spectrum utilization, we advocate the *cognitive acoustic* (CA) as a promising solution. CA is an intelligent acoustic communication system, which senses the surrounding spectrum environment and adapts its operation parameters to the incoming acoustic stimulation in real-time. With this capability, CA users are able to detect idle frequency bands and utilize them for communications without interfering with other systems.

A. MAKING COMMUNICATIONS ENVIRONMENT-FRIENDLY

Marine mammals use sound for communications and orientations, and are therefore susceptible to the interference of man-made signals generated by UANs, sonar users, ship transportation and oil drilling systems. In recent years, the increased concern on the effect of anthropogenic signals on marine mammals has manifested itself [6], [12].

Operation frequencies of UANs are heavily overlapped with plural marine animals, as depicted in Fig. 2. The transmission of users in UANs thus may considerably affect the activity of these ocean creatures. Nevertheless, the negative effects of UANs on ''natural systems'' has not been adequately addressed yet. Users in conventional UANs work with predetermined operation parameters (e.g. frequency band and modulation schemes) without any adaptation. The surrounding ''natural systems'' would be severely interfered and harmed if they use the same frequencies for communications or orientations. From the aspect of marine mammals, this kind of UAN is ''selfish'' and ''aggressive''.

The CA technique can help UANs to fulfil environment-friendly communications by actively avoiding interference with marine mammals. For instance, before sending and receiving, each user in an UAN first sense the surrounding spectrum. The sending and receiving are performed by CA users only when the sensing frequencies are idle. In this way, CA users can stop using frequencies which are occupied by marine mammals and search for new idle frequencies for communications. When marine organisms release the spectrum with their movement, a smart sensing strategy allow CA users to reuse these idle frequencies again.

B. ACHIEVING HIGH SPECTRUM UTILIZATION

In oceans, the precious spectrum resource is temporally and spatially underutilized. How to efficiently utilize vacant frequencies for high speed communications becomes a key problem in the UAN design.

In conventional UANs, techniques such as cooperative communication [13] and multiple-input and multiple-output (MIMO) [14], [15], are advocated to increase the spectrum utilization of the communication system in terms of spectrum efficiency, which is expressed in bits/sec/Hz. The total frequency bands utilized for communications, however, is fixed with these techniques, even if more idle frequencies exist.

Moreover, when signals are polluted by other acoustic sources on certain frequencies, conventional UANs resort to advanced signal processing algorithms [16] to address this interference. Though signal processing method offers a viable solution to mitigate the interference on UAN communications, it might not always be the best choice. For instance, when some frequencies of an UAN are jammed by surrounding acoustic systems, other frequencies may still be available for interference-free communications. In this scenario, spectrum efficient communications would be achieved if the UAN is able to jump to idle frequencies smartly.

The CA technique has come to prominence as a strategy for fully utilizing the spectrum resource. By intelligently sensing surrounding environments, CA users can efficiently ''monitor'' the spectrum usage in real-time. Based on this real-time information, CA users are able to detect and utilize consecutive or even discrete idle frequencies from the whole spectrum to increase the communication bandwidth. In this way, the UCAN can adapt to the underwater environment quickly for environment-frendly, spectrum efficient, and high speed reliable communications.

IV. COGNITIVE ACOUSTIC NETWORK FRAMEWORK

The framework of UCANs involves three main components, namely, the spectrum sensing, the dynamic power control and the spectrum management, as shown in Fig. 6. Cognitive acoustic starts from the spectrum sensing procedure. A sensing strategy schedules when and which frequency bands to sense. After the sensing process, CA users are aware of the spectrum usage of surrounding environments. Based on the sensing results, CA users identify whether the target frequency band is busy or not and distinguish primary users (PUs) from secondary users (SUs) in the spectrum decision algorithm. After getting the information about real-time spectrum usage, a spectrum sharing approach collaborated with a power control mechanism customize the transmission of UCAN nodes to efficiently share the idle spectrum while avoiding harmful interference to PUs.

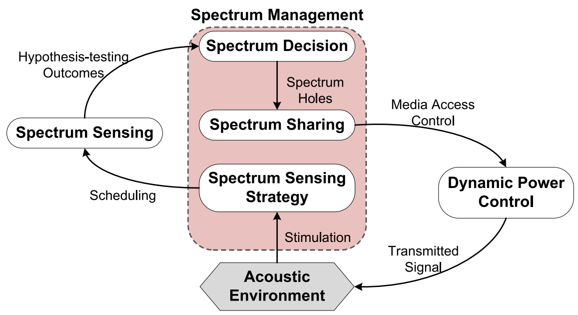

FIGURE 6. **Cognitive acoustic cycle.**

A. SPECTRUM SENSING

Spectrum sensing plays a crucial role in detecting the presence of PUs and identifying the idle frequency bands for CA users. It can be performed in frequency, time, space or code domains [17]. Typical sensing methods mainly fall into the following four categories.

Energy detection based sensing approaches calculate the cumulative receiving power within a fixed time period on the target spectrum [18]. *Power spectrum estimation based sensing approaches* estimate the power spectrum density (PSD) with various algorithms (e.g. periodogram, windowing and multitaper) in time-frequency domain. *Waveform-based sensing approaches* detect the presence of PUs by matching the received signal with a preknown signal pattern (e.g. preamble, pilot signal) [19]. *Cyclostationarity-based sensing approaches* detect the presence of PUs by calculating the spectral correlation function (SCF) of the received signal [20], [21].

B. DYNAMIC POWER CONTROL

In *overlay* based networks, where CA users can only utilize frequencies that are not occupied by PUs, dynamic power control is a critical part to improve the channel capacity and energy efficiency by assigning appropriate power on different frequencies. Dynamic power control is also crucial for *underlay* based networks [22], where CA users are allowed to utilize the frequencies that PUs are already using. In this situation, CA users need to control their transmission power carefully to insure that the total interference to primary receivers is lower than the interference temperature constraint[1] [24].

C. SPECTRUM MANAGEMENT

Spectrum management is a MAC layer scheduling algorithm including three parts, the spectrum sensing strategy, spectrum decision and spectrum sharing [25]. Spectrum sensing strategy is to schedule when and which frequency band to sense by CA users. Based on the spectrum sensing strategy, CA users are arranged to sense different frequencies to increase the spectrum access opportunity or to improve sensing accuracy. Spectrum decision is to identify whether the sensed spectrum is idle or not. The decision is made based on the sensing outcome of single user (local sensing) or by a combination of sensing results on multiple users (collaborative sensing). A channel allocation program may be performed in this stage to allocate vacant frequencies to different CA users for channel capacity maximization. Spectrum sharing is a design to help CA users to share idle frequencies. The collision probability, end-to-end delay and throughput of UCANs are considered in the spectrum sharing design.

V. UNIQUE FEATURES OF UNDERWATER ACOUSTIC SYSTEMS

To make cognitive techniques into reality in underwater environments, the spectrum management faces grand challenges posed by unique features of underwater channel and acoustic modems. Some of these features, like frequency-dependent attenuation and long propagation delays, have been extensively studied in conventional UAN design [26], [27]. Other characteristics, such as the narrow-band response of acoustic transducers, the long preamble of acoustic modems, the busy terminal problem and the fast varying acoustic channnel are still overlooked [28]. In this section, we provide some insight analysis on these unique features in the real system.

A. NARROW-BAND RESPONSE OF ACOUSTIC TRANSDUCERS

Narrow-band response of acoustic transducers is one of the most important reasons accounted for the limited bandwidth of existing acoustic modems. Acoustic transducers are usually designed to operate around their resonant frequency to achieve the best output performance in terms of piezoelectric transfer efficiency. The frequency response of the transducer drops quickly when working far beyond the resonant frequency.

People use the *quality factor* - Q, to present the relative bandwidth of transducers. The Q factor is defined as the ratio of the resonant frequency to the 3 dB bandwidth of the transducer. A typical value of Q ranges from 2 to 10 for general underwater transducers [29]. That is the 3 dB

[1] Interference-temperature is a metric recommended in [23] to quantify and manage the sources of interference in radio environments. The interference-temperature constraint is the maximum acceptable interference-temperature at the receiver on a specific frequency band.

TABLE 1. Preamble length and packet (400 bytes) duration time in different acoustic modems.

Modem	Data Rate	Preamble Length	Packet Duration Time
Benthos ATM-88X Modem	140 - 2400 bps (MFSK)	1.2 s	2.5 - 24.1 s
	2.56 - 15.4 kbps (PSK)		1.4 - 2.5 s
AquaSent OFDM Modem	3 kbps (1/2 coding rate, 4QAM)	0.5 s	1.57 s
	9 kbps (3/4 coding rate, 16QAM)		0.86 s
WHOI Micro Modem	80 bps (Standard)	0.87 s	40.87 s
	300 - 5000 bps (High PSK mode)		1.51 - 11.5 s

bandwidth of acoustic transducers is only $1/10$ to $1/2$ of the resonant frequency.

In underwater acoustic communications, the resonant frequency of transducers usually lies in the middle frequency range from 1 kHz to 40 kHz to mitigate the severe attenuation on high frequency bands. The low resonant frequency leads to a narrow-band response of acoustic transducers. Given a transducer with 20 kHz resonant frequency, its 3 dB bandwidth is only 2 kHz for Q=10 and 10 kHz for Q=2. For this reason, most existing acoustic modems, like Teledyne Benthos, operate with 4-5 kHz bandwidth. The three viable frequency bands of different series of Teledyne Benthos modems [30] are 9-14 kHz, 16-21 kHz and 22-27 kHz. EvoLogics [31] has developed a new technology called the Sweep Spread Carrier (S2C) to mimic dolphin chirping sound pattern. With a continuous change of frequencies, the EvoLogics modems spread the signal energy over a broad frequency bandwidth. The frequency band options are 7-17 kHz, 13-24 kHz, 18-34 kHz, 38-64 kHz and 48-78 kHz. Even with the advanced S2C technology, the frequency band of EvoLogics modems is still quite limited for UCANs.

B. LONG PREAMBLE OF ACOUSTIC MODEMS

In acoustic modems, a preamble is designed as a prefixing of each packet for the purpose of automatic gain control (AGC), burst data sequence detection, synchronization and channel response estimation.

In radio communications, the duration of a preamble signal is very short, normally within several hundreds of microseconds. For instance, the preamble in IEEE 802.20 mobile broadband wireless access (MBWA) standard is constituted of 8 symbols with 104 μs for each symbol, i.e. total 832 μs [32]. In IEEE 802.22 cognitive wireless regional area networks (WRANs) standard, the overall length of preamble segments, namely, superfame preamble, frame preamble and coexistence beacon protocol preamble, is less than 1 ms [33]. On the contrary, the preamble used in underwater acoustic modems is up to one second, three orders of magnitude longer than that of in radio communications, as listed in Table 1.

The long preamble of acoustic modems is essentially resulted from two folds, the low data rate of acoustic modem and the long multipath feature of underwater channel.

- **The low data rate of the acoustic modem** is the primary reason for the long preamble problem of acoustic modems. The synchronization sequence is one major part of preamble for packet reception. To achieve a good synchronization performance, a sequence of hundreds of known bits, such as pseudo-random noise (PN) sequence, is usually applied in communication systems. In radio networks, the high data rate insures a short transmission time of the PN sequence. However, the low data rate of acoustic modems (Table 1) greatly increases the transmission time of the same sequence. Taking 512-bit PN signal as an example, it only takes 22.6 μs in IEEE 802.22 standard with 22.69 Mbps bit rate, but extends to 0.64 s in acoustic modems with 800 bps data rate.
- **The long multipath of the underwater channel** is another fact that contributes to the long preamble in acoustic modems. The preamble is usually constituted of several blocks, with each block serving for different functionalities. To overcome the inter-block interference in severe multipath environments, a guard time for PSK and FSK based modems, or a CP signal for OFDM based modems is inserted between blocks. The length of guard time or CP sequence depends on the multipath effects. The radio channel has very short multipath owning to the high propagation speed of electromagnetic signal in air. The guard time or the CP thus is as short as tens of microseconds (e.g. 4.7/16.7/53.3 μs in 3GPP LTE standard on different channel conditions). On the contrary, the multipath is tens of millisecond or even longer in underwater communications, depending on the network deployment and channel condition. The length of the required guard time or CP signal in such long multipath environment is therefore considerably increased by almost 1000 times than that of in radio networks.

The long preamble of acoustic modems will bring on substantial overhead for message exchanging in collaborative spectrum sensing and spectrum management of UCANs.

C. BUSY TERMINAL PROBLEM OF ACOUSTIC MODEMS

Existing acoustic modems, such as Teledyne Benthos modem [30], WHOI Micro-Modem [34] and LinkQuest modem [35], have good support on point-to-point communications on the physical layer, but are less concerned with the demand of upper layers protocols. In current modem design, the packet reception cannot be interrupted once getting started, even if this packet is not addressed to it. If the modem is busy at the packet scheduled transmission time, the outgoing packet will be delayed until the false overhearing finishes. We call this phenomenon as *busy terminal problem* [28], [36]. The busy terminal problem become a grand challenge to UANs especially in high traffic load situation when the overhearing is significant. There are two factors together accounted for the busy terminal problem.

(a) **Half-duplex mode of acoustic modem.** Most of existing acoustic modems can only work in the half-duplex mode. That is the transmission and reception cannot be done simultaneous on a single modem. In the half-duplex mode, the busy terminal problem can be avoided only if the receiving action of the modem can be freely interrupted at any required time. However, due to the hardware pipelining typical to receivers [37], modems cannot stop while they are still working on the spuriously packet reception which has not been rejected.

(b) **Non-independent coding for MAC header.** The source and destination addresses are often carried on MAC headers. In existing modems, the MAC header and the data frame are coded together as a whole for uniform error-correction coding and modulation. The busy terminal problem can be mitigated by exploit independent coding on headers. However, challenges still occurs in the following two cases.

- In modulation schemes like OFDM, the information is carried on frequency. The receiver has to receive a full block before demodulation, unlike the bit-by-bit demodulation in FSK and PSK based modulation schemes. In this case, a user can not decode the MAC header immediately to decide either receiving the whole packet or ignoring the remaining segments until the whole block is received.
- When packet chain or superframe structure (e.g. frame structure in IEEE 802.22 [33]) is used for data transmission, different packets (frames) in the packet chain (superframe) might be addressed to different users. Receivers in this case had to keep receiving and decoding the MAC headers of every packet (frame) to make sure they will not miss any packet.

The busy terminal problem of acoustic modems has been identified sea experiments [38]. Fig. 7 shows the time difference between the actual transmission time on acoustic modems and the scheduled sending time by the MAC protocol. When the modem was busy with overhearing at the packet scheduled transmission time, the sending was postponed considerably. Up to 1.8 seconds delays were observed with Benthos modems. These delays are impulsive and unpredictable, which makes the medium access management futile.

D. FAST-VARYING CHANNEL

The high dynamic of underwater channel has been observed in sea experiments [39]. For communication systems, the dynamic underwater channel affects acoustic communications through rapidly time-varying multipath.

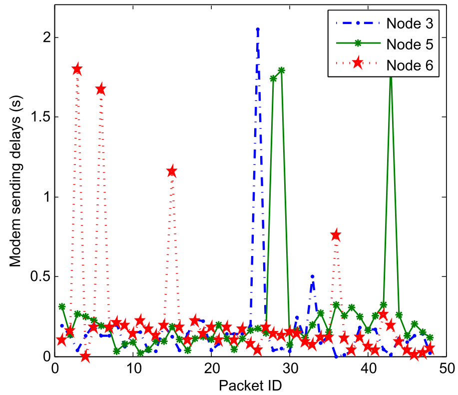

FIGURE 7. The random delay before data transmission caused by busy terminal problem.

The multipath response in deep sound channel (DSC) is mainly caused by the nonlinear sound propagation [10], [29]. Variations of temperature, water pressure and salinity with depth lead to a dynamic multipath response in DSC by affecting the propagation velocity of acoustic signals. In shallow water, the multipath is governed by the sound reflection from the surface and bottom. Due to the random fluctuation of surface waves, the underwater multipath response presents rapid time-variations. In Fig. 8, we show the strength of the multipath response in an Atlantic sea experiment at different time. We can observe apparent changes of the multipath response within a very short period. Fig. 9 illustrates the SNR variation among continuous data blocks in the same sea test. From these two figures we can see, both the multipath and the received SNR are highly dynamic. Especially the received SNR fluctuates 5 dB or even more between two neighboring blocks (270 ms) in the experiment.

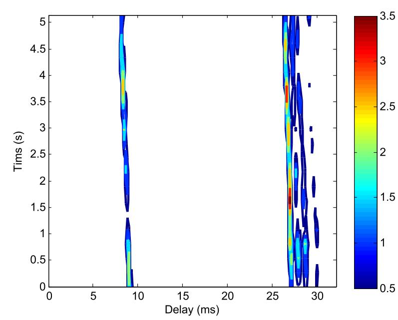

FIGURE 8. The fast multipath variation (Color represents the strength of the multipath signal.)

Moreover, the data transmission rate of acoustic modems and the sound propagation speed in water are very slow, usually three and five orders of magnitude lower than radios in air. These two factors lead to a long packet transmission and a large propagation delay. In this situation, the channel response would change considerably between two continues

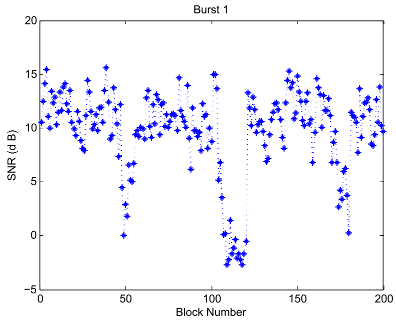

FIGURE 9. The SNR variation among continuous data blocks (270 ms interval between neighboring blocks).

packet transmissions, which challenges the dynamic power control in UCANs.

E. LONG PROPAGATION DELAY

Due to the heavy attenuation of radio signal in water, it cannot propagate far to support long distance communications in UANs. Optical waves are only suitable for very short distance communications because of the significant scattering. Alternatively, acoustic signals becomes a viable solution for underwater wireless communications. However, acoustic signals propagate at a speed about 1.5×10^3 m/s in water, five orders of magnitude lower than the light speed in terrestrial radio networks. Meanwhile, the distance between neighboring users could be up to several kilo meters in sparse UANs. The low sound speed and long communication distance lead to the long propagation delay. This problem has been extensively studied in conventional UAN designs, and therefore we will not discuss it here in detail.

VI. CHALLENGES ON UCAN DESIGN

In the previous section, we have investigated the unique characteristics of underwater channel and acoustic modems. In this section, we discuss how each feature challenges the UCAN design.

A. CHALLENGES ON SPECTRUM SENSING

In UCANs, the spectrum sensing design faces difficulties on detecting the presence of primary receivers, especially when they are in the receiving mode.

To detect the presence of primary receivers in CR networks, authors in [40] proposed to utilize the local oscillator leakage power that all RF receivers emit. However, this approach can not be applied to UCANs mainly because of two reasons.

(a) The proposed method requires primary receivers to use the superheterodyne architecture, which might has not been used in most of underwater communication systems. Since acoustic systems usually operate in low frequencies (1 kHz - 40 kHz) when compared with hundreds of MHz or GHz in radios, the bandwidth of baseband signal in underwater communications is comparable to its central frequency. In this situation, acoustic modems usually send the baseband signal directly, like OFDM signals, without high-frequency carriers. The mixer and local oscillator thus are not used in such systems. Moreover, some primary receivers, like marine mammals, are quiet when they are listening. Apparently, there is no way to detect their presence with leakage power detection.

(b) Even if signal leakage exists in some underwater acoustic receivers, the severe attenuation on acoustic channel imposes great threats to the long-range detection. To solve this problem, special sensors are suggested to be densely deployed to locate the primary receivers [40]. However, the extra cost on these sensors challenge the application of local leakage power approach in UCANs.

Another approach proposed in [41] transforms the primary receiver detection to detecting the primary transmitters' activity. The channel is identified to be available, if no PUs' transmission activity is detected within a distance of $R_p + R_s$, where, R_p and R_s is the transmission range of PUs and CA users, respectively. This approach, however, false alarms CA users when the primary receivers are out of the interference range.

To summarize, how to accurately sense the presence of primary receivers is still an open issue in the spectrum sensing design for UCANs due to the unique features of the underwater system and acoustic channel.

B. CHALLENGES ON DYNAMIC POWER CONTROL

The rapid variations of underwater channel and long packet duration time pose grand difficulties to dynamic power control in UCANs.

Dynamic power control approaches proposed for CR networks are usually based on the instantaneous channel state information (CSI) [24], in which channel is assumed to be stable within several continuous packet transmissions. In CRs, the assumption is reasonable, since the variation of the channel response in radio communications is relatively slow when compared with the short packet duration time. However, this assumption fails in UCANs. As shown in Fig. 9, the received signal strength fluctuated rapidly in oceans. Moreover, the limited data transmission rate in underwater communications results in the long packet duration time, as listed in Table 1. The channel state between two consecutive packet transmission time may change significantly, when taking into account the rapid variations of underwater channels. Instantaneous CSI based power control approaches in UCANs will need frequent channel measurement and lead to substantial overhead.

Although the instantaneous CSI in underwater channel is highly dynamic, its *statistical characteristics* (e.g. mean, variation and probability distribution[2]) are stable or change

[2]Rayleigh distribution [42], K-distribution [43] and Rice distribution [44], have been suggested to model the probability distribution function (PDF) of the underwater channel response.

slowly [45]. In UCANs, we can utilize these slow-varying features to design the dynamic power control scheme, but their performance in terms of channel capacity will be slightly degraded than instantaneous CSI based approaches. How to design an efficient dynamic power control method in the fast-varying underwater environment is a great challenge in UCANs.

C. CHALLENGES ON SPECTRUM SENSING STRATEGY

Spectrum sensing strategy in UCANs faces the high overhead issue, which is caused by the long propagation delay and the long preamble in acoustic modems.

In order to sense the presence of primary users reliably against severe shadowing and fading effects, it is suggested to share local sensing results among multiple secondary users for collaborative sensing. For instance, in parallel fusion based collaborative sensing, the local sensing outcomes from multiple users are transmitted to a fusion center (FC) for cooperative detection [46]. In game theory based collaborative sensing schemes, users need to interact with each other through control packets to decide their sensing behaviors [47]. In the aforementioned collaborative sensing approaches, additional traffic are generated for message exchanging in collaboration introducing heavy overhead to UCANs.

Most of existing collaborative sensing strategies focus on improving the detection probability in terms of collaborative gain [46]–[48]. However, the time and energy consumption on the control packet transmission is still overlooked. The long preamble induced by acoustic modems is in the order of second, which largely increases the transmission time and collision probability of control packets. Furthermore, the propagation delay, which can be ignored in CR networks, also leads to high latency for the collaborative sensing in UCANs. The sensing schemes requiring multiple iterative negotiation among users [47], can not to be applied to UCANs directly.

When evaluating a spectrum sensing strategy in UCANs, we have to assess its performance from practical perspective. Not only the collaborative gain but also the energy efficiency and spectrum utilization of the whole network need to be considered. We advocate the receiver initiated handshaking approach [49] to reduce the overhead on message exchanging. However, the dynamic data polling problem in the receiver initiated protocols is still an open issue.

D. CHALLENGES ON SPECTRUM DECISION

1) The long propagation delay is one of the most critical challenges to the spectrum decision in UCANs. In CR networks, the false alarm and miss detection of PUs is mainly caused by the *imperfect spectrum sensing* on CR users. In UCANs, however, besides the imperfect spectrum sensing, the long propagation delay may also lead to false alarm or miss detection of PUs. Due to the low propagation speed of sound in water, signals from PUs travel long time before being sensed by CA users. Therefore, the spectrum sensing results of CA users are always *out-of-date*. This delayed spectrum usage information might mislead the spectrum decision on CA users. Next, we use a simple example to illustrate the false alarm and miss detection events in UCANs.

Let $\{P_a, P_b\}$ and $\{S_a, S_b\}$ denote a pair of PUs and CA users, respectively. Suppose all four nodes can hear each other. The packet sent from P_a to P_b on frequency B_0 is denoted as D_1. Then we have:

- After a long propagation delay, if D_1 is detected by S_a during its sensing periods, S_a marks frequency B_0 as busy, and will not use it for data transmission. The false alarm occurs as B_0 is released after D_1's reception. This false alarm results in S_a wasting the idle frequency B_0 if it has data to send in the current time period, as shown in Fig. 10(a).
- During one sensing period on S_a, if the packet D_1 is still on the way because of the long propagation delay, S_a considers B_0 as idle falsely. In this case S_a misses detecting the transmission of P_1 on frequency B_0. If S_a takes B_0 for D_2's transmission, a conflict is caused to the primary user P_b, as shown in Fig. 10(b).

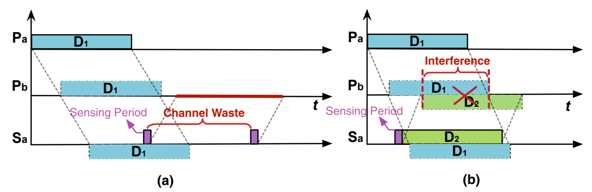

FIGURE 10. False alarms and miss detection events caused by the long propagation delay in UCANs: (a) false alarm; (b) miss detection.

Mitigating the long propagation delay effect to correctly identify the current spectrum usage of PUs based on the delayed sensing results in UCANs is still an open issue.

2) Natural signal identification is another challenges faced in the spectrum decision in UCANs. In the underwater world, the acoustic users not only include ''artificial systems'' but also involve ''natural acoustic systems''. How to identify signals from marine animals to achieve environment-friendly communications challenges the spectrum decision in UCANs.

Different man-made communication signals usually exhibit cyclostationary at different cyclic frequencies, depending on the symbol rate, coding scheme and guard periods of the signal [20]. From Fig. 11 we observe that both 4FSK and 4PSK signals from artificial communication systems exhibit strong cyclostationary property. By recognizing the cyclostationary pattern during spectrum sensing, the received signal can be classified accordingly.

However, besides the man-made signal identification, one primary objective of UCANs is to communicate in a environment-friendly way to avoid interference to marine organism. We would like to ask whether signals from ''natural acoustic system'' could be classified with cyclostationary. Unlike artificial signals which have strict format in transmission rates, modulation schemes and guard periods, signals

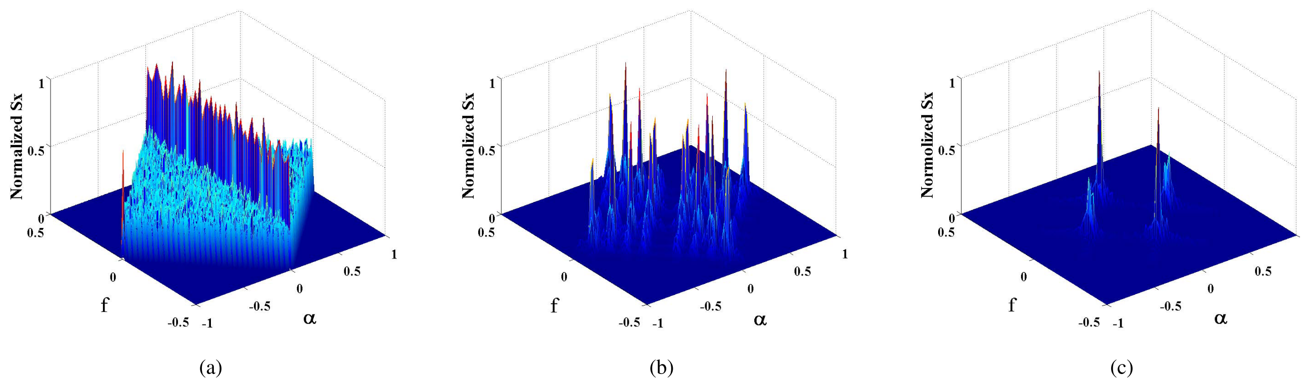

FIGURE 11. Cyclic cross periodograms of different acoustic signals in oceans. Ambient noise does not exhibit cyclostationary, as it has no peaks when $\alpha \neq 0$. 4FSK and 4PSK signals show distinguish peak patterns at different α. (a) Ambient noise. (b) 4FSK. (c) 4PSK.

of marine organism appear more diverse. Distinguishing the ''natural'' signal from ''artificial'' signal is still an unexplored research area in the UCAN design.

E. CHALLENGES ON SPECTRUM SHARING

1) BUSY TERMINAL PROBLEM

The busy terminal problem of acoustic modems makes the prearranged transmission pattern futile in spectrum sharing scheme by randomly delaying pre-scheduled data transmissions as shown in Fig. 7.

In CR networks, the busy terminal phenomenon is negligible owning to the short packet duration time. The time that users spent on overhearing a packet not addressed to them is within milliseconds. In UCANs, however, the busy terminal problem is significantly aggravated by the long preamble and the low data transmission rate. CA users may waste up to several seconds for one false overhearing. The prescheduled transmission might be considerably delayed due to the false overhearing, which potentially fails the collision avoidance mechanism in spectrum sharing.

In order to mitigate the busy terminal problem, one straightforward approach is to use full-duplex modems [31]. When the outgoing packet can be sent out freely even if another receiving action is performed at the same time, the busy terminal phenomenon will not happen. Another simple solution to mitigate the impact of busy terminal problem on UCAN is to use independent coding of MAC header which contains the destination address. In this way, the CA user can stop the packet overhearing timely as soon as the MAC header is decoded, rather than listening to the whole packet. With this approach, the users' reception might still be false triggered by the signal from unintended transmitter, but the duration of overhearing can be significantly reduced especially for long data packets.

2) LIMITED AVAILABLE BANDWIDTH

The bandwidth limitation caused by the severe frequency-dependent attenuation of acoustic signals has drawn significant attention from underwater research community. Fig. 12 presents the 3 dB bandwidth of acoustic communications on various distance considering the ambient noise and frequency-dependent attenuation in water. However, the constraint of narrow-band response of acoustic transducer is still overlooked.

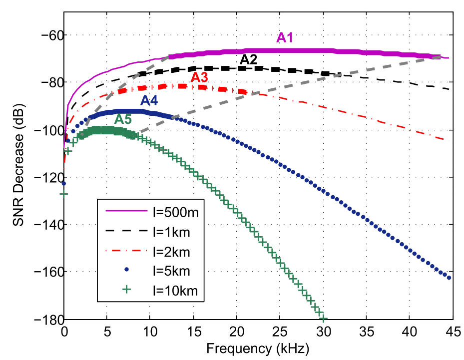

FIGURE 12. SNR degradation in acoustic communications with respect to frequency and distance. The 3 dB frequency bands are highlighted in bold.

As we discussed in Section V-A, the response bandwidth of acoustic transducers is narrow, ranging from several kilohertz to tens of kilohertz. It is interesting to ask whether the operation frequency of single transducer could cover the mid-frequency band from 1 kHz to 40 kHz, and how many transducers are required if not. The following simple calculation may answer this questions.

Denote f_H^i, f_L^i, f_C^i and B_i as the lower 3 dB cutoff frequency, upper 3 dB cutoff frequency, central frequency and the bandwidth of transducer i respectively, where

$$B_i = \frac{f_C^i}{Q}, \quad Q \in [2, 10]. \tag{1}$$

Substitute $f_C^i = \frac{1}{2}(f_H^i + f_L^i)$ and $B_i = f_H^i - f_L^i$ into (1), then we have

$$f_H^i = \frac{2Q+1}{2Q-1} f_L^i. \tag{2}$$

When $Q = 2$, transducers have the largest bandwidth. Making $f_L^1 = 1$ kHz and $f_H^i = f_L^{i+1}$ to have the minimum overlap between the operation frequencies of transducers, we have $f_H^i = (\frac{5}{3})^i$. $i = \log_{\frac{5}{3}} 40 \approx 7.22$ when $f_H^i = 40$ kHz. Accordingly, at least 8 transducers are required to cover the whole mid-frequency band from 1 kHz to 40 kHz, as shown in Fig. 13.

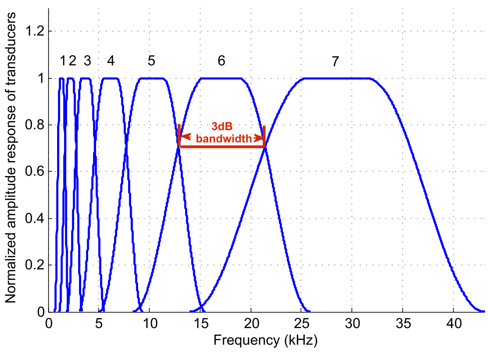

FIGURE 13. The group of transducers needed to cover the mid-frequency band.

Unlike CR users, which can operate on a wide frequency band [50], the usable frequency band for CA users with single transducer is very narrow. The narrow-band response of acoustic transducers can be solved by using plural transducers on each acoustic modem to expand the operation frequency for CA users. However, both the cost and the size of acoustic modems will be considerably increased. Another viable strategy is to carefully allocate frequency bands to different UANs to reduce unnecessary spectrum waste in the spectrum sharing among networks. This spectrum arrangement depends on the specific application, power constraint, channel quality and transducer response limitation. Designing a spectrum sharing scheme with efficient spectrum utilization under the aforementioned constraints has not been addressed yet in UCANs.

To summarize, besides the great opportunities of cognitive techniques in underwater networks, the UCAN design faces grand challenges due to the unique features of underwater channel, acoustic modems and unexplored ocean environments.

VII. RELATED WORK

The term of cognitive radio was first proposed by Joseph Mitola in 1999 [51], which was built on the software-defined radio, for a better utilization of the crowded wireless spectrum. With intelligent learning abilities, CR communication systems are capable of automatically reconfiguring parameters (e.g. transmit power, modulation schemes and frequency) adapting to the communication environment.

There have been substantial achievements in CRs [52]–[55], including the spectrum sensing, dynamic power control, spectrum decision and spectrum sharing issues. To date, several important progresses have been achieved to facilitate the applications of cognitive technique in real systems. IEEE 802.22 standard for cognitive wireless regional area networks (WRANs) helps the CR (or unlicensed) users to share the frequency band with the licensed users, namely, Television users in UHF/VHF TV bands between 54 and 862 MHz [56]. The research community advocates to reuse the frequency band 2.36-2.4 GHz in the U.S. for medical body area networks (MBANs) with the principal incumbent - aeronautical mobile telemetry (AMT) [57].

Based on the pioneering works in CRs, some research efforts have been presented in the literature to introduce the cognitive technique into UANs [58]–[65]. The underwater channel features, such as the limited available bandwidth of acoustic channel and the long propagation delay, have been discussed in these research.

However, the development of CA is still in its infancy. Only preliminary achievements are available for the UCAN design. In [60] and [61], a software-defined underwater acoustic modem design is discussed. By employing the field-programmable gate array (FPGA), the acoustic modems are able to reconfigure their operating frequency band and transmission power, which provides a possibility of applying cognitive technique to UANs. The underwater spectrum management is explored in [62]. The authors illustrated how various dynamic spectrum access models can be applied to different spectrum sharing scenarios. In [63], the authors proposed the spectrum signaling protocol to inform neighboring nodes of the channel allocation. A spectrum allocation approach is proposed in [64] to improve the channel capacity among users. The authors in [65] analyzed the channel capacity gain via spectrum sparing in UCANs, in which the depth of network deployment, the communication distance and the ambient noise from shipping and waves are taken into account.

Despite of the aforementioned innovative accomplishments, the CA technique is still in its early stage. As we have discussed in this work, the practical issues, like narrow-band response of acoustic transducers, the long preamble of acoustic modems and the fast varying underwater channel, are still challenging the UCAN design.

VIII. CONCLUSION

Cognitive acoustic (CA) is a promising technique to develop environment-friendly and spectrum efficient underwater acoustic networks. In this paper, we first dissect the spectrum usage in oceans, results of which demonstrate that the precious spectrum resource is underutilized temporally and spatially. The potentials of underwater cognitive acoustic networks (UCANs) in improving the environment-friendliness and spectrum utilization is then described. In addition, we investigate unique features of underwater channels and acoustic modems. The significant affects of these characteristics on the UCAN design are further analyzed. The unsolved issues and challenges identified in this paper may be used as a starting point of future research on UCANs. The ultimate objective of this paper is to call for research efforts on tackling unique underwater challenges to achieve efficient and environment-friendly spectrum utilization in UCANs.

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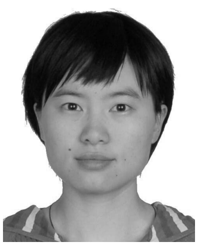

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