# Cooperative Underwater Acoustic Communications

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## ABSTRACT

This article presents a contemporary overview of underwater acoustic communication (UWAC) and investigates physical layer aspects on cooperative transmission techniques for future UWAC systems. Taking advantage of the broadcast nature of wireless transmission, cooperative communication realizes spatial diversity advantages in a distributed manner. The current literature on cooperative communication focuses on terrestrial wireless systems at radio frequencies with sporadic results on cooperative UWAC. In this article, we summarize initial results on cooperative UWAC and investigate the performance of a multicarrier cooperative UWAC considering the inherent unique characteristics of the underwater channel. Our simulation results demonstrate the superiority of cooperative UWAC systems over their point-to-point counterparts.

## INTRODUCTION

The abundance of water on Earth distinguishes our "Blue Planet" from others in the solar system. Nearly 71 percent of the Earth's surface is covered with water, 97 percent of it being sea water. This vast underwater world is extremely rich in natural resources such as valuable minerals and oil fields waiting to be explored. Underwater exploration activities are mainly hampered by the lack of efficient means of real-time communication below water. Although wireline systems through deployment of fiber optical links have been used to provide real-time communication in some underwater applications, their high cost and operational disadvantages become restrictive in many cases. Wireless communication is a promising alternative and an ideal transmission solution for a wide range of underwater applications including offshore oil field exploration/monitoring, oceanographic data collection, maritime archaeology, environmental monitoring, disaster prevention, and port security, among many others.

Wireless transmission of information under water can be achieved through radio, optical, or sound waves. Due to the high attenuation of radio frequency (RF) signals in water, long-range RF communication is problematic and requires the use of extra low frequencies, which necessitate large antennas and high transmit powers. Although early military use of underwater RF communications is known, the first commercial underwater RF modem was introduced only a few years ago.[1] However, their short transmission range (1–100 m) makes this option unappealing for most practical purposes. Optical waves do not suffer much attenuation, but are severely affected by absorption, scattering, and high levels of ambient light limiting the transmission ranges. Among the alternatives for wireless communications, acoustic transmission is the most practical and commonly employed method due to favorable propagation characteristics of sound waves under water.

As diverse and data-heavy underwater applications emerge, demanding requirements are further imposed on underwater acoustic communication (UWAC) systems. Future UWAC networks might consist of both mobile and stationary nodes that exchange data such as control, telemetry, speech, and video signals among themselves as well as a central node located on a ship or onshore. The submerged nodes (which can, e.g., take the form of an autonomous underwater vehicle/robot or diver) can be equipped with various sensors, sonars, video cameras, or other types of data acquisition instruments. Innovative physical layer (PHY) solutions are therefore required to develop efficient, reliable, and high-speed transmission solutions tailored to the challenging and diverse requirements of underwater applications. This tutorial article first provides a contemporary overview of UWAC and presents a summary of underwater channel characteristics. Then it investigates cooperative (i.e., relay-assisted) transmission as a powerful PHY solution in the context of UWAC considering the inherent characteristics unique to underwater acoustic channels.

The rest of the article is organized as follows. First, we present a literature overview of UWAC. Next, we provide a summary of the underwater channel characteristics, including path loss, fading, and ambient noise, that need to be considered in system design and analysis. We then introduce the multicarrier cooperative system

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[1] *http://www.wfsdefense.com/index.php/about_wfs_defense/*

  

model under consideration. We provide the outage performance of the cooperative UWAC system and compare its performance to conventional point-to-point transmission under the assumptions of various channel and system parameters. Finally, we provide concluding remarks and some future research directions.

## LITERATURE OVERVIEW OF UWAC

### EARLY YEARS: ANALOG MODULATION AND NON-COHERENT DIGITAL COMMUNICATIONS

Starting in World War I, research efforts first focused on the design of sonars to detect obstacles for navigation and targets. The development of UWAC was later, during World War II, when the U.S. Navy deployed underwater telephones for communication with submarines. This first underwater acoustic telephone operated at 8.3 kHz and used single-sideband suppressed carrier (SSB-SC) amplitude modulation. Until the 1980s, research efforts on UWAC were mainly dominated by military applications. In later years, following the advances of digital signal processing (DSP) and very large-scale integrated (VLSI) technologies, new generations of digital UWAC systems were introduced targeting a variety of applications for the civilian market [1].

In the 1980s, it was commonly believed that the time variability and dispersive multipath propagation characteristics of the ocean would not allow the use of phase-coherent modulation techniques such as phase shift keying (PSK) and quadrature amplitude modulation (QAM). The prevailing design choice for modulation in acoustic modems at the time was frequency shift keying (FSK). It is well known that FSK suffers from bandwidth inefficiency. Coupled with the limited bandwidth availability of the underwater channel, FSK became a bottleneck, limiting the operation of UWAC systems to very low rates unacceptable for many modern applications.

### 1990S–2000S: TRANSITION INTO PHASE-COHERENT SYSTEMS

In the 1990s, with increasing demands for higher data rates, the research focus shifted toward design of coherent acoustic modems. One approach toward this purpose was to employ differentially coherent detection to ease the problematic carrier recovery in underwater acoustic channels. However, differential techniques inevitably result in performance degradation with respect to coherent detection. In [1], Stojanovic *et al.* adopted "purely" phase-coherent detection and designed a receiver built on adaptive joint carrier synchronization and equalization. The maximum likelihood (ML) algorithm for such a joint estimator suffers from excessive complexity, particularly for the underwater channel characterized by long channel impulses. Therefore, as a low-complexity solution, the receiver algorithm in [1] adopts a decision feedback equalizer (DFE), the taps of which are adaptively adjusted using a combination of a recursive least squares (RLS) algorithm and a second-order phase locked loop (PLL). Since the seminal work of Stojanovic *et al.* in [1], there has been a growing interest in phase-coherent UWA communication systems. Much research effort has particularly focused on the design of low-complexity equalization schemes, which is a key issue for underwater channels with large delay spreads. Particularly, sparse channel estimation/equalization and turbo equalization have been investigated by several research groups [2, references therein].

### CURRENT STATE AND THE FUTURE

Emerging data-heavy underwater applications impose further requirements on UWAC system design. To address such challenges, recent advances in terrestrial wireless RF systems have been further exploited in the context of UWAC. One of the research breakthroughs in the last decade is multiple-input multiple-output (MIMO) RF communications. MIMO systems involve the deployment of multiple antennas at the transmitter and/or receiver side, and achieve significant improvements in transmission reliability and throughput. For example, in [3], Roy *et al.* have investigated the application of space-time trellis codes and layered space-time codes in UWAC systems. Through simulations and real-life experiments, they have demonstrated significant improvements over conventional single-input single-output (SISO) systems in terms of data rates and reliability.

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Although MIMO systems successfully exploit the spatial dimension, their practical implementation over frequency-selective channels (as encountered in underwater channels) is challenging considering the potential high complexity of spatio-temporal equalizers. This has further sparked interest in research on the combination of MIMO and orthogonal frequency-division multiplexing (OFDM) for the underwater channel that has been investigated extensively in recent literature [4, references therein]. Multicarrier communications implemented through OFDM is particularly attractive for underwater channels due to the fact that, with the use of a cyclic prefix longer than the multipath spread of the channel, the intersymbol interference is completely removed. Therefore, channel distortion can be compensated at the receiver on a subcarrier-by-subcarrier basis, eliminating the need for complex time-domain equalizers. For time-invariant channels, orthogonality between the subcarriers in a multicarrier OFDM system is maintained, which simplifies the transmission. However, for time-varying channels, the benefits come at a cost. Particularly, for time-varying channels with high Doppler values, multicarrier system implementation requires the deployment of judiciously designed intercarrier interference management techniques [5].

Another promising approach in the design of future UWAC systems is the potential deployment of cooperative communication techniques. The basic ideas behind cooperative transmission can be traced back to Cover and El Gamal's work on the information theoretic properties of the relay channel in 1979. The recent surge of interest in cooperative communication, however, was subsequent to the publications of Sendonaris *et al.*'s and Laneman *et al.*'s in 2003–2004. Cooperative communication (also known as user cooperation or cooperative diversity) exploits the broadcast nature of wireless transmission and

| | Frequency range | Related parameters | Field measurement locations | Laboratory measurements |
|---|---|---|---|---|
| Schulkin-Marsh (1962) | 2 kHz–25 kHz | Frequency, temperature, salinity, and pressure | North Atlantic Ocean | Yes |
| Thorp (1965) | 100 Hz–10 kHz | Frequency | Bahamas (500 miles between Bermuda and Eleuthera Island) | No |
| Mellen-Browning (1976) | ≤ 10 kHz | Frequency | North and South Pacific Ocean | No |
| Fisher-Simmons (1977) | 10 kHz–400 kHz | Frequency, temperature, and pressure | N/A | Yes |
| Francois-Garrison (1982) | 200 Hz–1 MHz | Frequency, temperature, salinity, depth, and acidity | Arctic, Northeast Pacific Ocean, Atlantic Ocean, Mediterranean, Red Sea, and Gulf of Aden | Yes |

**Table 1.** *Formulas for the calculation of sound absorption coefficient expression.*

relies on the cooperation of users relaying each other's information. When a source node transmits its signal, this is received by the destination node and also overheard by other nodes in the vicinity. If these nodes are willing to share their resources, they can forward the overheard information to the destination as a second replica of the original signal and act as "relays" for the source node, extracting a diversity order on the number of relays. For scenarios in which there is no direct transmission between the source and destination, multihop communication can be used. This does not bring diversity gain, but the deployment of relays enables extension coverage.

A rich literature already exists on cooperative communication for terrestrial wireless RF systems, for example, recently published books such as *Cooperative Communications and Networking* by Liu *et al.*, *Cooperative Communications: Hardware, Channel and PHY* by Dohler and Li, *Cooperative Communications for Improved Wireless Network Transmission* by Uysal, and the references therein. However, there are only sporadic results reported for UWA applications. In [6], Carbonelli *et al.* have considered a decode-and-forward relaying scheme and, through an error propagation analysis, shown that this multihop communication scheme is superior to direct transmission due to the fact that the channel attenuation is much better addressed with the use of relays. In [7], Vajapeyam *et al.* have proposed a time-reversal distributed space-time block coding scheme for UWAC with the use of intermediate relay nodes implementing amplify-and-forward type protocols. They report performance improvements with their proposed scheme over single-hop UWAC systems via simulations and experimental results.

In [8], Zhang *et al.* investigated a decode-and-forward type protocol with spatial reuse and periodic transmit/receive schedules for linear multihop UWAC networks. They considered the frequency-dependent signal attenuation, interhop interference, half-duplex constraint, and large propagation delays in their analysis. They demonstrated improved performance in multihop UWAC networks. In [9], Cao *et al.* investigated the channel capacity of relay-assisted UWAC and discussed time synchronization issues. They further looked into the effects of source to destination distance, transmit power allocation, and relay location on channel capacity for relay-assisted UWAC systems. They observed a capacity increase in relay-assisted UWAC systems compared to traditional direct link communication.

Inspired by these initial results, this tutorial investigates the performance of cooperative UWAC systems, considering the inherently unique characteristics of the underwater channel, and demonstrates the potential of the user cooperation concept in future UWAC networks.

## Underwater Acoustic Channel Model

In this section, we discuss the inherent characteristics of the underwater acoustic channel, emphasizing the main differences and similarities with the well-known RF channel models.

### Path Loss

The path loss in an underwater acoustic channel results from spreading and absorption losses. Let $s$ and $a(f)$ denote the spreading factor and absorption coefficient, respectively. The overall path loss[2] in dB is given by

$$L_U = 10s\log_{10}d_{SD} + 10d_{SD}\log_{10}a(f) \qquad (1)$$

where $d_{SD}$ is the distance between the transmitter and receiver. The spreading factor depends on the geometry of propagation, and a spreading factor of 1.5 is often taken as representative of practical spreading based on a partially bounded sphere. The absorption coefficient $a(f)$ is a function of frequency as well as pressure, temperature, salinity, and acidity. Moreover, viscosity of pure water, relaxation of magnesium sulphate, and relaxation of boric acid mainly contribute to sound attenuation at frequencies 100 Hz–100 kHz. Several empirical formulas have been developed over the years for the characterization of the absorption coefficient including Schulkin-Marsh (1962), Thorp (1965), Mellen-Browning (1976), Fisher-Simmons (1977), and Francois-

[2] *If the performance estimate in a specific geographical location is required, Bellhop software can be used assuming that one has access to some detailed information such as boundary conditions, general bathymetry, refracting sound speed profile, grazing angle, weather conditions, source angle, and receiver angle.*

Garrison (1982). A comparison of different models can be found in Table 1. Thorp's formula is widely used in the literature mainly due to its simplicity. However, this formula is merely a function of frequency and ignores other parameters of the acoustic channel. The most comprehensive formula for the absorption coefficient is that of Francois-Garrison's (FG) [10] and applies for the frequency range of 200 Hz–1 MHz.

In Fig. 1, we illustrate the underwater path loss with respect to distance for operating frequencies of 15 and 30 kHz. We consider $s = 1.5$ and use the FG formula for the calculation of absorption coefficient assuming temperature of 15° C, depth of 50 m (i.e., shallow water), acidity of 8 pH, and salinity of 35 parts/thousand. From Fig. 1, it is observed that underwater path loss increases drastically with distance. For distances larger than 4 km, increasing the distance brings about 2.5 dB of loss per kilometer for 15 kHz. Doubling the frequency from 15 to 30 kHz will bring 17 dB of loss for a fixed distance of 4 km. To emphasize the different propagation characteristics of underwater acoustic and terrestrial RF wireless channels, we further illustrate the path loss for an RF channel based on the well-known Okumura-Hata model. In the calculation of terrestrial RF path loss, we consider a medium-small city, carrier frequencies of 900 MHz and 1.5 GHz, and assume a base station antenna height of 70 m and mobile antenna height of 1.5 m. Under these typical scenarios, it is observed that the path loss in the underwater channel is much larger than that in the RF channel and becomes a particularly limiting factor in UWAC for larger values of operating frequencies. Such large path losses provide a strong motivation for relay-assisted transmission in UWAC.

### Fading

The average received power is determined by the path loss, but the instantaneous level of the received power fluctuates as a result of small-scale fading effects due to multipath propagation in underwater environments. In shallow water, multipath occurs due to signal reflections from the surface, bottom, and any objects in the water. In deep water, it is primarily due to a phenomenon known as ray bending, that is, the tendency of acoustic waves to travel along the axis of the lowest sound speed. Regardless of its origin, multipath propagation causes multiple echoes of the transmitted signal to arrive at the receiver with different delays overlapping each other. This leads to a frequency-selective channel model where distinct frequency components of the transmitted signal undergo different attenuations. The velocity of sound in underwater is around 1500 m/s. This relatively slow speed results in typical delay spreads of 10–100 ms. These are four orders of magnitude higher than those typically experienced in RF channels. The UWA channel also exhibits sparse channel characteristics; therefore, the impulse response consists of a large number of zero taps since the channel energy is mainly localized around several small ranges of delays.

The underwater acoustic channel is also subject to time selectivity due to surface scattering and internal waves. Doppler spreads are determined by wind speed and sea surface conditions.

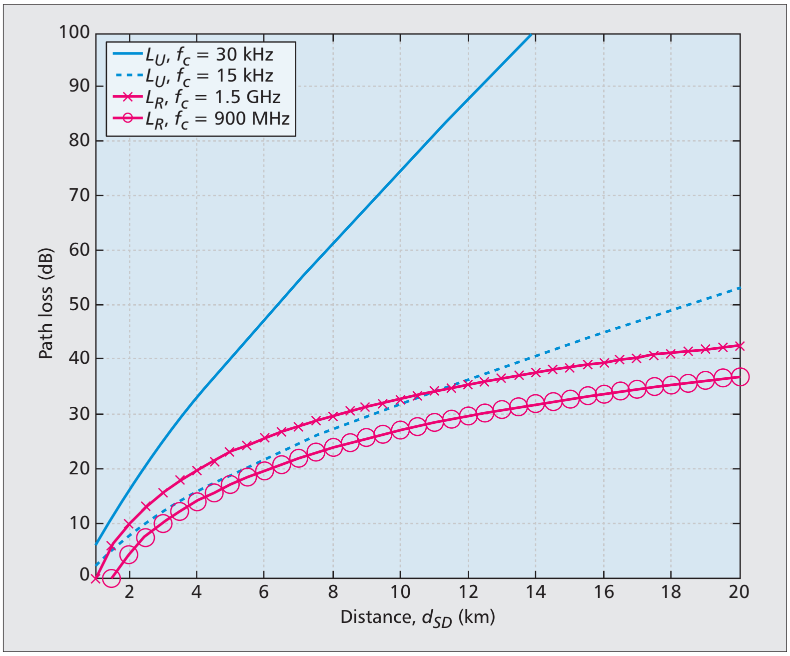


**Figure 1.** *Path loss comparison of underwater acoustic channel and terrestrial radio frequency channel.*

In mobile underwater applications, e.g., autonomous underwater vehicles, vehicle speed becomes the primary factor determining the time-coherence properties of the channel. It should be further emphasized that for underwater acoustic channels, the effects of Doppler shift is considerably different compared to the wireless RF channels due to the five orders of magnitude difference in the speed of light vs. the speed of sound. That is, the effect of even low Doppler shifts (corresponding to a relatively low transmitter/receiver speed) will demonstrate itself as a "Doppler scaling." For instance, for a speed of 9 m/s, one will observe a Doppler scaling factor of 0.006, meaning that the length of the received signal will be 0.6 percent longer or shorter than the transmitted signal length depending on the direction of motion. Receiver design for a UWAC system has to address issues related to the Doppler scaling for proper operation; if there is no compensation, the performance degrades considerably. For instance, in an OFDM system, uncompensated Doppler scaling effect will result in extremely high intercarrier interference levels, rendering the system useless. An effective method to solve the Doppler scaling problem to accomplish reliable transmissions is through a "resampling" operation, as discussed in [11].

The resulting time-selective and frequency-selective (also known as doubly selective) channel is commonly modeled as a tapped-delay line model with tap gains modeled as stochastic processes with certain distributions and power spectral densities. Although there is no general consensus within the research community about the theoretical distribution for statistical characterization of tap gains in underwater channels, the small-scale effects are often modeled as Rayleigh or Rician fading [6]. In this article, we also consider the Nakagami fading model as a generalized model.

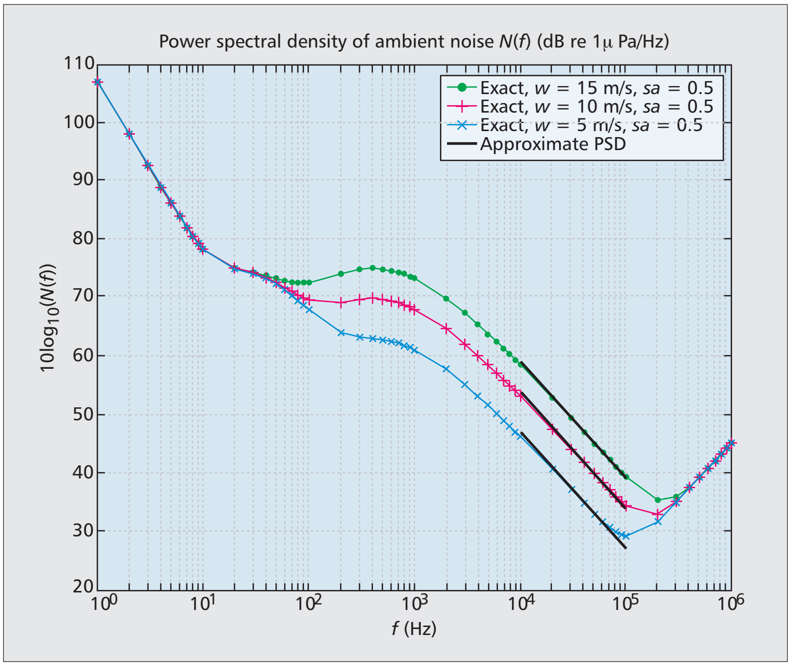


**Figure 2.** *Comparison of exact and proposed approximate ambient noise PSD.*

### NOISE MODEL

In underwater acoustic channels, there are many sources for ambient noise such as seismic events, shipping, thermal agitation, rainfall, and sound waves by marine animals among others. According to the widely used Wenz model [12], there are four main noise sources, each of which becomes dominant in different frequency ranges. In the frequency range below 10 Hz, turbulence in the ocean and atmosphere is the primary noise source. In the frequency range of 10–100 Hz, noise caused by distant ship traffic dominates and is modeled by shipping activity factor *sa*, which takes values between 0 and 1 for low and high activity, respectively. Surface agitation caused by wind-driven waves becomes the major noise source in the frequency range 100 Hz–100 kHz, which spans the major operating frequencies in UWAC systems. Wind speed $w$ is the main determining parameter for this type of noise. At frequencies above 100 kHz, thermal noise as a result of the molecular motion in the sea becomes the dominating factor.

In Fig. 2, we present the noise power spectral density (PSD) based on Wenz's model in the frequency range of 1 Hz–100 kHz. We assume a shipping activity of 0.5 and consider various wind speeds. Although a white Gaussian noise assumption is dominantly used in the literature (mainly for simplification purposes), it is apparent from Fig. 2 that the PSD significantly changes over the considered frequency range and exhibits non-white behavior. Even in the frequency range of 10–100 kHz where most current practical UWAC systems operate, the non-white nature of the noise is obvious and should be considered for a realistic performance analysis and system design/optimization. For a tractable and practical noise model, we can approximate the overall noise PSD by considering only the PSD of the noise due to waves. However, this PSD yields a so-called $1/f$ fractal random process, also known as $1/f$ noise or pink noise [13]. This is a special class of random processes characterized by fractional-power-law, self-similarity, or fractal behavior, and exhibits non-stationarity. Following a similar approach as in [13], it can be approximated as $N(f) \approx f_0\sigma_n^2/\pi\,(f^2 + f_0^2)$, where $f$ is the frequency in kilohertz, $\sigma_n^2$ is the variance of the zero-mean complex Gaussian random process, and $f_0$ is the lowest cut-off frequency (i.e., the frequency at which the shape of the spectrum changes to yield finite integral of approximate PSD). In Fig. 2, we further illustrate our proposed approximate PSD and confirm a close match between the approximate and exact PSDs in the region of 10–100 kHz.

## COOPERATIVE OFDM-BASED UWAC SYSTEM

As discussed earlier, there is growing attention on how to exploit cooperative communication techniques in the context of UWAC. In this section, we investigate the performance of a multicarrier cooperative UWAC system and demonstrate the premise of cooperation techniques for future UWAC networks. Specifically, we consider a cooperative precoded OFDM communication system in a single-relay scenario.

Following the discussions earlier, we assume frequency-selective sparse channels for source-to-destination (S→D), source-to-relay (S→R), and relay-to-destination (R→D) underwater links with intra-distances given by $d_{SD}$, $d_{SR}$, and $d_{RD}$. These channels are modeled by finite impulse response (FIR) filters with orders of $\tilde{L}_{SD}$, $\tilde{L}_{SR}$, and $\tilde{L}_{RD}$, respectively. Each complex fading channel for delay taps is assumed to have an amplitude following either Rayleigh, Rician, or Nakagami-$m$ distribution ($m \geq 0.5$). Let $\Omega_{SD}$, $\Omega_{SR}$, and $\Omega_{RD}$ denote the power delay profile (PDP), and let the elements of $\mathbf{v}_{SD}$, $\mathbf{v}_{SR}$, and $\mathbf{v}_{RD}$ vectors represent the locations of significant delay taps with $|\mathbf{v}_{SD}| = L_{SD} + 1$, $|\mathbf{v}_{SR}| = L_{SR} + 1$, and $|\mathbf{v}_{RD}| = L_{RD} + 1$ where $|.|$ denotes the dimension of a vector. Due to sparseness of typical underwater channels, we have $\tilde{L}_{SD} \gg L_{SD}$, $\tilde{L}_{SR} \gg L_{SR}$, and $\tilde{L}_{RD} \gg L_{RD}$.

We consider the orthogonal cooperation protocol (OCP) of [14] as shown in Fig. 3a. The nodes operate in half-duplex mode due to the large difference between transmitted and received signal levels. The cooperation protocol is built on a two-phase transmission scheme. In the first phase (broadcasting phase), the source broadcasts to the destination and the relay nodes. In the second (relaying) phase, the relay node forwards the received signal after proper processing (i.e., the type of processing depends on the employed relaying mode) to the destination. The destination node uses the received signals over two phases to make the decision on the transmitted signal.

The main processing steps in our system can be summarized as follows: At the source node (Fig. 3b), the input signal vector $\mathbf{x}$ is first applied to a linear constellation precoder $\Phi$ satisfying $\mathrm{Tr}\{\Phi\Phi^H\} = N$, where $N$ denotes the number of subcarriers. The resulting OFDM symbol is

*In DF relaying, the relay node fully decodes, re-encodes, and retransmits the source node's message. To avoid error propagation, the relay is activated only if it has decoded correctly otherwise remains silent. This is referred to as selective DF relaying.*

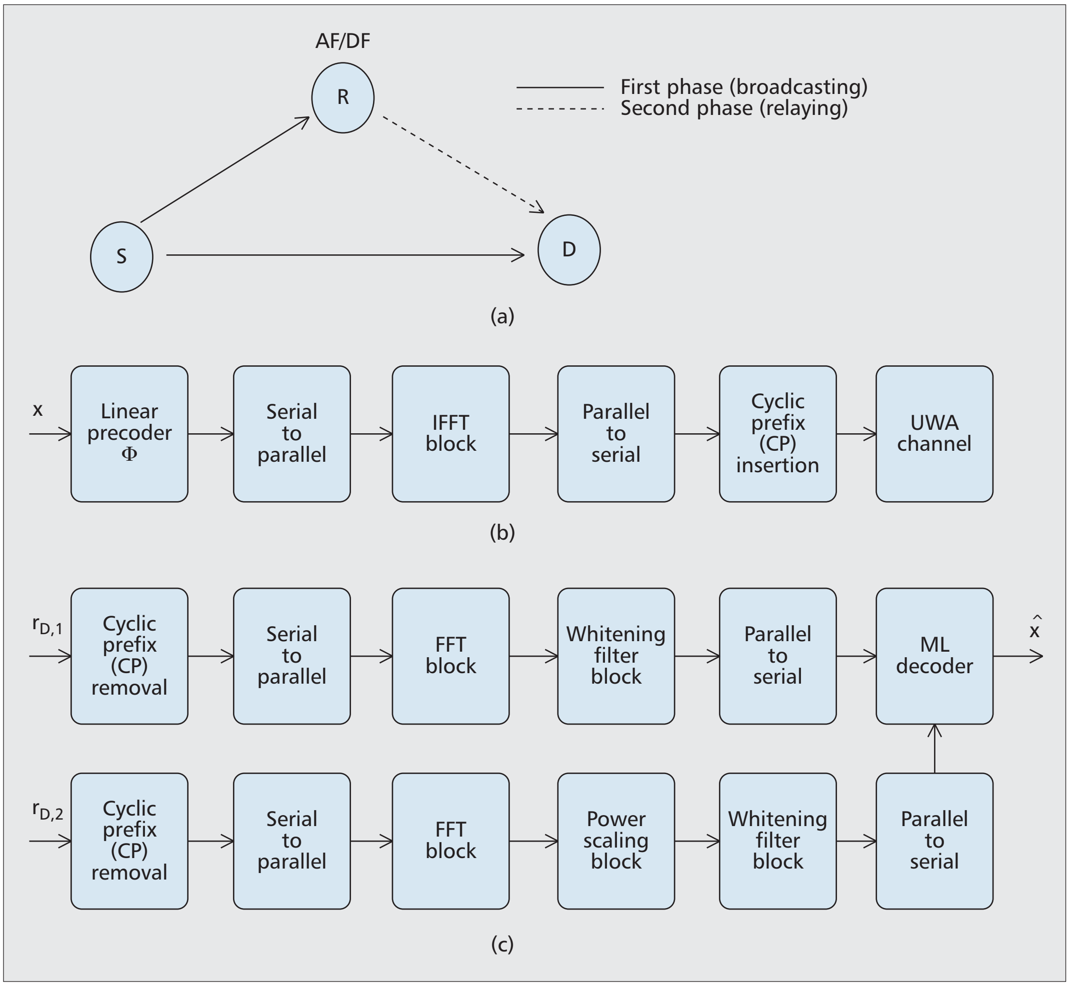


**Figure 3.** *Description of system model: a) half-duplex orthogonal cooperation model; b) OFDM block diagram at source node; c) OFDM block diagram at destination node.*

applied to a serial-to-parallel converter followed by an inverse fast Fourier transform (IFFT) block. The parallel stream is converted back into a serial stream, and a cyclic prefix (CP) of length $L_c = \max(\tilde{L}_{SD}, \tilde{L}_{SR}, \tilde{L}_{RD})$ is added to prevent interblock interference.

During the broadcasting phase, the source node transmits this signal, which is received by the destination node D and relay R in the presence of fading and noise. At the relay node, either amplify-and-forward (AF) or decode-and-forward (DF) mode can be used. In DF relaying, the relay node fully decodes, re-encodes, and retransmits the source node's message. To avoid error propagation, the relay is activated only if it has decoded correctly; otherwise, it remains silent. This is referred to as *selective* DF relaying and, in practice, can be implemented through the use of cyclic redundancy check with a very small overhead. In AF relaying, the relay performs an appropriate power scaling on the received signal and forwards it to the destination node. The destination node (Fig. 3c) makes the decision using the received OFDM blocks over broadcasting and relaying phases. After CP removal and FFT processing, the resulting signals are applied to a whitening filter (to remove the effects of correlated ambient noise) and finally to a maximum likelihood detector.

In the following, we present the outage performance of a cooperative OFDM UWAC system through Monte Carlo simulations. We consider a center frequency of 15 kHz with a bandwidth of 4 kHz, $N = 256$ subcarriers, and a transmission distance of $d_{\mathrm{SD}} = 3$ km, and assume that the relay node is located on the straight line connecting the source and destination nodes. For environmental parameters, we assume a temperature of 15° C, a depth of 50 m, an acidity level of 8 pH, a salinity of 35 parts/thousand, and a spreading factor of 1.5. We assume that all underlying links experience a multipath delay spread of 13 ms with a delay profile of [0, 5.25 ms, 8.5 ms, 13 ms]. This corresponds to $\tilde{L}_{SD} = \tilde{L}_{SR} = \tilde{L}_{RD} = 52$ and $L_{\mathrm{SD}} = L_{\mathrm{SR}} = L_{\mathrm{RD}} = 3$. The location vectors for the significant taps are given by $\mathbf{v}_{\mathrm{SD}} = \mathbf{v}_{\mathrm{RD}} = \mathbf{v}_{\mathrm{RD}} = \mathbf{v} = [0\ 21\ 34\ 52]$ with the corresponding PDP of $\mathbf{\Omega} = [\Omega_0\ \Omega_{21}\ \Omega_{34}\ \Omega_{52}] = [0.25\ 0.5\ 0.15\ 0.1]$.

In Figs. 4 and 5, we present the outage probability for the cooperative OFDM system with OCP assuming both AF relaying and selective DF relaying over Nakagami-$m$, Rayleigh, and Rician fading channels. Under Nakagami-$m$ fading, we consider the cases $m = 0.5$ (one-sided Gaussian) and $m = 1.5$. One can note that Nakagami-$m$ fading with $m = 1$ is equivalent to Rayleigh fading. For Rician fading, the Rician

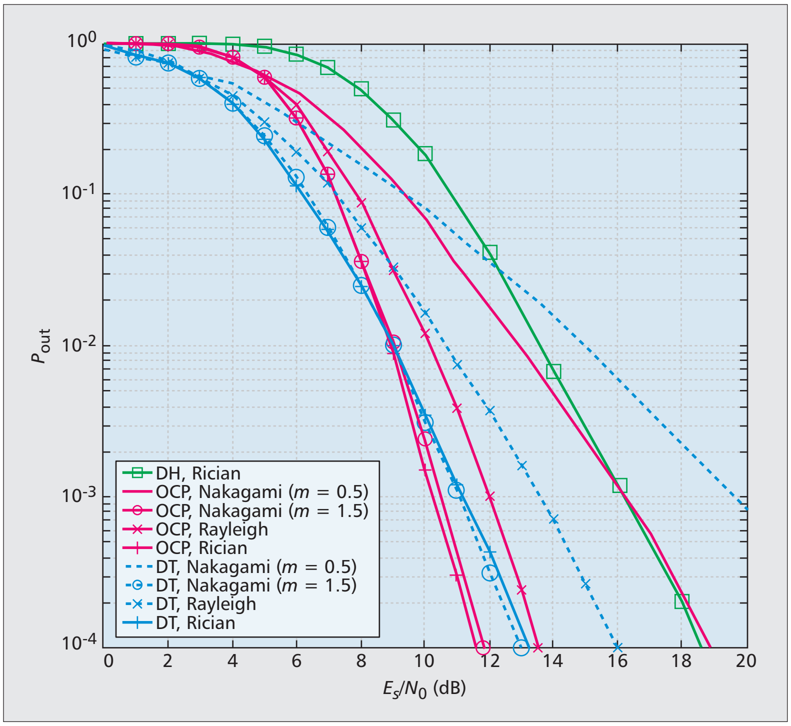


**Figure 4.** *Outage probability for the cooperative OFDM UWAC system with AF relaying. (OCP: orthogonal cooperation protocol, DH: dual-hop, DT: direct transmission).*

factor is assumed to be $K = 2$. We assume that the relay is located midway between the source and the destination. For comparison purposes, we also include the performance of direct (non-cooperative) OFDM transmission. Our results in Fig. 4 clearly demonstrate the superiority of the AF cooperative system over direct transmission within the practical signal-to-noise ratio (SNR) range. Specifically, we observe that the cooperative system outperforms the direct transmission for SNR values larger than 8.76, 8.84, 9.19, and 9.3 dB over Rician, Rayleigh, Nakagami-$m$ ($m = 1.5$), and Nakagami-$m$ ($m = 0.5$) fading channels, respectively. This is a result of the extra spatial diversity the cooperative OFDM system is able to extract. Outage performance under Rayleigh and Nakagami-$m$ fading with $m \leq 1$ reflects the effect of severe fading conditions. Our results in Fig. 5 depict similar observations for the case of DF relaying, but the cooperative system outperforms direct transmission at lower SNR values. At high SNRs, the slope of the performance curves indicates diversity orders of $(L_{SD} + 1) + \min(L_{SR} + 1, L_{RD} + 1) = 8$ and $L_{SD} + 1 = 4$ for cooperative and direct transmissions, respectively.

In Figs. 4 and 5, we have also included the outage performance of a dual-hop OFDM UWAC system in which there is no direct transmission between the source and the destination. As observed from Fig. 4, under the assumption of AF relaying and Rician fading channel, we observe a loss in performance compared to direct transmission, although the average SNR per hop has increased. This is due to the decrease in spectral efficiency and the additional channel uses in half-duplex mode. In general, the reduction in spectral efficiency is observed by a scaling pre-log factor of the number of relays. However, in dual-hop with DF relaying (Fig. 5), the outage performance becomes slightly better than that of direct transmission because the increase in average SNR per hop dominates the loss of spectral efficiency.

In Fig. 6, we study the effect of frequency band and relay location on the outage performance assuming Rician fading channel with $K$ =2. For operating frequencies, we consider 15 kHz, 20 kHz, and 25 kHz (with the same bandwidth). It is observed that for a targeted outage probability of $10^{-3}$, the additional SNR required for a 25 kHz system is 5.6 dB and 3 dB more than that required for 15 kHz and 20 kHz systems, respectively. This is a result of the highly dependent nature of underwater path loss on the frequency, as discussed earlier (Fig. 1). On the other hand, to investigate the effect of relay location, we adopt the parameter $\beta = d_{RD}/d_{SR}$ expressed in dB. The more negative this ratio is, the more closely the relay is placed to the destination terminal. Positive values of this ratio indicate that the relay is closer to the source terminal. Our results demonstrate that midway location (i.e., $\beta = 0$ dB) provides the most favorable condition over the depicted SNR range.

## Conclusions and Future Research Directions

This tutorial has presented a contemporary overview of UWAC and provided performance results on multicarrier cooperative UWAC systems. Our simulation results have demonstrated significant performance gains available through cooperation. In our view, such benefits make cooperative transmission an ideal solution for underwater applications that is capable of combating channel unreliability and large path losses in underwater channels and meeting future UWAC application requirements. It is important to emphasize that the numerical examples provided in the previous section assume a quasi-static fading channel. In particular, it is of interest to conduct research addressing significant time variations in the channel (e.g., the effects of Doppler scaling). For instance, it would be of interest to understand the receiver structure at the destination as well as its theoretical assessment when the source node and relay node transmit simultaneously in the same frequency band while moving in different directions with respect to the receiver. A further note is that the characteristics of underwater acoustic channels are not fully understood, and the models available are only approximations. This is very different than the usual wireless (radio) channels for which we have extremely precise characterizations for different environments and frequency bands. This observation brings up the point that it would be very desirable to verify through at-sea experiments the proposed cooperative UWAC systems. Finally, on top of the physical layer of cooperative UWAC system, we need an efficient medium access protocol. Due to the extremely long propagation delays, the design of such protocols is usually much more difficult than those for RF channels even without the use of relays; hence, the problem is compounded even more for the case of relay-assisted communications.

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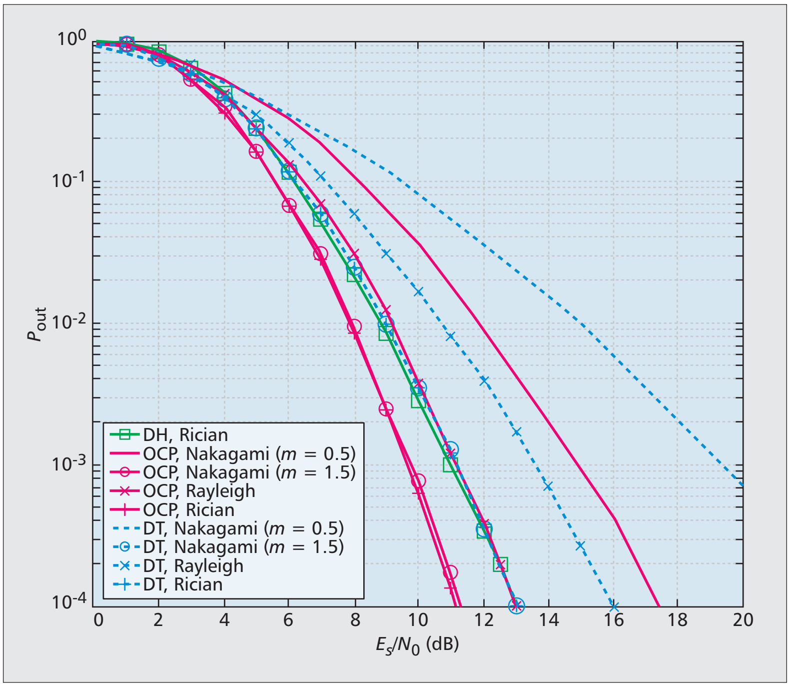


**Figure 5.** *Outage probability for cooperative OFDM UWAC system with DF relaying.*

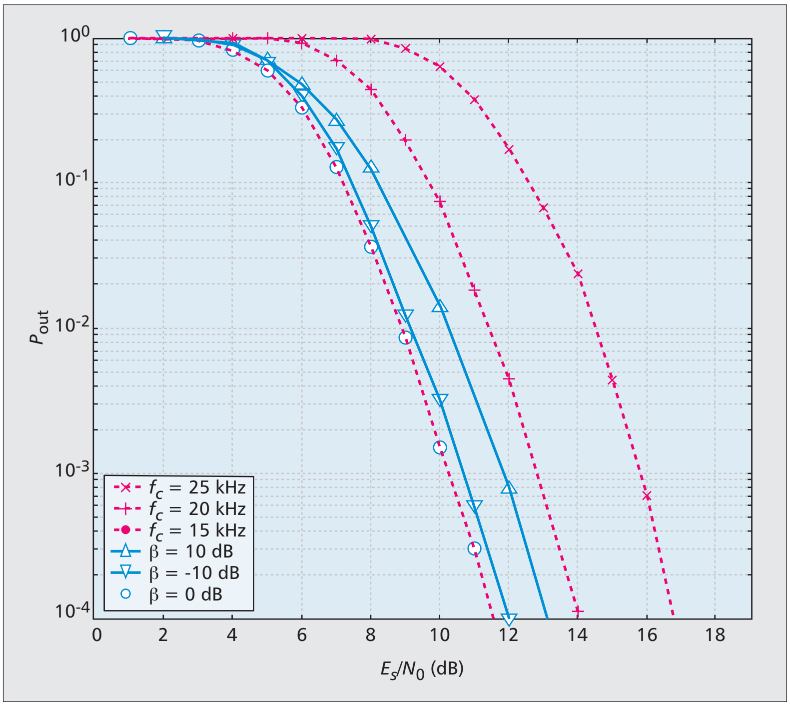


**Figure 6.** *Effect of carrier frequency and relay location on the outage probability of AF cooperative OFDM UWAC system with OCP over Rician fading channel.*

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