July-August 2020
ISSN: 0193-4120 Page No. 1315- 1325

Eco-friendly Communication through an Underwater Cognitive Acoustic Network

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Abstract

With the growing demand of ocean exploration and protection, more and more man-made acoustic systems like underwater sensor networks (UWSNs) are deployed in oceans. However, in oceans, there exist not only man-made systems but also natural acoustic systems like marine mammals. Due to the unique frequency depending attenuation feature of acoustic channel, both artificial and natural acoustic systems share the same frequency band. To avoid the possible negative impact resulting from anthropogenetic acoustic signal on marine mammals, we propose a framework of eco-friendly underwater cognitive acoustic networks, named ECOUCANs, using underwater cognitive acoustic technology. ECO-UCANs includes four main functions: spectrum management, eco-sensing, spectrum sharing and physical layer reconfiguration. Based on these four main components, the network can smartly sense and localize marine mammals. Once the marine mammals are localized, users in the network can reconfigure the operation parameters to limit the negative impact on these marine mammals. Based on the investigation of unique features of underwater channel and marine mammals, we also illustrate challenges on the existing methods to UCANs and propose possible solutions.

Keywords: *Eco-friendly, Cognitive acoustic, Underwater network*

1. INTRODUCTION

Underwater Sensor Networks (UWSNs) have attracted tremendous interests in recent years due to their wide civilian and military applications such as scientific/commercial exploration, disaster prediction, environmental monitoring and oceanography data collection [1]. This motivates more researches on a reliable and efficient UWSNs design. However, in underwater environment, exist not only artificial acoustic systems like UWSNs but also natural acoustic system like marine mammals as shown in Fig 1. The frequencies of sound which marine mammals rely on for navigation, foraging and communication mainly range from 30[Hz] to 40K [Hz] [2]. Due to the frequency depending attenuation characteristics of underwater acoustic channels, UWSNs usually operate on the frequencies from 1K[Hz] to 50K[Hz] [3]. In a word, marine mammals and UWSNs share the limited spectrum.

Furthermore, many researches have illustrated that anthropogenic noise including sonar, ship and acoustic communication can affect marine mammals by causing hearing injuries, masking of biological sounds or behavioral responses [2]. Therefore, the impact of acoustic signal on marine mammals should be taken into consideration when we develop underwater communication systems.

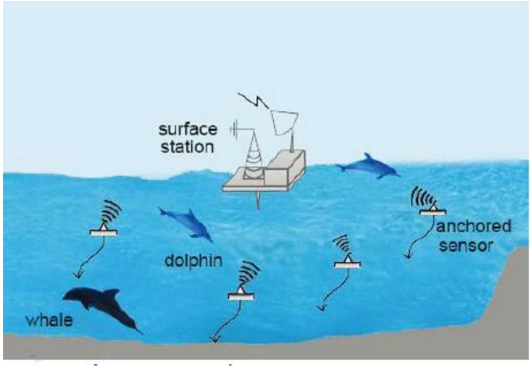

Fig. 1. underwater acoustic systems

On the other hand, however, the precious acoustic spectrum resource is still underutilized in UWSNs. For example, due to the long propagation delay of acoustic signal, slotted reservation based MAC schemes are considered as practical collision avoidance mechanisms for UWSNs. However, in such schemes, only a small part of time slots are used for data transmission, which makes the spectrum resource underutilized temporally. In addition, compared to radio based network, a relatively low spreading loss factor may cause a more large collision area, which makes the spectrum resource underutilized spatially in underwater environment.

To efficiently utilize the spectrum resource while avoiding negative interference with other acoustic systems, especially marine mammals, smart UWSNs should be aware of surrounding environment and reconfigure their operation parameters. In [4], the authors advocated cognitive acoustic (CA) as a promising technique to develop an environment friendly UWSNs. Through sensing the surrounding spectrum usage, CA users in the underwater cognitive network (UCAN) are able to intelligently detect whether there is a vacant frequency band and adjust their transmission frequency, power and other parameters to temporarily use the idle frequency without interfering with other networks.

In this paper, to coexist with other acoustic system, especially marine mammals, we propose a novel network framework for an eco-friendly underwater cognitive acoustic sensor networks (ECO-UCANs). Based on the cognitive technology, we modify some functions of existing framework of CA network, such as passive localization of marine mammals, making the new network more sensitive and friendly to surrounding eco-systems. In addition, we also analyze some possible challenges faced in the new system design and advocate some possible solutions.

The rest of the paper is organized as follows. We first provide a contemporary summary of underwater channel characteristic and present an overview of marine mammals' acoustic characteristic in section 2 and 3, respectively. Then we propose a network framework for an eco-friendly underwater cognitive acoustic sensor networks (ECO-UCANs) with presenting functional descriptions and current research challenges in section 4. Finally, our conclusions are drawn in section 5.

2. UNDERWATER CHANNEL CHARACTERISTIC

Underwater acoustic channels are generally considered as one of the most challenging communication media in use today. Acoustic propagation is characterized by three major factors: the frequency depending attenuation, multi-path propagation and doppler effect. Since a complete and accurate model of the underwater acoustic channel remains an open issue, in this section, we provide an overview of the acoustic channel properties.

2.1 Attenuation

The most distinguish property of acoustic channel is the fact that path loss, which is a consequence of absorption, depends on signal frequency. Besides the absorption loss, signal experiences a spreading loss. Therefore, the overall path loss is given by equation (1) [5] ,

$$A(l,f) = (l/l_r)^k . \alpha(f)^{l-l_r} \quad (1)$$

where f is the signal frequency, l is the transmission distance, l_r is a reference distance, k is the spreading loss, which usually values between 1 and 2 (for cylindrical and spherical spreading respectively) [6].

July-August 2020
ISSN: 0193-4120 Page No. 1315- 1325

The absorption coefficiency $\alpha(f)$ is an increasing function of frequency.

The attenuation characteristic of acoustic signal results two distinctive features of underwater acoustic networks. The first one is that the spatial reuse efficiency in underwater network is quite low due to the relatively lower spreading loss factor comparing to radio based network. To deal with this problem, transmission power control is considered to be a practical solution. The second feature is that the relatively low available frequency band due to the frequency depending attenuation characteristic. This feature cause that many underwater acoustic systems share the same frequency band resulting severe collision and interference problem.

2.2 Multi-path propagation

Multi-path propagation in underwater mainly comes from soundreflection and refraction.

In real acoustic systems, the multi-path propagation delay can be tens of milliseconds or even longer depending on the channel condition. To overcome such long multi-path propagation, long preamble is usually adopted by acoustic systems to avoid interblock interference. However, applying long preamble will increase overhead of message's exchange.

2.3 Doppler effect

The Doppler Effect coming from the motion of the transmitter or receiver can cause frequency shifting as well as additional frequency spreading. The value of shifting frequency is proportional to the ratio a = v=c of the relative transmitter/receiver velocity to the speed of sound.

Considering the speed of sound is quite slow (about 1500m=s). The Doppler distortion in underwater system can be extreme, which can result carrier interference, especially for underwater OFDM systems.

3. MARINE MAMMALS' ACOUSTIC CHARACTERISTC

To illustrate our motivation of the research on ECOUCANs, we will introduce the acoustic characteristic of marine mammals in this section. For most of marine mammals, sound is the main tool to collect environmental information, either through active echolocation or passive listening. However, these marine mammals having a good sense of hearing are vulnerable to human disturbance. Due to a mechanical coupling between the swim bladder and hearing organ, many species of marine mammals have optimum hearing sensitivity from several kilo [Hz] to a hundred kilo [Hz]. Fig 2 depicts the hearing curves for various of marine mammals.

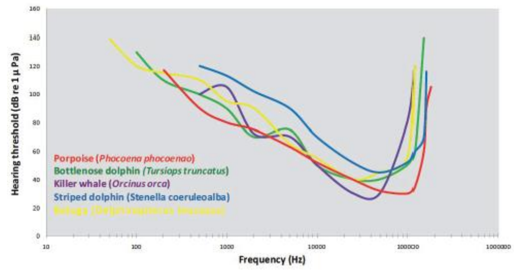

Fig. 2. Hearing curves of marine mammals [2]

From Fig 2, we can observe that the frequency band on which marine mammals are most sensitive is the band used for underwater acoustic communication (1K-40K [Hz]) [3] . Furthermore, many researches on sonar systems with the operating frequency on 1K-10K [Hz] have demonstrated that such signal can affect marine mammals by changing their normal behaviors [2].

Authors in [7] investigated the reasons of a fourteen beaked whales' stranding in the Canary Islands, 2002, which is close to the site of an international naval exercise (Neo Tapon, 2002). They presented evidence of acute and chronic tissue damage in stranded cetaceans that resulted from the formation in vivo of gas bubbles. The incidence of such cases during a naval sonar exercise indicates that acoustic

July-August 2020
ISSN: 0193-4120 Page No. 1315- 1325

factors could be important in the aetiology of bubble-related disease.

To prevent injury on marine animals by exposing them to anthropogenic noise, National Marine

Fisheries Services (NMFS) has developed guidance on sound characteristic likely to cause damage and behavioral disruption, as shown in Table 1, where PTS is permanent threshold shift and TTS is temporary threshold shift.

Table 1
NOAA Fisheries Current In-Water Acoustic Thresholds [8]

Criterion	**Criterion definition**	**Threshold**
Level A	PTS(injury) conservatively	180[*dB_Pa*]
Level B	Behavioral disruption	160[*dB_Pa*]

Based on the guidance, some parameters, especially transmission power, should be taken into consideration while developing communication systems to avoid causing injury to marine mammals.

4. ECO-UCAN NETWORK FRAMEWORK

As discussed above, a smart underwater network should be aware of surrounding environment and can smartly adapt their operation parameters. In this section, we will propose the framework of the smart underwater network: ECO-UCAN.

The framework of an ECO-UCAN involves four main components, namely, spectrum management, ECO-sensing, spectrum sharing and physical layer reconfiguration, as shown in Fig 3. If a user has data for transmission, it will start from spectrum management procedure. An eco-sensing strategy schedules when and which frequency bands to sense. Meanwhile, the passive localization procedure is activated to localized marine mammals. After the sensing process, users are aware of spectrum usage of surrounding users. With the sensing result, proper spectrum bands can be selected by spectrum decision function. Once there are several available vacant spectrum bands for users to access, spectrum sharing component can help users to access channels to avoid collisions, which plays a similar role as a traditional MAC scheme. Finally, at physical layer, transmission parameters such as power are adjusted and a spectrum mobility component is implemented to deal with the appearance or departure of spectrum holes. All these components are discussed in this section.

Similar to existing cognitive network, there are two kinds of users in ECO-UCANs, namely primary users and secondary users respectively. To better protect marine mammals, in ECO-UCANs, we define marine mammals are primary users (PUs), whose demand of frequency occupation is of first priority. The man-made underwater acoustic system, says UWSN in this paper, are considered as the secondary users (SUs) [9,10].

4.1 spectrum management

- **Eco-sensing strategy:** Eco sensing requires the detection of weak signals of unknown types with high reliability. However, due to the dynamic channel condition in underwater between targets and users, the detection performance is usually compromised. In addition, in UWSNs, each cognitive user can only determine spectrum availability based on its local observation. Nevertheless, the observation range of one single user is usually limited, especially for a sparse underwater deployment. Therefore, to improve the reliability and range of spectrum sensing, cooperative sensing among users have been recently illustrated. With such schemes, in ECO-UCANs, if a user detects marine mammals' activities, it should notify its observation promptly to its neighbors. As a consequence, a network of cooperative users experiencing different surrounding environment would have better detecting performance.

In past decades, many researches dedicated to cooperative sensing strategy have been proposed. All these approaches can be classified into three categories: centralized, distributed and relay assisted.

July-August 2020
ISSN: 0193-4120 Page No. 1315- 1325

In centralized approaches, a base station called fusion center (FC) controls the process of sensing with the following three steps: 1. FC selects a channel of interest for sensing and inform users to individually perform local sensing. 2. Users report their sensing result via control channel. Then FC combines the reported information and determines the presence of primary users. 3. FC sends the decision back to cognitive users.

Unlike centralized cooperative sensing strategy, in distributed cooperative sensing approach, cognitive users exchange information among them and converge to unified decision on the presence or absence of Pus by iterations. In addition to above two schemes, the third one is relay-assisted cooperative sensing. Since both sensing channel and report channel may not be perfect, a cognitive user observing a weak sensing channel and a strong report channel, for example, can complement and cooperative with each other to improve the performance of cooperative sensing.

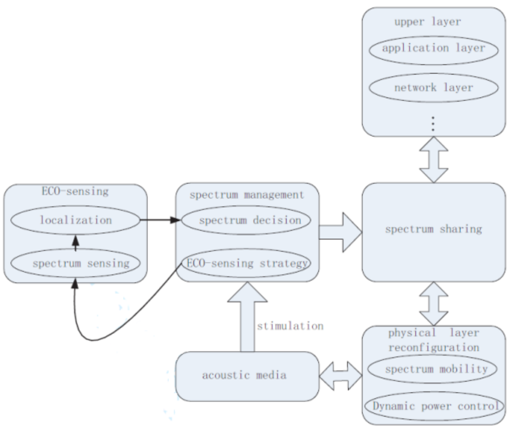

Fig. 3. ECO-UCANs framework

- **Spectrum decision:** Once available spectrum bands are identified through spectrum sensing, the networks need to select the most proper spectrum bands according to the application requirement. This process is referred to as spectrum decision. In this work, spectrum decision involves two main functions: spectrum characterization and spectrum selection.

For spectrum characterization, once vacant spectrum bands are identified by spectrum sensing, each spectrum band is characterized based on local observation and statistical information of marine mammals. Acoustic frequency environment characterization is a process of estimating for the following elements:

a. Channel identification. Primary channel identification is the first important step to be performed by each user. Since marine mammals communicate stochastically, we can only describe the stochastic patterns using probabilities and statistics because their spectrum usage tends to exhibit great variations in time and space.

b. Channel capacity estimation. Traditionally, channel capacity is measured by using signal-to-noise (SNR) as an indicator. However, it has been shown that using the SNR leads to non-optimal spectrum decision. In addition, some unique design of acoustic communication systems' performance may not strictly rely on SNR. For instance, in underwater OFDM acoustic modem system, a new parameter named effective SNR (ESNR) is proved as a more effective indicator to describe the channel state as shown in [11].

Since there is no guarantee that a spectrum band will be available during the entire SUs' communication period, it is necessary to consider how often PUs may appear on the spectrum band. Using the learning ability of the cognitive users, the history of the spectrum usage information can be used for predicting the future profile of the spectrum. Table 2 lists the statistical result of a long-time observation of the dolphin's six types of whistle which are shown in Fig 4.

July-August 2020
ISSN: 0193-4120 Page No. 1315- 1325

Table 2: Summary Of 13 Survey Days With Total Number Of Whistles [12]

Recording time	Total good Whistles	Flat	Down	Rise	U-Shape	Convex	Sine
2h36m9s 349	349	179	62	24	8	55	21
1h22m7s	57	22	19	5	0	9	2
36m20s	10	0	7	0	2	0	1
1h53m37s	167	81	22	39	4	14	7
1h35m28s	69	10	5	10	28	6	10
2h46m39s	89	30	8	11	3	31	6
3h23m59s	195	81	30	46	5	19	14
4h38m25s	314	98	102	39	27	30	18
4h44m15s	317	160	88	27	16	17	9
4h33m56s	57	29	5	12	2	6	3
5h18m27s	107	40	46	6	5	6	4
2h40m1s	91	31	21	8	6	12	13
2h48m41s	829	157	114	109	127	158	164
38h58m4s(total)	2651	918	529	336	233	363	272

As a result, the major difference and challenge between the existing spectrum decision function and the one implementing in ECO-UCANs is how to model PU's activities. Since the activity of marine mammals may vary among species, it may necessary to build up a database to collect the statistical result like Table 2.

Once spectrum bands are characterized, the next step is to choose the best spectrum band to satisfy the user's specific quality of service (Qos) requirement.

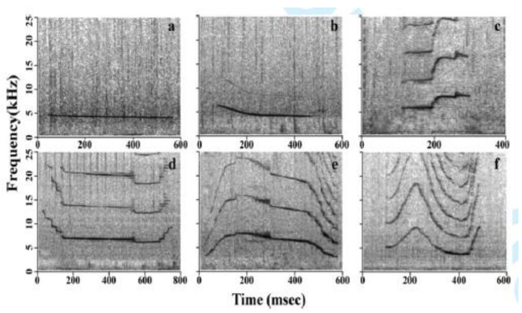

Fig. 4. whistle types of dolphin

In a centralized network, spectrum selection can be conducted at the base station (BS) or access point (AP). However, most of spectrum selection schemes dedicated to centralized network cannot be applied to distributed network directly. In addition, for most UWSNs, users are connected in a distributed way with multi-hop. In order to address spectrum selection in multi-hop underwater network, joint spectrum and routing selection design approaches are ideal solutions. By acquiring some knowledge from lower layer (physical or MAC), routing algorithm can make an intelligent decision.

With a consideration of the possible large scale of underwater network, cooperative spectrum selection can be an advanced approach. However, a challenge for cooperative spectrum selection is how to collect information from cooperative users while limiting transmission overhead.

4.2 Eco sensing

- **spectrum sensing:** An ECO-UCAN is designed to be aware of and sensitive to the existing/change in its surrounding

July-August 2020
ISSN: 0193-4120 Page No. 1315- 1325

environment, which makes spectrum sensing an important functionality of the network. Spectrum sensing enables cognitive users to adapt to the environment by detecting spectrum holes. In general, spectrum sensing method can be categorized into matched filter detection, energy detection and feature detection.

- **Matched filter**: With the full prior knowledge of the PUs' signal, the optimal detector in stationary Gaussian noise is the matched filter. This kind of approach requires minimum sensing time. However, matched filter technology is susceptibility to frequency offsets and requires synchronization.
- **Energy detection:** Considering that prior knowledge of PUs' signal may not be acquired in some circumstance, energy detection is another approach for spectrum sensing. An implementation of energy detection consists of a low pass filter, an A/D converter and a square law device to compute the energy. However, energy detection is not flexible for narrow band signals and is susceptible to uncertainty in noise power by generating false alarms.
- **Feature detection:** Generally speaking, modulated signal are characterized by built-in cycle-stationary such as cyclic-prefixes in OFDM and code sequences in CDMA. A cycle-stationary showing periodic behaviour , is exploited in a detector to measures a signal property. This kind of method can achieves a high robustness to uncertainty in noise power at the expense of high computationally complex and long observation times.
- **Challenges:** Most of current researches focus on improving the reliability or the cover range of sensing strategy. However, they may neglect the energy consumption on spectrum sensing. For underwater nodes, energy is a critical and limited resource. Both sensing and transmission consume energy. With a given level of transmission power, sensing more channels with more times can help explore the diversity among different channels. Nevertheless, such frequently sensing channels may reduce the amount of time left for data transmission in the case that the total energy budget is fixed. This is the tradeoff involved in the spectrum sensing strategy design. With the help of the research of acoustic characteristic, we can focus on some certain channels on which marine mammals usually occupied. In addition, considering our main sensing targets are some marine mammals, matched filter detection approach can be a feasible method to sense the existence of marine mammals. For instance, if researches have well established databases including a large amount of sound samples of marine mammals, a matched filter algorithms can be reached by extracting the unique features (frequency, duration).
- **Localization:** In order to reduce the influence of acoustic communication on marine mammals, we have to schedule the communication process properly. For instance, when some marine mammal have been detected, we are supposed to control the transmission power under a threshold which gives a limitation that marine mammals can bear. In this case, we have to determine the location of marine mammals. Generally, localizing marine mammals plays an important role in peaceful coexistence of network with marine mammals. Only with information on the motion area of marine mammals can we make an efficient and reasonable decision in spectrum sharing and power control.

The most distinctive feature of localization schemes applied in ECO-UCANs is that the target to be located here are usually marine mammals rather than

July-August 2020
ISSN: 0193-4120 Page No. 1315- 1325

man-made systems. Most of existing localization algorithms localizing target rely on message exchanges between anchors and targets. However, it is impossible to "communicate" with marine mammals. Therefore, a passive localization scheme is considered as a practical method. For example, based on the strength of receiving power level and a reference sound level range of marine mammals, a search method can help us to locate the target's position.

Besides "communication" issue, the mobility of targets is another challenge for localization. Considering the time consumption for localization (tens of seconds), the distance that marine mammals can move (dolphin, for example) hundreds of meters, which makes the localization result meaningless. To solve this problem, a prediction based approach may be helpful. Due to the Doppler effect resulting from the target's mobility, we can estimate the value and direction of moving speed of the target relying on the frequency shifting of receiving signal, which can improve the accuracy of localization result.

4.3 Spectrum sharing

Cognitive acoustic MAC enables multiple users to share the spectrum resource by determining who will access the channel and when will it access to it. In this paper, to differentiate it from the traditional MAC issue, we refer CA MAC to spectrum sharing issue.

Spectrum sharing is responsible for providing efficient and fair spectrum allocation or scheduling solutions among PUs and SUs. The major difference between spectrum sharing and traditional generic media access control scheme is that, in cognitive radio acoustic network, the network users equipped with cognitive radio/acoustic can make intelligent decisions based on the evaluation on spectrum usage and on the other users' activities. Therefore, it is natural to study the intelligent behaviors and interactions of network users (cooperative, selfish or even malicious) for spectrum sharing from the game theoretical perspective.

In general, a game in the strategic form has three elements: a set of players, the strategy of each player and the utility function which measures the outcome and payoff of each user. The players in the ECOUCANs network consist of both marine mammals and UWSN users. The strategy space for each user includes which channel they will access; what transmission parameters (power, rate, modulation scheme) to apply and so on. Finally, the utility function represents the common communication goal, for example, the network capacity.

Base on the network structure, we have non-cooperative spectrum access, which are usually applied in distributed network and cooperative spectrum access game for centralized network. Considering the lack of centralized authorization and users' selfishness, distributed spectrum sharing needs to be further exploited by studying users intelligent behaviors from the non-cooperative game theoretical point of view.

Several approaches have been proposed dedicating to efficient and fair spectrum allocation distributively using local information. However, all existing game theory based spectrum access solutions assume that the PUs are some certain man-made systems with highly predictable behaviors. Referring to ECO-UCANs network, however, the PUs are some marine mammals, whose behaviors' modeling is still a great challenge. Therefore, the utility function of the system should take the impact on marine mammals into consideration as well as some extra limitations, interference threshold for example, should be included while solving the optimal game.

4.4 Physical layer reconfiguration

spectrum mobility: In ECO-UCANs, spectrum mobility occurs when the current channel performance deteriorates or marine mammals appear around the UWSNs. Since the appearance and departure of "licensed" users and channel quality variation are highly random, the appearance and departure of spectrum holes are also highly random. Base on the primary objective of spectrum mobility,

July-August 2020
ISSN: 0193-4120 Page No. 1315- 1325

it can be divided into two processes: spectrum handoff and connection management.

Spectrum handoff is the process of transferring ongoing data transmission from the current channel to another free channel because of PUs arrival or link quality degradation. All existing spectrum handoff strategies can be classified into 3 categories with characterizing them by identifying when spectrum sensing and handoff are perform.

a. Non-handoff strategy

In this approach, SUs keep staying in the current channel and being "silent" until the channel becomes free again. The weakness of such approach is that it may introduce high waiting latency. In delay-sensitive applications, this kind of approach may fail to meet Qos requirements.

b. Pure reactive handoff strategy

In this kind of strategy, SUs applies reactive spectrum sensing and reactive handoff action approach. SU performs spectrum sensing to find target backup channel only when a handoff triggering event occur. Compared with non-handoff strategy, pure reactive handoff strategy can get an accurate target channel. However, it may also experience long handoff latency due to on-demand spectrum sensing.

c. Pure proactive handoff strategy

Different from pure reactive handoff strategy, SU, based on the knowledge of PUs' traffic model, performs sensing to find a backup target channel in pure proactive handoff strategy. For this kind of approach, handoff latency can be very short. However, the drawback of this strategy is that the backup target channel can remain obsolete. There is a chance that backup target channel is already occupied by other users. Additionally, poor prediction may degrade the overall spectrum mobility performance.

d. Hybrid handoff strategy

In this strategy, target channel is performed proactively and handoff action is performed reactively. That is to say, target channel selection is prepared beforehand or during SU data's transmission while spectrum handoff is performed after triggering event happens. Hybrid handoff can balance the accuracy and latency of spectrum mobility.

From the discussion above, we can conclude that the performance of spectrum handoff strategy depends on unique characteristic of the PU network. For example, non-handoff approach is suitable for PU network with short data transmission pattern and in the situation where other licensed spectrum bands are highly congested. As to ECO-UCANs, considering the great impact on transmission pattern with the existing of marine mammals or not, a hybrid handoff strategy can be applied. With an observation of marine mammals, a non-handoff approach may be a proper strategy while a proactively handoff strategy may be a best choice without marine mammals.

- **Dynamic power control:** Most of existing spectrum sharing scheme try to avoid the interference to PUs by transmitting messages in different spectrum bands. In that case, cognitive users only need to control their transmission power to avoid the interference among themselves. However, since the available bandwidth is quite limit and PUs may occupy the whole frequency band in underwater scenario, it is obviously that such schemes are not efficient ways to improve the network capacity while considering the UWSNs scenario.

To improve the earlier proposed cognitive spectrum access schemes, some recent studies have extended the cognitive protocols to allow both PUs and SUs transmitting simultaneously in the same spectrum band by controlling the SUs' transmission power.

To cooperatively transmit with PUs, it is essential for SUs to obtain the information about the Pus including position and channel fading characteristic for example. However, while applying these power control schemes to UWSNs, there may exist a number of grand challenges: 1. Most of existing power control schemes are relying on the acquired information about PUs. However, the process of information collection of marine mammals, location, for example, can be time and energy consuming. In addition, the interference threshold of marine mammals, which is the most important parameter for power control algorithm, is still an open issue. 2. The channel condition, especially the fading characteristic, can highly affect the performance of power control algorithms. For example, the slower fading characteristic of underwater acoustic channel can lead to a larger interference range and lower spatial reuse efficiency.

Unfortunately, the channel condition in underwater tends to be highly dynamic. Most of power control algorithms relying on such instantaneous channel state information cannot be well applied. However, researches have showed that channel state is predictable to some extend and its statistic result (eg. Probability distribution) are stable. Therefore, a channel state prediction based power control algorithm should improve the system's performance.

5. CONCLUSIONS AND FUTURE WORK

With the growing demand for ocean exploration and surveillance, more and more man-made acoustic communication systems like UWSNs have been deployed in oceans. To avoid possible negative impact resulting from anthropogenic acoustic signal on marine mammals, we propose a eco-friendly underwater network framework, named ECO-UCANs, using cognitive acoustic technology.

The ECO-UCANs involves four main functions including spectrum management, eco-sensing, spectrum sharing and physical layer reconfiguration. Based on investigation of unique features of underwater channels and marine mammals, we identify some possible problems or challenges while applying existing methods, algorithms or schemes. To make the network better co-exist with marine mammals, we have proposed some possible solutions or research direction to each function of the ECO-UCANs.

Our future work will include developing detail schemes, especially for marine mammals' sensing and localization, as well as conducting field test to validate the proposed schemes.

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