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Review:

Underwater acoustic communication and the general performance evaluation criteria*

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Abstract: Driven by the huge demand to explore oceans, underwater wireless communications have been rapidly developed in the past few decades. Due to the complex physical characteristics of water, acoustic wave is the only media available for underwater wireless communication at any distance. As a result, underwater acoustic communication (UAC) is the major research field in underwater wireless communication. In this paper, characteristics of underwater acoustic channels are first introduced and compared with terrestrial communication to demonstrate the difficulties in UAC research. To give a general impression of the UAC, current important research areas are mentioned. Furthermore, different principal modulation-based schemes for short- and medium-range communications with high data rates are investigated and summarized. To evaluate the performance of UAC systems in general, three criteria are presented based on the research publications and our years of experience in high-rate short- to medium-range communications. These three criteria provide useful tools to generally guide the design and evaluate the performance of underwater acoustic communication systems.

Key words: Underwater acoustic communication; Underwater acoustic channels; High data rate; Communication range; Bandwidth efficiency; General evaluation criterion

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1 Introduction

Seventy-five percent of the Earth's surface is covered with water and there are a lot of precious resources underwater. Oceans provide a lot of energy resources, from mineral resources, like oil and gas, to renewable energy. Underwater communication has rapidly been more important in the last few decades due to its key role in many applications, for example, environmental monitoring, offshore exploration, oceanographic data collection, and disaster warning. Although there is enormous demand for underwater communications in ocean exploration, the underwater acoustic communication (UAC) is quite different from terrestrial communication and very difficult. Constrained by the physical characteristics of water, communication media other than acoustic waves suffer from severe propagation loss and refraction distortion. Radio frequency and optical waves can transmit messages very fast over a very short range underwater, but acoustic wave is still the only medium for underwater wireless communication at any range.

Compared with terrestrial radio frequency communication channels, underwater acoustic channels are affected by severe transmission loss, time-varying multipath propagation, severe Doppler spread, limited and distance-dependent bandwidth, and high propagation delay. These disadvantages make the underwater acoustic channel one of the

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most difficult channels to use. The propagation loss depends on the signal frequency and transmission distance. As a result, it is impossible to simultaneously achieve high data rates and long communication distances. Research has been active in high-data-rate short- and medium-range UAC systems and low-data-rate long-range UAC systems. Based on the physical layer, further research on underwater acoustic networks, for example, the medium access control (MAC) layer, routing layer, and application layer, has been conducted to construct functional and reliable underwater acoustic networks.

The limited bandwidth for long-range underwater communication restricts the increase of data rate. On the contrary, the relatively large available bandwidth for short- and medium-range communication systems makes it possible to investigate high-data-rate schemes. Among various high-rate technologies, single-carrier time-domain equalization (SC-TDE), single-carrier frequency-domain equalization (SC-FDE), orthogonal frequency division multiplexing (OFDM), and orthogonal signal division multiplexing (OSDM) are four principal modulation/detection techniques for short- and medium-range UAC systems. Much related research focused on the advanced design of receivers with the goal of providing reliable and efficient short- to medium-range underwater communications.

Although much research has pushed the performance limits of UAC systems, little has clearly stated the corresponding evaluation criterion. With years of UAC research experience, three criteria, i.e., the bit error rate (BER) versus signal-to-noise ratio (SNR), the product of the data rate and communication range, and the product of bandwidth efficiency and communication range, are presented to evaluate the performance of UAC systems in general. These three criteria are usually jointly applied as one tool to provide assistance to researchers in UAC system design.

2 Characteristics and difficulties of the underwater acoustic communication

There are several media for underwater communications. Cable communication can provide robust communication performance, but its cost is very high and it is difficult to move once it is established. In underwater wireless communication, media other than acoustic waves are less capable of long-range underwater transmission due to severe propagation loss and scattering, including radio frequency electromagnetic waves and optical waves. Radio frequency electromagnetic waves, which are customary in terrestrial communication, have high attenuations especially at higher frequencies in ocean due to the conductive nature of salt water. Thus, they are usually used for only short-range (< 100 m) and very-short-range (< 1 m) transmission (Zoksimovski et al., 2012). Optical waves are another mean of short-range communication, but they are affected by the scattering caused by the suspended particles and plankton. In addition, the high level of ambient light is a disadvantage for optical communication. Compared with other media, acoustic waves have relatively low absorption in the underwater environment, which enables communication over long-range links. At present, acoustic waves are the primary choice for wireless underwater communication.

Underwater acoustic communication has been regarded as significantly different from terrestrial wireless communication. Except for the different carrier media, underwater acoustic channels have unique characteristics. Underwater acoustic channels are commonly regarded as one of the most challenging channels for communication. Compared with terrestrial radio channels, underwater acoustic channels have severe transmission loss, limited and distance-dependent bandwidth, time-varying multipath propagation, and severe Doppler spread. Although acoustic channel models are needed for developing and evaluating UAC techniques, there is not a widely accepted underwater acoustic channel model at present due to the complexity and variety of realistic acoustic channels. However, systematic analysis of experimental data has been provided to characterize underwater acoustic channels. The measurements of realistic channels proposed by Yang (2012) and van Walree (2013) revealed the large variety of underwater acoustic propagation channels.

2.1 Transmission loss

Transmission loss is caused mainly by attenuation and geometric spreading during the propagation of acoustic signals in water. Attenuation is generally caused by absorption when acoustic energy is transferred into heat. A distinguishing property of acoustic channels is that the absorptive loss for acoustic waves will increase with both propagation distance and frequency. In underwater acoustic communication, whose carrier frequencies are less than 50 kHz, the absorption coefficient α can be expressed using Thorp's empirical formula (Thorp, 1967) with respect to frequency f in kHz as

$$\alpha(f) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + \frac{2.75}{10^4}f^2 + \frac{3}{10^3}. \quad (1)$$

The absorption coefficient is shown in Fig. 1. It is obvious that the absorption coefficient increases rapidly with the frequency. Hence, the available frequency for transmission is limited for underwater acoustic communication.

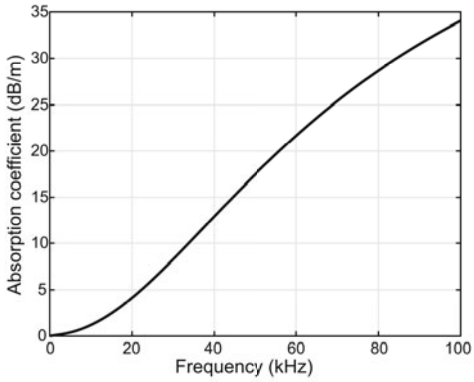

Fig. 1 Absorption coefficient $\alpha(f)$

Geometric spreading loss is caused by the spreading of acoustic energy into a larger area as a consequence of acoustic wave expansion. Generally, there are two types of geometric spreading loss: spherical and cylindrical. Spherical spreading occurs when the source is omnidirectional and acoustic waves spread spherically, and it is usually applied for deep-sea acoustic communication. Cylindrical spreading occurs when acoustic waves spread horizontally and it is applicable for shallow water acoustic communications. In practical underwater channels, geometric spreading is a hybrid of spherical and cylindrical spreading. The geometric spreading is dependent on only propagation distance and it is frequency-independent.

The transmission loss (TL) for a signal can be expressed as

$$10\log \mathrm{TL}(d,f) = k\cdot 10\log d + d\cdot\alpha(f), \quad (2)$$

where f denotes the frequency in kHz, and d represents the transmission distance in meters. The transmission loss is expressed in decibels. The first term of Eq. (2) describes the geometric spreading loss and k is the spreading factor, which indicates the geometry of propagation; k is usually set as 1.5 (1 for cylindrical and 2 for spherical spreading). The second term of Eq. (2) demonstrates the attenuation caused by the absorption factor α and distance d.

2.2 Ocean environment noise

Acoustic noise in the underwater communication channel can be either ambient noise or man-made noise. Man-made noise is caused mainly by machinery. Even in the quiet deep sea, ambient noise still exists. There are four main sources for ambient noise in the ocean: turbulence, shipping, waves, and thermal noise. Because of the multiple sources, the ambient noise can be approximated as a non-white Gaussian variable. The level of underwater ambient noise may also vary based on time and location. The power spectral density of these four noise components is given by an empirical formula (Stojanovic, 2006b) in dB re μPa/Hz (the sound pressure at reference sound power per Hz) as a function of frequency in kHz as

$$10\log N_{\mathrm{t}}(f) = 17 - 30\log f, \quad (3)$$

$$10\log N_{\mathrm{s}}(f) = 40 + 20(s-5) + 26\log f - 60\log(f+0.03), \quad (4)$$

$$10\log N_{\mathrm{w}}(f) = 50 + 7.5\sqrt{w} + 20\log f - 40\log(f+0.4), \quad (5)$$

$$10\log N_{\mathrm{th}}(f) = -15 + 20\log f, \quad (6)$$

where N_{t}, N_{s}, N_{w}, and N_{th} denote the turbulence, shipping, waves, and thermal noise, respectively, w is the wind speed, and $s\in[0,1]$ is the shipping activity factor. Then the power spectral density of ambient noise relative to f is given by

$$N(f) = N_{\mathrm{t}}(f) + N_{\mathrm{s}}(f) + N_{\mathrm{w}}(f) + N_{\mathrm{th}}(f). \quad (7)$$

Fig. 2 shows the overall power spectral density of ambient noise. As shown in Eq. (7), the noise level is dependent on the signal frequency. In general, the noise level decreases with the increase in frequency. As shown in Eq. (2), choosing a lower frequency could reduce the transmission loss, but the noise level increases. Thus, multiple factors must be comprehensively considered when choosing a frequency band.

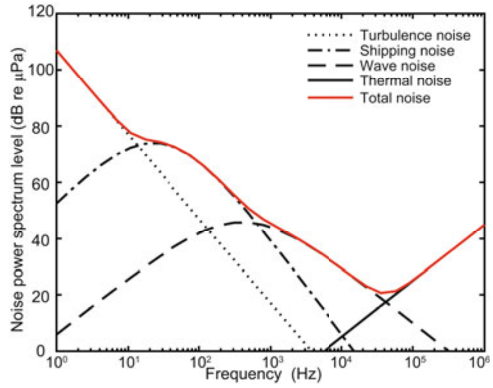

Fig. 2 Power spectral density of the ambient noise in oceans

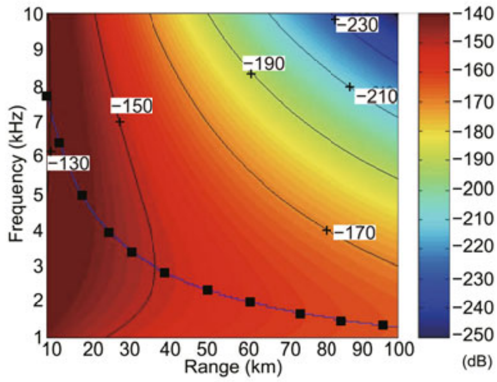

Fig. 3 Optimal frequency versus range

2.3 Optimal carrier frequency and frequency band

As discussed above, both the transmission loss (attenuation) and the noise power spectral density depend on the frequency. The transmission loss and noise can basically determine the SNR observed over a distance d when the transmission power and signal frequency are known. The narrow-band SNR can be expressed as

$$\mathrm{SNR}(d,f)=\frac{P/\mathrm{TL}(d,f)}{N(f)\Delta f}, \tag{8}$$

where P and f are the power and frequency of the transmitted signal, respectively, and Δf is the receiver noise bandwidth. Then according to Eq. (8), we can calculate the factor $1/(\mathrm{TL}(d,f)N(f))$, which gives the combined effect of transmission loss and noise in acoustic communications. Fig. 3 shows the relationship between the optimal working frequency and transmission distance d. The lines with the plus (+) notation represent the different transmission losses in decibels (note that the 130-dB curve is on the leftmost side). As the transmission distance d increases, the optimal working frequency decreases. The line with square in Fig. 3 is the optimal center frequency we can choose in different communication ranges (Stojanovic, 2006b).

2.4 Significant multipath propagation

Complex multipath propagation is an important physical phenomenon when sound waves propagate in oceans. Because of the low speed of sound, the propagation delays in different paths are quite different. In underwater acoustic channels, the multipath spreads depend on the direction of propagation. Vertical channels usually have little time dispersion. On the contrary, the multipath spreads increase to tens or hundreds of symbol intervals for horizontal channels. The propagation delay of common underwater acoustic horizontal channels is 10 ms, while it can even reach 50–100 ms in some cases. Such a large delay spread leads to severe signal time dispersion, causing serious inter-symbol interference (ISI).

The formation of multipath propagation in the ocean depends mainly on two effects: acoustic reflection from sea surface and seafloor, and acoustic refraction in seawater caused by sound speed variation with depth. The acoustic refraction occurs mainly in deep oceans, where the sound wave always bends in the direction of limited sound speed. Generally, the sound speed is affected by temperature, salinity, and pressure. Thus, the deep sea sound velocity distribution has a minimum value at a certain depth. There exists a special acoustic channel in the deep ocean, called the 'deep-sea acoustic channel axis', which is affected by the deep ocean sound velocity distributions and the bending of sound waves. When sound sources are located near the depth at which the minimum value of sound velocity occurs, acoustic signals can be transmitted far along the channel axis, where the multipath expansion and phase fluctuation are small. Using the feature of deep-ocean acoustic channels, long-range underwater acoustic communication (30–1000 km) is possible. Fig. 4 shows a simulated ray of sound in deep oceans based on BELLHOP software. The sound sources are located in the acoustic channel axis. Therefore, the location of hydrophones needs to take this effect into account, especially for long-range communication.

The channel impulse response for time-varying

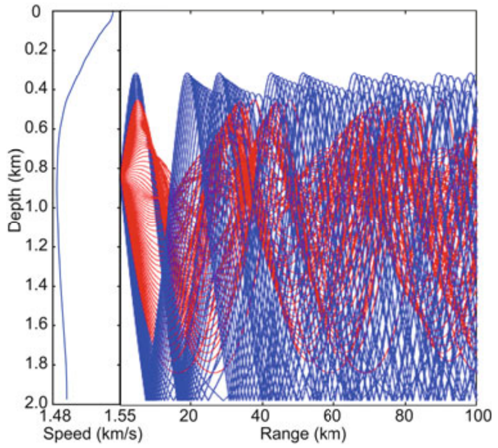

Fig. 4 Sound ray propagation in deep oceans
The red curves represent sound rays that are bent only by the variation of sound speed, while the blue lines are the sound rays affected by sound speed and reflection. References to color refer to the online version of this figure

multipath underwater acoustic channels can be expressed as

$$h(\tau, t) = \sum_{p} h_p(t)\delta(\tau - \tau_p(t)), \tag{9}$$

where $h_p(t)$ and $\tau_p(t)$ denote the time-varying path amplitude and time-varying path delay, respectively. This expression is usually used in simulation studies. Fig. 5 shows a measured channel from a lake experiment. It indicates that the channel has severe multipath and the maximum delay is almost 30 ms.

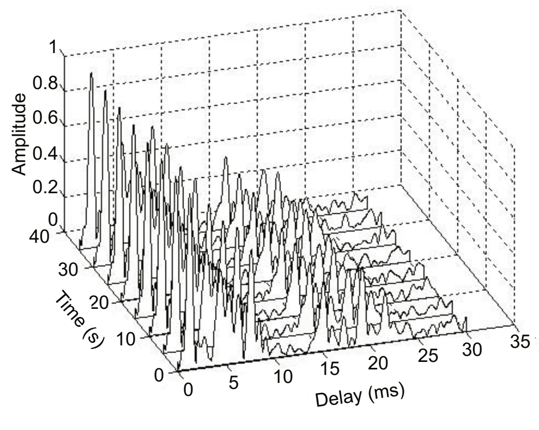

Fig. 5 Multipath from an experiment

2.5 Severe Doppler effect

Doppler effect occurs when there is a movement of the transmitter or receiver. The resulting Doppler effect causes frequency shifting and bandwidth spreading. The Doppler effect of underwater acoustic communication is affected by the transmitter-receiver relative velocity and the speed of sound. Doppler factor ρ can be expressed as

$$\rho = \frac{v}{c}, \tag{10}$$

where v is the transmitter-receiver relative velocity and c the speed of sound.

The low speed of sound which is about 1.5 km/s in the water results in severe Doppler effects. Compared with terrestrial radio frequency communication, whose speed is approximately 3×10^5 km/s, Doppler factors in acoustic channels are much larger than those in terrestrial radio channels. Generally, the speed range of an underwater vehicle is 1.5–30 m/s. The corresponding Doppler factor $\rho = 1 \times 10^{-3}$–2×10^{-2}. In a radio frequency communication system, the Doppler factor $\rho = 1 \times 10^{-7}$–6.7×10^{-7} assuming that the speed of the vehicle is 30–200 m/s. This shows that the Doppler shift in the UAC is several orders of magnitude higher than that of the Doppler shift in radio frequency (RF) communications. The large Doppler factor results in two major non-negligible effects. First, it causes shifting of frequencies, which results in severe interferences among different signal frequency components. This is a major difficulty in high-data-rate mobile underwater acoustic communications. Second, Doppler effects result in compression or dilation of transmitted signals in the time domain, also known as 'Doppler spreading'. Unlike terrestrial radio frequency communication, large Doppler spreading demonstrates the need for explicit symbol synchronization in UAC communication.

2.6 Underwater acoustic channel models

As discussed before, there are no universal underwater acoustic channel models because acoustic channels are complex and variable. However, different methods have been proposed to characterize underwater acoustic channels as well as possible, such as the ray tracing model described by Porter and Liu (1994) and the wave-front-based model proposed by Tindle (2002). Apart from these theoretical models, analysis of realistic field measurement provides detailed propagation models for specific channel conditions. van Walree (2013) revealed a large variety of propagation effects and scattering conditions in acoustic communication channels based on years of field measurement of different shallow-water acoustic channels. Sea-trial data collected in shallow water under various conditions analyzed by Yang (2012) illustrate the effects on signal properties caused by ocean environments, including amplitude and phase variations and temporal coherence of individual paths.

Underwater acoustic channel simulators can contribute to evaluations of UAC algorithms before field experiments. Although channel simulators cannot replace real-field measurement, they may reduce the high cost of repetitive UAC field experiments. BELLHOP is a widely used simulator based on ray tracing models. Various files describing the environment must be provided to produce a large amount of useful output including transmission loss and arrivals. Because it is an open-source software available online (Porter et al., 2014), BELLHOP has become the kernel module in many simulators (Qarabaqi and Stojanovic, 2013), and it can generate large-scale channel simulations.

There are two main differences between underwater acoustic communication and terrestrial radio frequency communication. The first one is that the carriers are different. For underwater acoustic communication, the carriers are acoustic waves, whereas the carriers of radio communication are electromagnetic waves. The low speed of acoustic waves introduces the severe Doppler effect. Furthermore, transmission loss of acoustic waves is the main factor that affects the system frequency, transmission distance, and receiver SNR. The second difference is that the channels are different. Underwater acoustic channels have more uncertainties and are thus harder to model and estimate than RF channels. The complexity of acoustic channels imposes the difficulties and obstacles in UAC research. Ocean environment noise decreases the received SNR, and the significant multipath propagation and severe Doppler effect require effective modulation and signal processing technologies.

3 Main important research areas in underwater acoustic communication

In the past few decades, UAC has experienced a great improvement. One important objective of UAC is increasing the data rate while improving the communication performance. Due to the characteristics of underwater acoustic channels, sound propagation is dependent on the signal frequency and transmission distance. For long-range communication, the optimal working frequency is too low to achieve a high receiver SNR. Therefore, it is difficult to obtain high data rates for long-range UAC; it is impossible to achieve high data rates and long-distance communication, simultaneously. Thus, we can divide underwater acoustic communication systems according to their transmission distances and data rates. Table 1 gives the classification results and the maximum data rate for different communication ranges based on current published experimental results.

Table 1 Communication range categories

Typical parameter	Short range	Medium range	Long range
Range (km)	< 10	10–30	30–1000
Data rate (kb/s)	< 100	< 15	< 2

At present, most UAC research focused on the high-data-rate UAC for short and medium communication ranges, whose experimental verifications are relatively easy to implement. For UAC systems with a long range but a low data rate, experimentation is expensive. Hence, only few organized institutions of maritime power are studying this area. The UAC network has become a popular research area in recent years because many UAC applications have extended point-to-point communication to networks. In addition, UAC applications have always been a very active research area and produced a lot of new research topics.

3.1 High-data-rate underwater acoustic communication for short- and medium-range communications

Currently, a major research interest in UAC is short-range (<10 km) and medium-range (10–30 km) communications. Non-coherent modulation has robust performance and has been used for rapid time-varying channels, such as shallow-water communications. Frequency shift keying (FSK) modulation (Catipovic et al., 1989; Scussel et al., 1997; Green and Rice, 2000) uses different frequencies to map digital information. Due to the robustness of FSK, it has been applied in many commercial modems. The key drawback of non-coherent modulation is its low data rate.

To increase the data rate of UAC systems, phase-coherent modulation techniques have been introduced. Based on Stojanovic et al. (1993, 1994), phase-coherent modulation techniques have been a major research interest in high-rate UAC. Many signal processing techniques have been proposed for phase-coherent modulation, such as channel-estimation-based adaptive decision feedback equalizers (DFE) (Stojanovic et al., 1999), turbo equalization (Zhang and Zheng, 2011), sparse partial response equalizers (Roy et al., 2009), blind equalization (Labat et al., 2003), inter-carrier interference (ICI) equalization (Rugini et al., 2006; Huang et al., 2011), and time reversal combination (Yang, 2004, 2005; Xia et al., 2012).

Multiple-input-multiple-output (MIMO) technology is an effective way to use spatial diversity and improve the data rate without increasing the consumed bandwidth. Because the underwater acoustic channel is bandwidth-limited, MIMO-UAC systems have become a hot research topic for high-data-rate short- and medium-range communications. Since the successful MIMO sea trial in Woods Hole, conducted by researchers from the Woods Hole Oceanographic Institution (WHOI) (Roy et al., 2004), MIMO has been used in both single-carrier systems (Tao et al., 2010; Zheng et al., 2010) and multi-carrier systems (Li et al., 2008a, 2009). This subsection provides only a brief introduction of high-data-rate UAC applied in short- and medium-range communications. Section 4 will introduce high-data-rate UAC in detail.

3.2 Low-data-rate underwater acoustic communication for long-range communications

The characteristics of underwater acoustic channels make it very hard to realize long-range communication in shallow water because the shallow water channel suffers from extended multipath caused by random reflections from the sea bottom and the surface. Compared with the shallow water, the deep water long-range channel response can be well approximated as having finite duration. With the development of autonomous underwater vehicles (AUVs) and gliders, long-range UAC in deep water has been attracting attention in recent years. To increase the SNR at the receiver, combined multi-channel techniques are usually employed (Stojanovic et al., 1993, 1994). Underwater time-reversal (TR) techniques are also applicable to long-range communication (Cho et al., 2013). Recently, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) carried out a series of long-range acoustic communication experiments in deep water. TR approaches and BPSK modulation have been successfully applied in the experiments (Shimura et al., 2010, 2012a, 2012b).

3.3 Underwater acoustic communication networks

Apart from point-to-point communication, some of UAC applications need to be supported by networks. A large amount of research has been carried out on the design and application of underwater acoustic sensor networks. These works have investigated various aspects of underwater acoustic sensor networks, such as the physical layer, MAC layer, routing layer, and application layer.

MAC protocols are investigated to avoid data collision among different users. Data collision will degrade the overall performance of networks. Energy efficiency, latency, and scalability are also considered in MAC protocols. Due to the unique characteristics of underwater acoustic channels, most terrestrial MAC protocols cannot be directly employed in the underwater environment. For example, underwater networks suffer from space-time or space-temporal uncertainty (Syed et al., 2007) due to the long propagation of underwater transmission. Despite these problems, two classic schemes, slotting time (time-division multiple access (TDMA)) and sensing the channel prior to transmission (carrier sense multiple access (CSMA)), are also used in UAC networks (Kredo et al., 2009; Pompili et al., 2009; Watfa et al., 2010; Climent et al., 2012; Fan et al., 2013).

The routing layer selects a best path from the data source node to the destination node. Although there are many studies on ad hoc routing for wireless radio networks, routing design for underwater networks is still being actively studied. Routing protocols for terrestrial networks can be divided into three categories: proactive, reactive, and geographical. There are several drawbacks for underwater acoustic communications (Pompili and Akyildiz, 2009). Depending on the unique application fields for UAC networks, the presented protocols can be classified in many ways (Climent et al., 2014).

3.4 Other underwater acoustic communication research from applications

In addition to the above-mentioned research, there are many studies from applications of underwater acoustic communications. The research of UAC applications is also very important and will generate great benefit once these applications are properly exploited. In general, there are three main categories for UAC applications: scientific, industrial, and military applications. For example, monitoring is a major application of UAC. UAC could be used to monitor the underwater environment and collect ocean data, such as water quality monitoring (Yalcuk and Postalcioglu, 2015), habitat monitoring (Trevathan et al., 2012), disaster monitoring (Casey et al., 2008; Kumar et al., 2012), and monitoring underwater explorations (Thornton et al., 2012). Another main application of UAC is navigation (Carroll et al., 2012; Guo and Liu, 2013). Because the current underwater environment is unexplored, assisted navigation employing UAC is very necessary. UAC is also employed to assist military applications, like finding underwater mines, securing ports and submarines, monitoring, and surveillance. At present, a very popular topic is the integration of space, aeronautics, ground, and sea information. Currently, integration of space, aeronautics, and ground information is almost completed. The last task is how to integrate underwater information.

4 Current research on high-data-rate underwater acoustic communication

High-data-rate UAC systems for short- and medium-range communications have been an active major research area in UAC. Brief introductions and analysis are provided in this section. Limited bandwidth restricts the increase in the data rate for long-distance transmission systems. However, the relatively large available bandwidth for short- and medium-range communication systems makes it possible to have high-data-rate communication schemes. To increase the data rate and bandwidth efficiency, phase-coherent underwater acoustic communication systems, such as phase shift keying (PSK) and quadrature amplitude modulation (QAM), have been developed and expanded by researchers in the last few decades. However, the severe inter-symbol interference caused by multipath effects in the underwater acoustic channels prevents performance improvement of phase coherent-based high-rate UAC systems. To provide reliable high-rate communications, equalization techniques to combat the ISI are required.

Currently, there are mainly four high-data-rate modulation schemes that are widely applied in UAC systems. Based on the number of carriers, they can be categorized as single-carrier and multi-carrier systems. Based on equalization schemes, they can be defined as frequency- and time-domain equalization systems. With the improvement in UAC technologies, MIMO techniques have been applied to UAC systems to further increase the data rate.

4.1 Single-carrier time-domain equalization

From the mid-1990s, single-carrier time-domain equalization (SC-TDE) has been widely used to diminish the multipath effects in high-rate single-carrier UAC systems. SC-TDE is a system using a single carrier for transmission, whose equalization is performed in the time domain. A typical SC-TDE receiver using a decision feedback equalizer is shown in Fig. 6. The equalizer parameters $a_m[n]$ can be determined by several criteria, such as the minimum mean squared error (MMSE) criterion. The detected results will be fed back to update the equalizer taps.

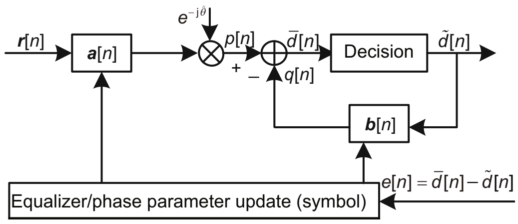

Fig. 6 Single-carrier time-domain equalization receiver structure

A milestone in SC-TDE is the adaptive DFE combined with digital phase locked loops (DPLL) proposed by Stojanovic et al. (1994). The DPLL aims at tracking and compensating for phase fluctuations. The initial experimental results of this genius scheme were provided by Stojanovic (1996). The results showed that this scheme could provide a reliable underwater acoustic communication system with data rates of 30–40 kb/s through a rapidly varying one-mile shallow-water channel. The effectiveness of this algorithm has been further proved by

Stojanovic (1996), Yeo et al. (2000), Freitag et al. (2004), and Preisig (2005).

However, SC-TDE suffers from several internal limitations. First, the computational complexity tremendously increases with the growth of multipath delay. The computational load for a typical SC-TDE UAC system is always high because the multipath delay can be as long as hundreds of symbols. Second, SC-TDE requires careful tuning of the equalizer taps and DPLL coefficients, which greatly affects its stability and robustness in different channel conditions. Furthermore, the determined coefficients do not automatically adjust to the time-varying channel conditions, causing sharply degraded performance in a quickly varying UAC channel. Much research has been done to decrease the computational complexity. The DFE in the spatial domain using beam-forming and multichannel combining algorithms was studied by Yang (2007). Another important scheme to reduce the computational load is applying passive time reversal communication. Time-reversed methods for underwater acoustic communication were first proposed by Kuperman et al. (1998) and Fink (2001). The time reversal scheme has returned as a promising technique to reduce the complexity of high-rate SC-TDE UAC systems. Time reversal can compress the channel dispersion; the multipath delays are shortened. As a result, it will reduce the overall complexity of the time-domain adaptive equalizer. Many attempts have been made to investigate the use of a time-reversed scheme with an adaptive equalizer. Time reversal was proved by a sea trial as an effective communication technique that mitigates the ISI caused by multipath effects (Edelmann et al., 2002). A time-reversal system that implements a DFE to reduce the residual ISI was proposed by Edelmann et al. (2005). The experimental results showed that the DFE improves the BER performance. A point-to-point time-reversed scheme has been extended to array-to-point communications (Candy et al., 2005). Unlike the commonly used BPSK and QPSK modulation, the performance of time-reversed communications applying multilevel quadrature amplitude modulation (M-QAM) in shallow water was demonstrated by Edelmann et al. (2005) and Song et al. (2006). The results showed that the performance is improved significantly by cascading an adaptive channel equalizer to remove the residual ISI and adopting low-complexity adaptive algorithms. A theoretical characterization of the equalization performance was proposed by Pajovic and Preisig (2015). Based on the theoretical characterization, Pajovic and Preisig (2015) suggested that the optimal number of equalizer coefficients is a trade-off between the MMSE requirement for longer constituent filters and the insight that the finite number of observations can effectively adapt to only a limited number of equalizer weights.

4.2 Orthogonal frequency division multiplexing

Multi-carrier methods, such as OFDM, have been adopted to overcome the long delay spread in underwater acoustic channels. The multi-carrier system divides the high-speed symbol stream into several low-speed streams, which transforms the frequency-selective channel into several narrow, flat, and fading channels. Under this division, the corresponding symbol duration can be larger than the maximum multipath delay, and it therefore effectively reduces the ISI caused by multipath effects. OFDM is a special multi-carrier technique that divides bandwidth into several orthogonal sub-carriers. The use of orthogonal sub-carriers allows the spectra to overlap, thus increasing the spectral efficiency. Adding a cyclic prefix (CP) in each sub-band turns the linear convolution into cyclic convolution. With the CP padded data structure, the OFDM can be modulated using the inverse fast Fourier transform (IFFT) and be demodulated using the fast Fourier transform (FFT). Apart from the easily implemented modulation, equalization for an OFDM system can be performed by a single tap equalizer. Thereby, receiver complexity is significantly reduced compared with SC-TDE. A typical system structure of OFDM is shown in Fig. 7.

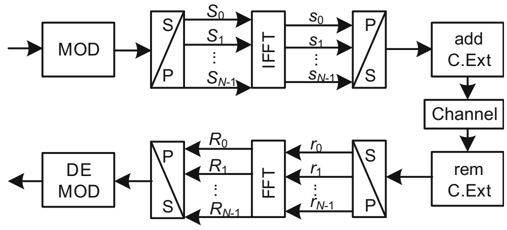

Fig. 7 Orthogonal frequency division multiplexing structure

There are two inherent challenges in OFDM systems. First, the peak-to-average power ratio (PAPR) is relatively high compared with a single-carrier system. In a UAC system, a high PAPR will severely affect the efficiency, security, and working time of power amplifiers and transducers. A high PAPR prevents the application of OFDM in long-range UAC communication due to the energy consumption problem. Second, OFDM signals are sensitive to Doppler effects. Compared with the low acoustic speed (approximately 1500 m/s), the Doppler shift caused by movement can be larger than that of the sub-carrier interval. The Doppler shifts vary among sub-carriers in a wideband UAC system, and as a result, orthogonality no longer holds and inter-carrier interference (ICI) arises. In addition, because UAC channels are wideband in nature, different frequencies are shifted by different amounts, which causes non-uniform frequency shifts compared with RF channels, where the Doppler effect translates all frequencies by the same amount as that for the carrier frequency (Stojanovic, 2008). Apart from these two major challenges, UAC OFDM systems also suffer from time-variant channels. A common assumption is that a channel remains the same in one OFDM block, but it may change from one block to another. However, the validity of this assumption decreases as the block length increases.

Earlier attempts of applying OFDM focused on system analysis and simulation-based studies (Bejjani and Belfiore, 1996; Lam and Ormondroyd, 1997). Recent research focuses on maintaining the orthogonality among sub-carriers, especially with respect to Doppler detection and compensation. Stojanovic (2006a) proposed a Doppler tracking and compensation technique using a single adaptively estimated parameter representing the Doppler rate. A two-step approach for mitigating the Doppler effects in a zero-padded OFDM was proposed by Li et al. (2008b). First, they implemented non-uniform Doppler compensation via re-sampling. Second, the residual Doppler was compensated for using a high-resolution technique. An iterative carrier frequency offset and channel estimation for a low-density parity-check (LDPC) coded OFDM system were proposed by Kang and Iltis (2008). Unlike the typical assumption of common time scaling on every path, the choice of re-sampling a parameter for a multi-scale scenario was examined by Yerramalli and Mitra (2011). An optimal re-sampling over multi-scale-multi-lag channels was proposed by Beygi and Mitra (2012) from a Bayesian perspective. Apart from the above-mentioned re-sampling-based Doppler compensation schemes, a partial FFT demodulation for OFDM communication was considered by Yerramalli et al. (2012). Each OFDM symbol was divided into several smaller intervals, and FFT was performed on each interval. By combining the weighted partial FFT outputs, ICI was reduced significantly compared to banded equalization, and low-complexity symbol-by-symbol detection was applicable with this partial FFT scheme. The BER performance can be further improved when combined with error-correcting codes, especially applying turbo codes or LDPC codes (Huang et al., 2008; Sang et al., 2009).

CP insertion can be replaced by zero-padding (ZP), leading to ZP-OFDM (Muquet et al., 2002). The reasons for using ZP-OFDM are as follows: (1) The UAC channel has a large delay spread, and thus the CP portion would consume a considerable fraction of the transmission power (Li et al., 2006); (2) ZP-OFDM may have better performance than CP-OFDM when appropriate receivers are used (Muquet et al., 2002). The application of ZP-OFDM in underwater acoustic communication was proposed by Li et al. (2007a, 2007b) and Wang et al. (2012). Apart from ZP-OFDM and CP-OFDM, an OFDM system padded with pseudo-random noise (PN) sequences is another research interest. PN sequences are adopted as training sequences for channel estimation or Doppler estimation as well as guard intervals for eliminating multipath effects. Because of the dual functions of PN sequences, research on PN-OFDM focuses mainly on synchronization and channel estimation (Hao et al., 2012; Chen et al., 2013).

OFDM underwater acoustic communication has been extended to MIMO systems in recent years. A block-by-block-based receiver for MIMO-OFDM UAC systems was proposed by Li et al. (2009). The proposed system uses null sub-carriers for Doppler compensation and pilot sub-carriers for channel estimation. The receiver jointly uses a successive interference cancellation algorithm and a soft MMSE equalization scheme with LDPC channel decoding for iterative detection on each sub-carrier. More experimental results for the MIMO-OFDM system (Li et al., 2009) with higher-order modulation were demonstrated by Li et al. (2008a). With large constellations and MIMO spatial multiplexing, the bandwidth efficiency can approach 3.5 bits/(s · Hz) in three different configurations. A MIMO-OFDM receiver with nonuniform Doppler prediction and tracking was proposed by Carrascosa and Stojanovic (2010). Nearly error-free performance was observed in experiments conducted in several shallow-water channels with Bose-Chaudhuri-Hocquenghem-coded quadrature phase-shift keying (QPSK) signals.

4.3 Single-carrier frequency-domain equalization

Single-carrier frequency-domain equalization (SC-FDE) is another method for eliminating the ISI effect. The SC-FDE system is computationally simpler than time-domain equalization for channels with severe delay spread, because in OFDM the equalization is performed in the frequency domain block by block. The typical structure of an SC-FDE system is shown in Fig. 8. The structure is very similar to that of OFDM except that both FFT and IFFT operations are implemented at the receiver. Similar to OFDM, the insertion of CP transforms the linear convolution relationship between the transmitted signal and the channel impulse response into a circular convolution. After removing CP at the receiver end, the received signal can be equalized using a one-tap equalizer. Consequently, SC-FDE delivers the same performance and overall complexity as OFDM (Falconer et al., 2002). In addition, SC-FDE modulated signals have a smaller PAPR and they are less Doppler sensitive than those of OFDM.

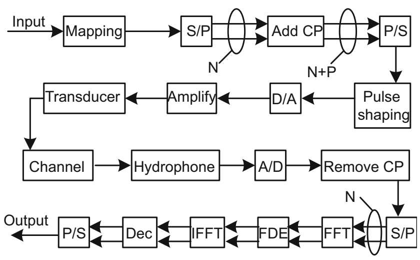

Fig. 8 Single-carrier frequency-domain equalization structure

The research on SC-FDE underwater acoustic communication focuses mainly on equalizer design (Huang et al., 2007), channel estimation (Zheng et al., 2007), and Doppler compensation (Zheng et al., 2010). A fractionally spaced MMSE frequency-domain equalization was implemented for a cyclic prefixed single-carrier transmission for high-speed underwater acoustic communication (Huang et al., 2007). The received signal was sampled with twice the symbol rate, and the samples of each block were divided into an odd group and an even group. These two groups were combined before an IFFT operation for detection after MMSE frequency-domain equalization. A more mature SC-FDE UAC system was studied by Zheng et al. (2007). A small-block training signal was inserted before a pack of signal blocks for initial channel estimation. The channel transfer function matrices were re-estimated by using the detected data and received signals of the current block. The time-domain Doppler compensation was then employed in a group-wise algorithm. In the field experiments conducted off the coast of Panama city, the uncoded BER for transmitted QPSK signals is between 4.5×10^{-4} and 1.2×10^{-3} for 5- to 6-channel diversity systems under a typical fading channel with the length of 10 ms. More experimental results for the proposed algorithms (Zheng et al., 2007) were studied by Zheng et al. (2008). Inspired by Sharif et al. (2000), He et al. (2009) proposed a training-sequence-based single-carrier modulation with low-frequency-domain equalization for long-range underwater acoustic communication. The maximum likelihood estimators for robust initial phase error and Doppler shift by using a training sequence were derived as well. Different from channel estimation (Zheng et al., 2007) and applying an extra training sequence before a series of blocks, the channel impulse responses were estimated block by block using the inserted training sequences in front of each block. In a sea trial, the proposed UAC communication system with a single transmitter and a single receiver can achieve an uncoded BER of 4 out of 8333 (BPSK) and 103 out of 16 666 (QPSK). In Zheng et al. (2010), a new phase-correction scheme was adopted in the SC-FDE system (Sharif et al., 2000). The new phase correction scheme uses a few pilot symbols in each data block to estimate and correct the initial phase shift. Then time-varying instantaneous phase drifts were re-estimated and compensated for adaptively by averaging the phase variation across a group of symbols rather than symbol by symbol (Zheng et al., 2010). SC-FDE performance was evaluated using data collected from the 2009 Cooperative Array Performance Experiment (CAPEx09) near Seattle, WA, USA (Xia et al., 2014).

The above studies focus on single-input-single-output (SISO) or single-input-multiple-output (SIMO) SC-FDE underwater communication systems. To further increase the data rate and use the spatial diversity, SC-FDE systems have been extended to MIMO transmissions. A bandwidth-efficient FDE scheme with decision-directed channel estimation was proposed for single-carrier-MIMO UAC communications (Zhang and Zheng, 2010). The proposed scheme greatly increases the data efficiency with low overhead on a pilot block. By employing an overlapped-window FDE scheme, the system performance was significantly improved with slightly increased computational complexity. The proposed scheme has been shown to reach an average uncoded BER of 0.6%–1.4% with approximately one third of transmission overhead of traditional FDEs by analyzing data collected during the Rescheduled Acoustic Communication Experiment 08 (RACE08). A robust detection scheme for high-data-rate single-carrier MIMO underwater acoustic communications was proposed by Tao et al. (2010). The new scheme adopts turbo block DFE, where the soft-decision equalizer performs successive soft interference cancellation of both inter-symbol interference in the time domain and multiplexing interference in the space domain (Tao et al., 2010). Instead of applying a convolution encoder (Tao et al., 2010), a low-complexity turbo-detection scheme for single-carrier MIMO UAC communication systems employing LDPC channel coding was introduced (Rafati et al., 2014).

4.4 Orthogonal signal division multiplexing

Orthogonal signal division multiplexing (OSDM) is a new type of multiplexing modulation scheme that was first introduced in terrestrial wireless communication to achieve reliable transmissions. OSDM allows for a flexible trade-off between resource management flexibility and PAPR (Han et al., 2018). A three-step implementation procedure of OSDM was introduced by Han et al. (2018), and the structure is shown in Fig. 9. Assume that the transmitted symbol sequence is d with length $K = MN$. The first step is to write d row-wise into an $N \times M$ matrix $\boldsymbol{D}$; each row is referred to as a vector. Second, N-point inverse discrete Fourier transforms (IDFTs) are performed column-wise to matrix $\boldsymbol{D}$. Finally, the resulting matrix $\boldsymbol{S}$ is read out row-wise to form the base-band signal s. It can be seen from Fig. 9 that OSDM turns into the traditional OFDM system if $N = K$. On the other hand, OSDM becomes equivalent to single-carrier modulation when $N = 1$. Consequently, OSDM provides a unified framework to bridge the gap between OFDM and SC-FDE.

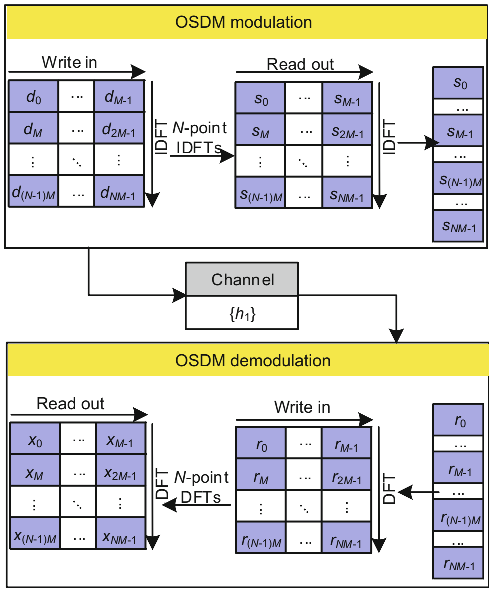

Fig. 9 Orthogonal signal division multiplexing structure
IDFT: inverse discrete Fourier transform; DFT: discrete Fourier transform

A comprehensive tank experiment has been conducted to compare OSDM to existing modulation schemes (Ebihara and Mizutani, 2014). By introducing a multi-channel receiver, OSDM was verified to outperform conventional OFDM and single-carrier systems which adopt a DFE with a recursive least squares algorithm. A Doppler-resilient OSDM (D-OSDM) was proposed by Ebihara and Leus (2016) with the channel being modeled by a basis expansion model (BEM). Simulations and tank experiments proved that D-OSDM can reliably transmit information over underwater acoustic channels with large delay and Doppler spreads. An iterative per-vector equalization for OSDM over time-varying underwater acoustic channels was proposed by Han et al. (2018). The results of numerical simulations and a field experiment suggested that OSDM is a promising candidate for high-rate communications over time-varying underwater acoustic channels.

SC-TDE, SC-FDE, and OFDM are three well-developed high-data-rate modulation schemes in short- and medium-range UAC systems. Their performances have been largely improved by advanced receiver designs in the last decade. Unlike these three modulations, OSDM is a new research in UAC. Its performance shows that OSDM is a promising modulation scheme for high-rate UAC. Furthermore, high-rate UAC systems have been extended from SISO to MIMO, further increasing the achievable data rate and band efficiency.

5 Criteria for evaluating the performance

In existing underwater acoustic communication systems, there are different kinds of signals being transmitted: control, telemetry, speech, and video (Stojanovic, 1995). The system performance demands for these signals vary from system to system.

From the perspective of UAC system designers, there are three essential factors to be considered in advance: BER, data rate, and communication range. Different demands on these factors lead to various UAC system designs. However, these three factors are closely related to each other. If one factor is fixed, it is essentially impossible to improve the other two simultaneously in a hardware-fixed UAC system. For example, if the BER is fixed, the increase in the data rate will be at the cost of decreasing the communication range. Thus, designers should comprehensively consider these three essential factors.

Based on our years of research and data collected from the literature, three general performance evaluation criteria for high-rate UAC systems in short- and medium-range communications are statistically presented. The three criteria are: (1) P: BER versus SNR; (2) I: the product of data rate and corresponding communication range; (3) E_s: the product of bandwidth efficiency and communication range. As far as we know, none of the previous work related to UAC systems has clearly demonstrated performance evaluation criteria.

5.1 Bit error rate versus signal-to-noise ratio

The first criterion, P, demonstrates the relationship between BER and SNR. BER is defined as the number of bit errors divided by the total number of bits transmitted during a given time interval, generally denoted as a percentage. BER is affected by many factors, including noise, interference, and distortion. A typical method to visualize the BER performance of a communication system is to draw the BER curve corresponding to a certain SNR or E_b/N_0 (the energy per bit to noise power spectral density ratio) range. In other words, P can be denoted as a function related to BER and SNR, $P \sim f(\text{BER, SNR})$.

The function of P is twofold. First, it is critical in evaluating the performance of UAC modulation-based algorithms. The evaluation can be conducted by comparing either the SNR required to achieve a certain BER level or the BER level at a fixed SNR value. The one with the lower BER at the same or a smaller SNR needed for a certain BER is considered to be better if the same data rate is achieved. The SNR difference obtained is defined as the SNR gain. QPSK has an SNR gain of 4 dB over 8PSK at BER $= 10^{-4}$ (Fig. 10). Second, P can help the design of hardware in UAC systems. BER curves demonstrate the minimum SNR value to achieve a desired BER performance. The system should guarantee a minimum of 8 dB received E_b/N_0 after pre-processing to realize a BER smaller than 10^{-4} at the receiver (Fig. 10).

Fig. 10 shows the BER comparison among three different modulation algorithms.

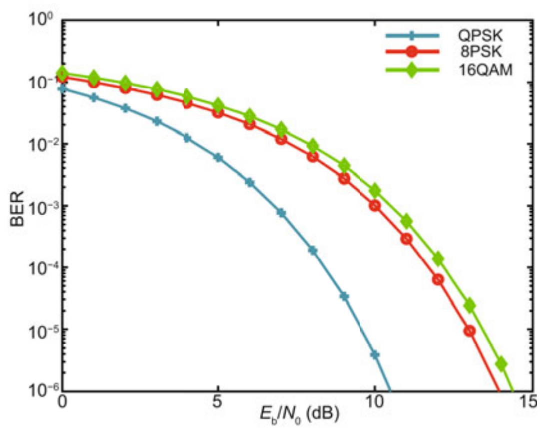

Fig. 10 Bit error rate comparison among three different modulation algorithms

5.2 Product of data rate and communication range

The second criterion is the product of the data rate and the corresponding communication range, expressed as I = data rate (kb/s) × communication range (km). The transmission loss in an underwater acoustic communication system is largely caused by the energy spreading and sound absorption. Although the energy spreading loss depends only on the propagation distance, the absorption loss increases not only with distance but also with frequency, thus setting the limit on the available bandwidth (Stojanovic, 1995). In other words, the data rate and communication range are closely correlated. The channel capacity (the maximum data rate that can be supported by an acoustic channel for a given source power and system configuration) is approximately inversely proportional to the range (Hayward and Yang, 2007). Experiment results summarized by Kilfoyle and Baggeroer (2000) imply that there exists a threshold of the product of the data rate and communication range in practical UAC systems. Thus, criterion I is used as a combination of data rate and range to evaluate the functional systems and products in general.

Fig. 11 shows the performance of short-range (< 10 km) UAC systems before year 2000 in the form of range (km) versus data rates (kb/s) (Kilfoyle and Baggeroer, 2000). It is clear that high data rates are less possible in long-range communication, due to worse channel conditions and larger energy absorption over long distances.

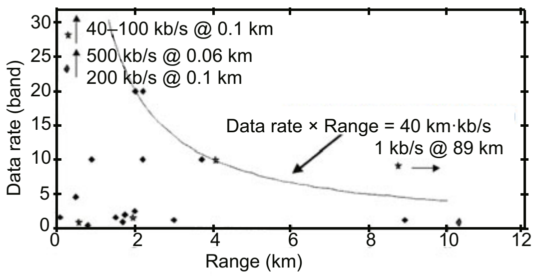

Fig. 11 Performance of short-range underwater acoustic communication systems before year 2000

In the past decade, new technologies in UAC systems have pushed the practical performance upper bound to a new level. An OFDM system was tested in a sea trial and achieved reliable transmission over 30 km at 1.6 kb/s in 2007 (Wu et al., 2010). The corresponding I is 48 km·kb/s. In a more recent study on a current underwater acoustic communication system (Song and Hodgkiss, 2013), the achievable data rate was 60 kb/s over a 3-km communication range, whose I reaches 180 km·kb/s. To demonstrate the improvement in the 21st century, UAC system performances after the year 2000 are summarized in Table 2. Unlike the data collected by Kilfoyle and Baggeroer (2000) focusing on short-range underwater acoustic communications (<10 km), Table 2 presents experimental results from short- to medium-range (≤30 km) UAC systems.

It can be seen that with the application of newly developed UAC techniques, the achievable product of data rate and communication range increases far beyond the 40 km·kb/s threshold (Kilfoyle and Baggeroer, 2000), especially those for MIMO schemes. It should be clear that the data collected here are not normalized, especially those of MIMO systems. Strictly speaking, experimental MIMO data should be normalized according to the method applied by Kilfoyle et al. (2003, 2005). Compared with SISO systems, MIMO schemes improve the performance at the cost of conditions, like hardware expense and source energy.

A new threshold of I = 100 km·kb/s for UAC systems is statistically posted based on these recent experimental results (Fig. 12). It can be seen that almost one-third of investigated experimental results are beyond 40 km·kb/s and two of them pass the 100 km·kb/s threshold. Thus, the 100 km·kb/s threshold is appropriate for short- and medium-range UAC systems in the beginning of the 21st century.

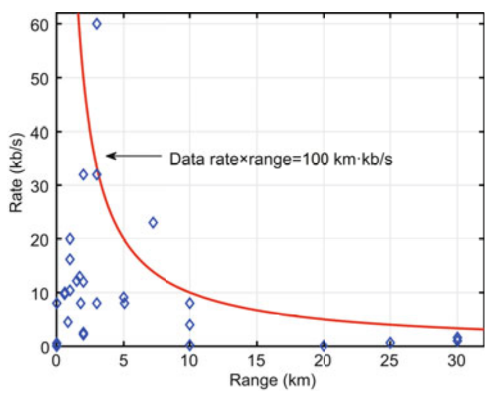

Fig. 12 Performance of short- and medium-range UAC systems after year 2000

Table 2 Performance of underwater acoustic communication systems after year 2000

Reference	Range (km)	Data rate (kb/s)	Bandwidth (kHz)	Data rate×range	Bandwidth efficiency (bit/(s · Hz))	Bandwidth efficiency×range
Huang et al., 2005	5	9.09	5	45.45	1.818	9.09
Wei and Huang, 2006	25	0.64	2.6	16	0.246	6.15
Song et al., 2006	2	2.5	1	5	2.5	5
Rouseff et al., 2007	2	2.174	0.96	4.348	2.272	4.544
*Roy et al., 2007	2	12	3	24	4	8
Jurdak et al., 2007	0.01	0.048	1	0.000 48	0.048	0.000 48
Xu et al., 2007	30	1	1.024	30	1	30
Aydinlik et al., 2008	0.016	0.55	4	0.0088	0.1375	0.0022
Leus and van Walree, 2008	52	◇0.078	3.6	4.056	0.022	1.144
Leus and van Walree, 2008	20	◇0.08	3.48	1.6	0.023	0.46
*Li et al., 2008a	0.4	–	–	–	3.52	1.408
Li et al., 2008b	0.6	9.7	12	5.82	0.808	0.4848
Otnes and Eggen, 2008	0.85	4.5	4	3.825	1.125	0.956 25
*Cai et al., 2009	0.0175	8	4	0.14	2	0.035
*Li et al., 2009	0.45	◇125.7	62.5	56.565	2.01	0.9045
*Li et al., 2009	1.5	◇12.18	12	18.27	1.015	1.5225
Berger et al., 2009	1.72	◇12.96	7.8125	22.2912	1.65	2.838
Wu et al., 2010	30	1.6	0.4	48	4	120
*Huang et al., 2010	1	10.4	9.7656	10.4	1.064	1.064
Li and Huang, 2010	1	20	10	20	2	2
Li and Huang, 2010	10	8	10	80	0.8	8
Zheng et al., 2010	3	8	5	24	1.6	4.8
Zheng et al., 2010	5.06	8	5	40.48	1.6	8.096
Song et al., 2011	2	32	7	64	4.57	9.14
Zhang and Zheng, 2011	1	◇16.2	9.7656	16.2	1.659	1.659
Benson et al., 2012	0.05	80	80	4	1	0.05
Song and Badiey, 2012	3	32	22	96	1.45	4.35
Song and Hodgkiss, 2013	3	60	22	180	2.72	8.16
Riedl and Singer, 2013	7.2	◇23	10	165.6	2.3	16.56
Shimura et al., 2017	10	0.2	0.1	2	2	20
He et al., 2017	7.4	8	4	59.2	2	14.8
Li and Zakharov, 2018	110	0.33	1.024	36.3	0.33	36.3

* denotes experimental results of MIMO systems and ◇ represents the net data rate

5.3 Product of bandwidth efficiency and communication range

The last criterion is related to the bandwidth efficiency, which helps optimize UAC systems. Bandwidth efficiency is an important index especially for band-limited communication systems, like UAC systems, so we should pay special attention to this index. Bandwidth efficiency E refers to the data rate R_b that can be transmitted over a given bandwidth W in a specific communication system in the form of bit/(s · Hz), and could be expressed as

$$E = \frac{R_\mathrm{b}}{W}\ (\mathrm{bit/(s\cdot Hz)}). \tag{11}$$

It measures how efficiently a limited frequency spectrum is used by the system. The system is more efficient with a larger E.

Based on the various data summarized in Table 2, the bandwidth efficiency is categorized into five levels (Table 3). For most UAC products, E is normally less than 1 bit/(s · Hz). Academic research focuses mainly on bandwidth efficiency larger than 1 bit/(s · Hz). Typically, UAC systems with E in the range of 2–3 bits/(s · Hz) are considered 'good' systems. Extraordinary bandwidth efficiency larger than 4 bits/(s · Hz) is the research direction. Thus, it is reasonable to set 4 bits/(s · Hz) as the threshold of E in UAC systems.

However, the separate evaluation of E without considering the communication range is insufficient for UAC systems, because the achievable E is related to distance (Stojanovic, 2006b), which can also be seen from Table 2. The close relationship between E and the range is reflected by the product of E and the communication range, named E_s, which is the third general evaluation criterion for UAC systems represented as

$$E_s = E \times \text{range}. \quad (12)$$

Table 3 Bandwidth efficiency categories

Bandwidth efficiency (bit/(s · Hz))	Category
< 1	Products
$1-2$	Fair
$2-3$	Good
$3-4$	Advanced
> 4	Extraordinary

Fig. 13 demonstrates the bandwidth efficiency at different ranges in recent studies. Based on the data we collected, a threshold of $E_s = 40$ km·bit/(s · Hz) is proposed. However, it is unreasonable that the bandwidth efficiency E would be larger than 10 bits/(s·Hz) at a short range (≤ 4 km) based on the threshold of $E_s = 40$ km·bit/(s · Hz). Considering the fact that UAC systems with $E \geq 4$ bits/(s·Hz) are regarded as extraordinary systems, a modified threshold for optimized UAC systems is posted by the combination of E_s (40 km·bit/(s · Hz), for range ≥ 10 km) and E (4 bits/(s · Hz), for range < 10 km) as in Fig. 13.

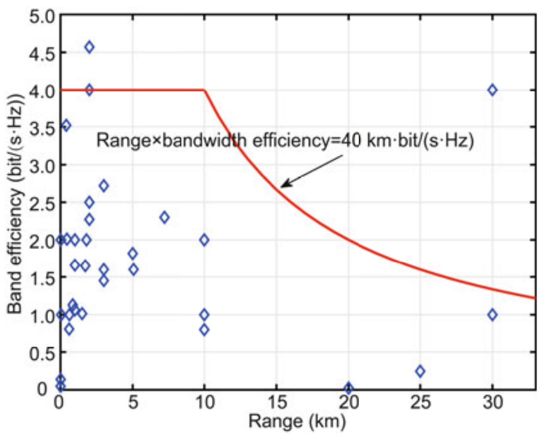

Fig. 13 Bandwidth efficiency at different ranges

In summary, the relationship between the UAC system design and the three general performance evaluation criteria (P, I, and E_s) is depicted in Fig. 14. Criterion P measures the performance of methods or algorithms in UAC systems and also helps in system hardware design. Criterion I evaluates the general performance of a designed and established system in a real underwater environment, whereas criterion E_s helps optimize UAC systems. The three criteria (P, I, and E_s) are not only an evaluation tool for general UAC performance, but also an indicator for UAC system design and optimization. It should be noticed that systems are basically optimized if P, I, and E_s are close to or beyond their thresholds, respectively.

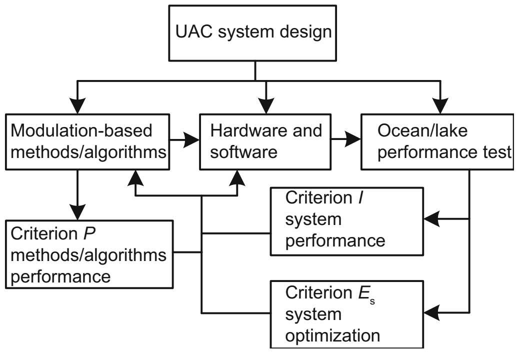

Fig. 14 Relationship between underwater acoustic communication system design and general performance evaluation criteria P, I, and E_s

The proposed criteria (P, I, and E_s) are based on the collected field experimental data, which cannot replace the technical indices. The original intention of P, I, and E_s was to statistically demonstrate the current performance threshold and show the potential of UAC systems based on experimental data, but not compare different algorithms or systems. A strict way for comparison of UAC systems should assume that all the configurations are the same, including bandwidth, sound source power, receiving sensitivity, and similar channel condition. Thus, P, I, and E_s are not strict judgment criteria for different UAC systems. However, they give designers of UAC systems an intuitive way to evaluate general performance and helps release the potentials of actual systems.

6 Conclusions

To give a brief introduction of underwater acoustic communications, the characteristics and difficulties of underwater acoustic channels have been summarized first. Compared with terrestrial radio frequency communication, underwater acoustic channels suffer from severe difficulties, e.g., transmission loss, time-varying multipath propagation, and severe Doppler spread. These difficulties are obstacles to the development of UAC systems.

In addition, major research in UAC has been mentioned, varying from the physical layer to the network layer. Research on the physical layer can be generally divided into two parts based on the communication range and the corresponding data rate: high-data-rate, short- to medium-range communications, and low-data-rate, long-range communications. In both scenarios, novel techniques have successfully pushed the limits of underwater communications. In applications of underwater communication networks, research on the MAC layer, routing layer, and application layer has been made to adapt to the characteristics of underwater acoustic channels.

Furthermore, current widely used high-data-rate modulation schemes have been summarized. SC-TDE, SC-FDE, and OFDM are the three principal modulations applied in short- and medium-range UAC systems. Research has been focused on advanced receiver design to eliminate the effects caused by multipath propagation and Doppler deviation. OSDM is a new technology providing high-rate transmission in underwater communication. It is a unified framework to bridge the gap between OFDM and SC-FDE.

With years of research on UAC systems and investigation into recent research, the P, I, and E_s criteria have been statistically proposed as a tool to evaluate the general performance and assist the design of UAC systems from the perspective of system designers. These three criteria support the design and optimization from modulation-based algorithms to the systems, including hardware and software. After ocean/lake performance tests, UAC systems can be further optimized considering the criteria.

Experimental results of short- and medium-range UAC systems with high data rates after the year 2000 have been summarized as supplement data to proposed UAC general performance evaluation criteria. Specific performance thresholds were investigated based on these collected results. For criterion I, the threshold was 100 km·kb/s. For criterion E_s, a combined threshold of 40 km·bit/(s · Hz) for E_s and 4 bits/(s · Hz) for E was posted. If the system performance reached the thresholds, UAC systems can be basically considered as optimized. On the contrary, UAC systems can be optimized to improve performance if it is far from the thresholds. The proposed UAC general performance evaluation criteria help designers of UAC systems release potentials of actual systems.

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