# Chapter 2
# Underwater Acoustic Channel Models

In this chapter, we introduce two prevailing UWA channel models, namely, the empirical UWA channel model and the statistical time-varying UWA channel model, to capture the features of RA-UAC systems from different aspects. In addition, the relationship between the coherence time and transmission distances is also explored to reveal the fundamental difference between the short-range UAC and the medium-long range UAC.

## 2.1 Empirical UWA Channel Model

The empirical UWA channel model is measured through sea trials. The signal attenuation $\mathcal{A}$ of a path is dependent on both distance $d$ and subcarrier frequency $f_k$:

$$\mathcal{A}(d, f_k) = d^e a(f_k)^d, \tag{2.1}$$

where $e$ is the path loss exponent reflecting the geometry of acoustic signal propagation. We adopt $e = 1.5$ for practical spreading. The frequency dependency is captured by $a(f_k)$, which is given by Thorp's formula [1] in dB/km:

$$10 \log a(f_k) = \frac{0.11 f_k^2}{1 + f_k^2} + \frac{44 f_k^2}{4100 + f_k^2} + 2.75 \cdot 10^{-4} f_k^2 + 0.003. \tag{2.2}$$

In (2.1) and (2.2), frequency $f_k$ is in kHz.

In addition, the noise variance is also frequency-dependent and empirically modeled as

$$10 \log \mathcal{N}(f_k) = \mathcal{N}_1 - \eta \log(f_k) + 10 \log \Delta f, \tag{2.3}$$



X. Cheng et al., *Cooperative OFDM Underwater Acoustic Communications*, Wireless Networks, DOI 10.1007/978-3-319-33207-9_2

where $\mathcal{N}_1$ and $\eta$ are constants with empirical values $\mathcal{N}_1 = 50\,\mathrm{dB}$ re μPa per Hz and $\eta = 18\,\mathrm{dB/decade}$, respectively. Frequency $f_k$ is in kHz, and the subcarrier spacing $\Delta f$ is in Hz.

## 2.2 Statistical Time-Varying UWA Channel Model

Due to the slow propagation of UWA waves, signals reflected from the sea surface and bottom arrive at the receiver with distinct delays. This results in a sparse multipath channel [2, 3]. We consider the long-term path loss and the short-term random fading to model the discrete-time baseband UWA channels. The long-term pass loss is modeled as a deterministic discrete-time UWA channel $\bar{\boldsymbol{h}} = [0, \cdots, \bar{h}_{l_0}, 0, \cdots, \bar{h}_{l_1}, 0, \cdots, \bar{h}_{l_{L_{nz}-1}}]^T$, within which only $L_{nz}$ taps are nonzero. Each nonzero tap $\bar{h}_l,\ l \in \{l_0, \cdots, l_{L_{nz}-1}\}$ corresponds to the pass loss of the $l$th arrival with delay $\tau_l = l\Delta t$, where $\Delta t = 1/B$ is the tap length and $B$ is the system bandwidth. The randomness of nonzero taps is modeled as independent Rayleigh fading [4, 5]. The resultant channel coefficients are given as an $L \times 1$ vector $\boldsymbol{h} = [0, \cdots, h_{l_0}, 0, \cdots, h_{l_1}, 0, \cdots, h_{l_{L_{nz}-1}}]^T$ with each nonzero tap $h_l,\ l \in \{l_0, \cdots, l_{L_{nz}-1}\}$ following the independent complex Gaussian distribution, i.e., $h_l \sim \mathcal{CN}(0, |\bar{h}_l|^2)$. The discrete-time baseband CIRs of the time-varying UWA channels are given as

$$h(t, \tau) = \sum_{l \in \{l_0, \cdots, l_{L_{nz}-1}\}} h_l(t)\delta(\tau - l), \tau \in \{0, 1, \cdots, L-1\}. \tag{2.4}$$

Jake's model is utilized to capture the channel variation, i.e., $\mathbb{E}[h_l(t)h_{l'}^*(t')] = R_h(t-t', l)\delta(l-l')$. $R_h(t-t', l) = |\bar{h}_l|^2 J_0(2\pi f_d(t-t'))$ is the autocorrelation between time $t$ and time $t'$ for path $l$. $f_d$ is the maximum Doppler shift, and $J_0(\cdot)$ is the zeroth-order Bessel function of the first kind. It is confirmed in [6] that as long as the motion-induced nonuniform Doppler shift is removed through received signal resampling, the Doppler scaling factor $a$ can be very small, i.e., $a < 10^{-4}$. With carrier frequency $f_c = 17\,\mathrm{kHz}$ as an example, the maximum Doppler shift $f_d = af_c$ is less than 1.7 Hz. After residual carrier frequency offset (CFO) compensation, $f_d$ can be further reduced [7]. Therefore, we assume that after the major Doppler effect has been removed through received signal resampling and residual CFO compensation, $f_d$ is very small ($f_d < 0.5\,\mathrm{Hz}$), which means $h_l$ changes slowly over a few seconds.

For an OFDM-based communication system, the channel response in the FD is given as $\boldsymbol{H} = \sqrt{N}\boldsymbol{F}_N\boldsymbol{P}\boldsymbol{h}$, where $N$ is the subcarrier number, $\boldsymbol{F}_N$ is $N \times N$ discrete Fourier transform (DFT) matrix with $\boldsymbol{F}_N\boldsymbol{F}_N^H = \boldsymbol{I}_N$, and $\boldsymbol{P} = [\boldsymbol{I}_L\ \boldsymbol{0}_{L\times(N-L)}]^T$ is the zero-padding matrix. The $k$th element of $\boldsymbol{H}$ is $H_k = \sum_{n=0}^{L-1} e^{-j\frac{2\pi}{N}kn} h_n, k = 0, \cdots, N-1$ and is complex Gaussian distributed, i.e., $H_k \sim \mathcal{CN}(0, \eta)$ where $\eta = \sum_{n=0}^{L_{nz}-1} \mathbb{E}[|h_{l_n}|^2] = \sum_{l\in\{l_0,\cdots,l_{L_{nz}-1}\}} \left|\bar{h}_l\right|^2$. $\eta$ is actually the channel power, i.e., the total energy of all nonzero channel paths, which depends on the transmitter and receiver locations as well as the sea geometry.

## 2.3 Relationship Between Coherence Time and Transmission Distances

According to Clarke's model [8], the coherence time is defined as

$$T_c = \sqrt{\frac{9}{16\pi f_d^2}} \approx \frac{0.423}{f_d} = \frac{0.423}{af_c}, \tag{2.5}$$

where $f_d$ is the Doppler shift, $f_c$ is the carrier frequency, and $a$ is the Doppler scaling factor. Suppose the distance between the transmitter and the receiver is $D$. Then the round-trip delay time is $\Delta_T = 2D/c$. The quasi-static channel assumption during the feedback signal propagation holds if the coherence time is larger than the round-trip delay time, i.e.,

$$T_c > \Delta_T, \tag{2.6}$$

or

$$D < D_c = \frac{0.212c}{af_c}. \tag{2.7}$$

In an UWA channel with $c = 1500$ m/s, $f_c = 17$ kHz, and $a = 3 \times 10^{-5}$, the transmission distance $D$ has to be less than $D_c = 624$ m. This means that for short-range UAC ($0.1 \sim 1$ km), the instantaneous CSI feedback from the receiver to the transmitter is feasible, especially with the help of channel prediction. However, for medium-long-range UAC ($\gg 1$) km, due to the slow propagation speed of UWA signal ($c \approx 1500$ m/s), the propagation time of the feedback signal could be much larger than the coherence time and nullify the instantaneous CSI feedback. Therefore, the adoption of the instantaneous CSI feedback depends on the transmission distances and the level of channel variation after Doppler compensation.

In summary, the unique features of UWA channels have great impacts on the design of the energy-efficient and reliable RA-UAC.

## References


1. L. Berkhovskikh, Y. Lysanov, *Fundamentals of Ocean Acoustics* (Springer, New York, 1982)
2. M. Stojanovic, On the relationship between capacity and distance in an underwater acoustic communication channel, in *Proceedings of the 1st ACM International Workshop on Underwater Networks*, Los Angeles, 25 September 2006, pp. 41–47
3. C.R. Berger, S. Zhou, J.C. Preisig, P. Willett, Sparse channel estimation for multicarrier underwater acoustic communication: from subspace methods to compressed sensing. IEEE Trans. Signal Process. **58**(3), 1708–1721 (2010)

4. M. Chitre, A high-frequency warm shallow water acoustic communications channel model and measurements. J. Acoust. Soc. Am. **122**(5), 2580–2586 (2007)
5. C. Choudhuri, U. Mitra, Capacity bounds and power allocation for underwater acoustic relay channels with ISI, in *Proceedings of the Fourth ACM International Workshop on UnderWater Networks*, Berkeley, 3 November 2009, p. 6
6. A. Radosevic, R. Ahmed, T.M. Duman, J.G. Proakis, M. Stojanovic, Adaptive OFDM modulation for underwater acoustic communications: Design considerations and experimental results. IEEE J. Ocean. Eng. **39**(2), 357–370 (2014)
7. B. Li, S. Zhou, M. Stojanovic, L. Freitag, P. Willett, Multicarrier communication over underwater acoustic channels with nonuniform Doppler shifts. IEEE J. Ocean. Eng. **33**(2), 198–209 (2008)
8. T.S. Rappaport, *Wireless Communications: Principles and Practice* (New Jersey:Prentice Hall PTR, Upper Saddle River, 2001)

Springer

http://www.springer.com/978-3-319-33206-2

Cooperative OFDM Underwater Acoustic Communications

Cheng, X.; Yang, L.; Cheng, X.

2016, XII, 104 p. 41 illus., 31 illus. in color., Hardcover
ISBN: 978-3-319-33206-2