Connectivity of Underwater Cognitive Acoustic Networks under Spectrum Constraint

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ABSTRACT

There is an extensive attention on underwater cognitive acoustic networks (UCANs) since acoustic spectrum becomes deficient owning to the proliferation of human activity in ocean. This paper presents an overview of our recent progress in investigating the connectivity of secondary users (SUs) in UCANs. In particular, this model takes both topological connectivity and spectrum availability into account. Simulation results verify the accuracy of the proposed model.

1. INTRODUCTION

Underwater sensor networks generally use acoustic communications instead of electromagnetic communications because electromagnetic waves have high attenuation in underwater environment. Nonetheless the acoustic spectrum of the underwater environment is becoming a deficient resource. One of the most encouraging solutions for the acoustic-spectrum deficiency problem is underwater *cognitive* acoustic networks (UCANs). UCANs include two types of users: primary users (PUs) and secondary users (SUs). It is prioritized for PUs to use the acoustic spectrum. Only when the communications of SUs do not disturb the communications of PUs, SUs can use the spectrum. Since underwater acoustic communications undoubtedly differ from terrestrial wireless communication systems for the features of underwater channel, many studies focus on UCANs recently [2–4]. However, quality-of-service (QoS) of SUs in UCANs only draws few attentions.

Substantially, SUs are constrained by the acoustic spectrum in UCANs. Hence, guaranteeing QoS of SUs is more difficult than that of PUs. The connectivity is one of the most significant QoS metrics; it concerns the possibility whether a pair of nodes can establish a communication link. Figure 1 presents an example of UCANs, where we can observe that an SU pair can establish links only if it is far away enough from PUs (*i.e.*, SUs doesnot hamper the communication of PUs). *To the best of our knowledge, the connectivity of SUs in UCANs has not been investigated in prior studies.* Therefore, the goal of this paper is to investigate the connectivity of SUs in UCANs. In particular, we first develop an analytical model. Then we conduct simulations to verify the accuracy of this model. The more extensive analytical and simulation results can be referred to [5].

2. OVERVIEW OF OUR METHODOLOGY

2.1 System Model

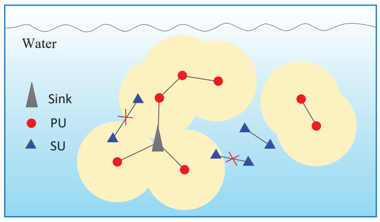


Figure 1: Underwater cognitive acoustic networks.

In our network model, we assume that PUs are scattered geographically according to homogeneous Poisson point process (HPPP) with intensity λ_p within a 2-D plane [1]. Each PU emits the acoustic signal with the identical transmission power denoted by P_p. An SU pair is located at the center of this network with the transmission power denoted by P_s.

The attenuation of the acoustic signal is expressed as follows

$$A(d, f) = d^k \alpha(f)^d, \tag{1}$$

where k is the spreading factor (ranging from 1 to 2), d is the distance between a transmitter and receiver and $\alpha(f)$ is the absorption coefficient of signal frequency f.

Commonly, Eq. (1) is given in dB by $10 \log A(d, f) = k \cdot 10 \log d + d \cdot 10 \log \alpha(f)$, where the absorption coefficient $10 \log \alpha(f)$ in dB/km for f in kHz is given by

$$\begin{aligned} 10 \log \alpha(f) = 0.11 \cdot \frac{f^2}{1+f^2} + 44 \frac{f^2}{4100+f^2} \\ +2.75 \cdot 10^{-4} f^2 + 0.003. \end{aligned} \tag{2}$$

2.2 Connectivity

The connectivity of SUs in UCANs is evaluated by the *probability of connection*; it is the probability that two SUs can successfully establish a bidirectional link. In UCANs, a bidirectional link between two SUs can be established if and only if 1) both the two SUs can connect topologically; (2) both the two SUs have the spectrum.

2.2.1 Topological connection condition

The probability that two SUs can topologically connect each other is denoted by p_{top}, which is expressed as,

$$p_{top} = \mathbb{P}[SNR_{dB} \geq \delta_s], \tag{3}$$

where SNR_{dB} is the signal-to-noise ratio (SNR) in dB between a pair of SUs and δ_s is the threshold that a receiver can successfully received information.

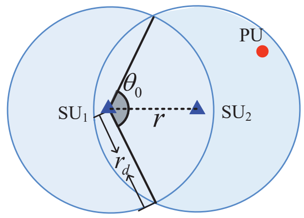
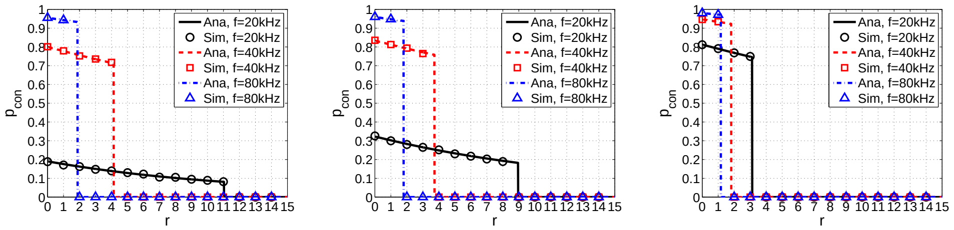


Figure 2: Detection region of a pair of SUs



(a) $k = 1, w = 0$ m/s (b) $k = 2, w = 0$ m/s (c) $k = 2, w = 20$ m/s

Figure 3: Probability of connection p_{con} versus distance r with different spreading factor k and wind speed w. System parameters are set by $P_p = 110$ dB, $P_s = 100$ dB, $\lambda_p = 0.003$, $s = 1$, $\delta_s = 20$ dB and $\delta_d = 20$ dB

The SNR between the SU pair is given by,

$$SNR = \frac{P_s}{\int\limits_B A(r,f)df \int\limits_B N(f)df}, \tag{4}$$

where B is the bandwidth, which is normalized for that we just concern with the relationship between f and SNR.

Then p_{top} is expressed as,

$$p_{top} = \mathbb{P}[k{\cdot}10\log r + r{\cdot}10\log\alpha(f) + 10\log N(f) \le 10\log P_s - \delta_s]. \tag{5}$$

Letting LHS of the inequality be equal to RHS, we can have the *maximum communication distance*, denoted by $r_{\max}$. Then, p_{top} is expressed as,

$$p_{top} = \begin{cases} 1 & r \le r_{\max} \\ 0 & r > r_{\max} \end{cases}. \tag{6}$$

2.2.2 Spectrum availability

We assume that an SU cannot have spectrum if the SNR (dB) at an SU is no less than a detection threshold δ_d (dB). In other words, $SNR_{dB} = 10\log P_p - 10\log A(r,f) - 10\log N(f) \ge \delta_d$. We can obtain the *detection range* of an SU, which is defined as the maximum distance that an SU can detect PUs, denoted by r_d.

Then we consider that an SU pair can have the spectrum if no PUs fall in the detection region of two SUs (*i.e.*, blue region in Figure 2). According to the fact that PUs follow HPPP, we have the probability that two SUs can have the spectrum, denoted by p_{spe}, given as

$$p_{spe} = e^{-S\lambda_p}, \tag{7}$$

where S is the detection region area of two SUs, given by

$$S = \begin{cases} \pi r_d^2 + (\pi - \theta_0)r_d^2 + r_d \sin(\dfrac{\theta_0}{2})r & r \le 2r_d \\ 2\pi r_d^2 & r > 2r_d \end{cases}, \tag{8}$$

where $\theta_0 = 2\arccos\frac{r}{2r_d}$.

After combining Eq. (8) with Eq. (7), we can have

$$p_{spe} = \begin{cases} e^{\left(\pi r_d^2 + (\pi-\theta_0)r_d^2 + r_d\sin(\frac{\theta_0}{2})r\right)\lambda_p} & r \le 2r_d \\ e^{2\pi r_d^2 \lambda_p} & r > 2r_d \end{cases}. \tag{9}$$

2.2.3 Connectivity

Finally, the probability of connection can be given as:

$$p_{con} = p_{top}{\cdot}p_{spe} = \begin{cases} e^{\left(\pi r_d^2 + (\pi-\theta_0)r_d^2 + r_d\sin(\frac{\theta_0}{2})r\right)\lambda_p} & r \le 2r_d \\ e^{2\pi r_d^2 \lambda_p} & 2r_d < r \le r_{\max} \\ 0 & r > r_{\max} \end{cases}. \tag{10}$$

If $2r_d > r_{\max}$, p_{con} can be expressed as:

$$p_{con} = \begin{cases} e^{\left(\pi r_d^2 + (\pi-\theta_0)r_d^2 + r_d\sin(\frac{\theta_0}{2})r\right)\lambda_p} & r \le r_{\max} \\ 0 & r > r_{\max} \end{cases}. \tag{11}$$

3. SIMULATION RESULTS

As shown in Figure 3, there is an excellent agreement between simulation and analytical results, indicating that this model is accurate. From the results, we observe that the connectivity depends on frequency f, spreading factor k, wind speed w. The connectivity of UCANs is significantly different from that of terrestrial cognitive radio networks.

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4. REFERENCES

[1] H. ElSawy, E. Hossain, and M. Haenggi. Stochastic geometry for modeling, analysis, and design of multi-tier and cognitive cellular wireless networks: A survey. *IEEE Communications Surveys Tutorials*, 15(3):996–1019, Third 2013.

[2] Y. Luo, L. Pu, H. Mo, Y. Zhu, Z. Peng, and J.-H. Cui. Receiver-initiated spectrum management for underwater cognitive acoustic network. *IEEE Transactions on Mobile Computing*, 16(1):198–212, 2017.

[3] Y. Luo, L. Pu, M. Zuba, Z. Peng, and J.-H. Cui. Challenges and opportunities of underwater cognitive acoustic networks. *IEEE Transactions on Emerging Topics in Computing*, 2(2):198–211, 2014.

[4] D. Wang, Y. Zhang, X. Hu, R. Zhang, W. Su, and Y. Xie. A dynamic spectrum decision algorithm for underwater cognitive acoustic networks. In *Proceedings of WUWNET*. ACM, 2016.

[5] Q. Wang, H. N. Dai, C. F. Cheang, and H. Wang. Link connectivity and coverage of underwater cognitive acoustic networks under spectrum constraint. *Sensors*, 17(12), 2017.