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M-ary CDMA multiuser underwater acoustic communication and its experimental results

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Abstract A novel M-ary code division multiple access (M-ary CDMA) underwater acoustic communication (UAC) that utilizes quasi-orthogonal sequences has been proposed for the multiple mobile unmanned underwater vehicle (UUV). Its performance has been verified in both four-user synchronous and three-user asynchronous scenarios through a lake experiment over a very shallow-water channel. At a chip rate of 2 kilochips per second, good bandwidth efficiency and robust links have been achieved both at 5 and 15 km distances. The performance of M-ary CDMA in mobile condition (3 m/s) is demonstrated by using the recorded lake experimental data. Experimental results show that the proposed scheme is suitable for multi-user communication platform in long-range shallow-water channel with simple receiver algorithms.

Keywords underwater acoustic communications, M-ary code division multiple access (M-ary CDMA), Doppler shift compensation, shallow-water acoustic network, unmanned underwater vehicle

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1 Introduction

With the development of ocean exploration and unmanned underwater vehicle (UUV), underwater acoustic communications and networks have been studied extensively in recent years [1, 2]. Performances of underwater acoustic communication systems are mainly influenced by the underwater acoustic (UWA) channel. One of the most critical obstacles is that the available bandwidth of the underwater acoustic channel depends on both range and frequency. Spread spectrum and code division multiple access (CDMA) provide several benefits, such as resistance against multipath effect, and low probability of detection (LPD). For these reasons, spread spectrum methods have received much attention these years in UAC community [3–8], and CDMA becomes a suitable candidate for shallow-water acoustic communication networks [9–13]. Direct-sequence CDMA (DS-CDMA) has been studied for underwater acoustic networks [9]. Ref. [10] suggested the implementation of the DS-CDMA technique with Rake receivers and space diversity techniques. The performance of DS-CDMA and multi-carrier CDMA (MC-CDMA) has been evaluated and compared under different simulation scenarios in [11]. A four-user scenario was demonstrated in [12] and [13]. The multiuser test signal was constructed by first adding signals of all

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four users before being transmitted to connect two ships. The signals were added at equal power asynchronously. Two receivers that utilized multi-channel processing of asynchronous multiuser signals were proposed: the symbol decision feedback (SDF) receiver and the chip hypothesis feedback (CHF) receiver. The achieved maximum chip rate was reported to be 19.2 kbps with 20 kHz bandwidth at the range of 2 km [12].

The aforementioned conventional DS-CDMA underwater acoustic communication systems usually employ advanced signal processing algorithms, such as spatial diversity, complicated adaptive multi-channel equalization combined with digital phase-lock loop (PLL) or Rake receivers. The performances of these receivers are also sensitive to the parameter choices of adaptive equalizers including, but not limited to, the number of taps in the feed-forward filters, and the step size or forgetting factor [12]. The optimum choices of such parameters vary a great deal according to different channel conditions [12, 13]. In these reported DS-CDMA architectures, one of the most important characteristics is that each user is assigned one spreading code. This bandwidth efficiency is only the reciprocal of the length of spreading code. Thus, in the bandwidth limited UWA channels, the data rate of DS-CDMA is quite slow. In mobile condition, the receiver of DS-CDMA becomes more complicated. To reduce MAI, M-ary quasi-orthogonal signaling can be employed for CDMA. Because both spreading and dispreading were processed symbol-by-symbol rather than bit-by-bit in the system that employed M-ary pseudorandom noise (PN) signaling, the data rate could be increased [14]. In UWA environment, the spread spectrum scheme based on quasi-orthogonal sequences for single user has been studied in [4], [6] and [7].

In this work, a multiuser M-ary CDMA system based on quasi-orthogonal sequences for shallow-water acoustic communication network with multiple mobile nodes has been designed and tested. In our proposed M-ary CDMA network, M unique PN sequences (such as m sequences, Gold sequences, or Kasami sequences) are assigned to each user and a group of correlators whose implementation is described in detail later is used for demodulation. As in M-ary FSK, the receiver simply demodulates each possible transmitted symbol and makes decisions in favor of the one which maximizes an energy metric. Through real-time underwater test data, the performance of the proposed M-ary CDMA is demonstrated. Both four-user synchronous CDMA network and a three-user asynchronous CDMA network are considered. Our signal transmission between the source and a single hydrophone receiver was carried out in a distance range of 5–15 km with a depth of 40–100 m. A Doppler shift compensation method for M-ary CDMA UWA communication system is also verified by the recoded lake test data. The results demonstrate the system's capability to support multiple mobile users in long range horizontal shallow-water channels.

The rest of this paper is organized as follows. The system model is described in section 2. The proposed receiver algorithm is presented in section 3. The lake test results are presented in section 4 and the conclusion is given in section 5.

2 System model

In M-ary CDMA system, M PN sequences are assigned for each user as orthogonal signaling waveforms. One sequence will be selected to denote the particular bits. In effect, M-ary CDMA system is a form of orthogonal signaling. The transmitted signal of the kth user of M-ary CDMA is given by

$$s_k(t) = \sum_{n=0}^{L-1} a_k(n) p(t - nT_c), \quad 0 \leqslant t \leqslant T, \tag{1}$$

where $T = LT_c$ is symbol duration and T_c is the chip interval. $\{a_k(n), 0 \leqslant n \leqslant L-1\}$ is one real-valued PN sequence with $a_k(n) = \pm 1$. Each PN sequence belongs to the set of M PN sequences allocated to the kth user. The transmission of one PN sequence is determined by the $\log_2 M$ input bits. L is spreading gain and $p(t)$ is transmitter shaping pulse.

The data rate of per user in M-ary CDMA is expressed as

$$\eta = \frac{\log_2 M}{T}, \tag{2}$$

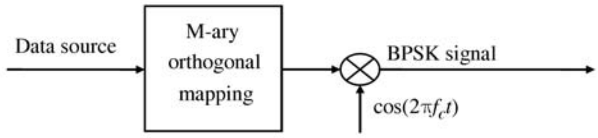

Figure 1 Transmitter structure of M-ary CDMA.

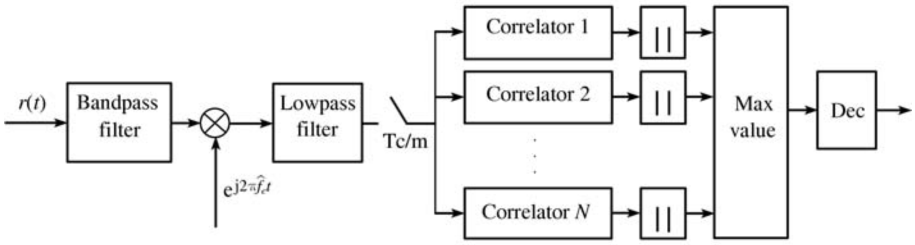

Figure 2 Receiver structure of M-ary CDMA.

while the data rate of per user in traditional DS-CDMA is expressed as

$$\eta = \frac{1}{T}. \tag{3}$$

In this way, it is possible to improve the bandwidth efficiency of traditional DS-CDMA. In our design, a four-user synchronous network and a three-user asynchronous shallow-water network are considered. The transmitter architecture of one user that we used to generate the M-ary CDMA signal is depicted in Figure 1. The transmitter groups the input data stream into $k = \log_2 M$ bits in each group. One of the M sequences is selected according to the k input bits for transmission.

3 Proposed receiver algorithm

3.1 Receiver structure

The block diagram of the M-ary CDMA receiver is shown in Figure 2. After bandpass filtering, the received signal is down-converted into baseband $r(t)$. Thereafter, correlators are used to detect which sequence is transmitted. This kind of receiver structure is usually used for synchronization and channel estimation in UWA communication. The same receiver structure can be used for every user except for the difference in the PN sequences (correlators). The received baseband signals are sampled N times per information symbol of LT_c. The received signals are first correlated with the M correlators and the estimated symbol is decided by applying maximum likelihood detection which selects the largest correlator output.

This receiver is implemented in the frequency domain. Thus, the detected symbol is

$$\hat{s}_i = \arg\max_i |Re(\mathrm{IFFT}(R(\omega)A_i^*(\omega)))|. \tag{4}$$

This structure is optimal for single user in the AWGN channel. Under multipath, it does suffer any performance loss. Small Doppler shift will further degrade the system performance if uncompensated. Still, in our receiver only FFT/IFFT operations are used, giving rise to a very simple receiver structure.

3.2 Doppler effect for wideband signal

In underwater acoustic channel, the effect of platform motion on a wideband signal is more accurately modeled as a complete time scaling (expansion or compression) of the signal waveform [15]. The Doppler effect can be expressed as

$$r(t) = s((1+\alpha)t), \tag{5}$$

where $s(t)$ and $r(t)$ are the transmitted and Doppler-shifted received signals, respectively. The relative Doppler shift α is defined as the ratio of the relative platform speed to the sound speed

$$\alpha = \frac{\Delta f}{f_c} = \frac{v}{c}. \tag{6}$$

For a wideband signal, the expansion or compression of a symbol results in a symbol synchronization error when only the carrier frequency offset is considered. The symbol duration of Doppler-shifted received signal is given by

$$T' = (1+\alpha)T. \tag{7}$$

Hence, per-symbol synchronization error due to Doppler shift is

$$\Delta T = T' - T = \alpha \cdot T. \tag{8}$$

This error is cumulative. The synchronization error at time t (counted from the first symbol) is

$$dt = \frac{t}{T}\Delta T. \tag{9}$$

The symbol at time t will be out of synchronization when $dt > T$. The percentage of expansion or compression is given by the ratio of platform speed to sound speed. If the Doppler shift is 1%, then the symbol synchronization will be off by one symbol after a hundred of symbols. The latter part of the signal needs re-synchronization.

3.3 Doppler shift compensation

PN signal, a Doppler sensitive signal, is commonly used in radar and sonar because of its good temporal resolution of autocorrelation function. The ambiguity function shows the matched filter response against delay and Doppler shift variations of the incoming signal. For a wideband continuous time signal, the definition of the ambiguity function is given by

$$\chi_s(\tau,\alpha) = (1+\alpha)\int_{-\infty}^{\infty} s((1+\alpha)t)s(t-\tau)dt. \tag{10}$$

A numerical measure of the Doppler tolerance of a PN signal by considering the ambiguity surface is approximately given by

$$\beta = \frac{1.6}{BT}, \tag{11}$$

where B is the signal bandwidth, and T is the signal duration.

For PN signals, a slight Doppler-affected received signal can still be compressed properly by a correlation receiver although the peak will be diminished in amplitude and will appear at the output shifted in time. Synchronization error is compensated symbol-by-symbol via time shift estimation from previous symbol. Then, the estimated τ is used to compensate for the synchronization error of following symbols

$$r'(t) = r(t-\tau), \tag{12}$$

which is defined as resynchronization method.

Assume

$$z_m(t) = \{Re(\mathrm{IFFT}(\mathrm{FFT}(r'(t)(\mathrm{FFT}(a_m(t)))^*))\}, \quad 0 \leqslant t \leqslant T, \quad 1 \leqslant m \leqslant M, \tag{13}$$

where τ is the synchronization error of previous symbol, and $a_m(t)$ is the reference signal.

The receiver makes of decision based on statistics

$$\max_{1\leqslant m\leqslant M}\max_{0\leqslant t\leqslant T} z_m(t). \tag{14}$$

If we get the maximum value when $m = n$, then, the synchronization error of current symbol τ is estimated based on

$$\hat{\tau} = \arg\max_t z_n(t). \tag{15}$$

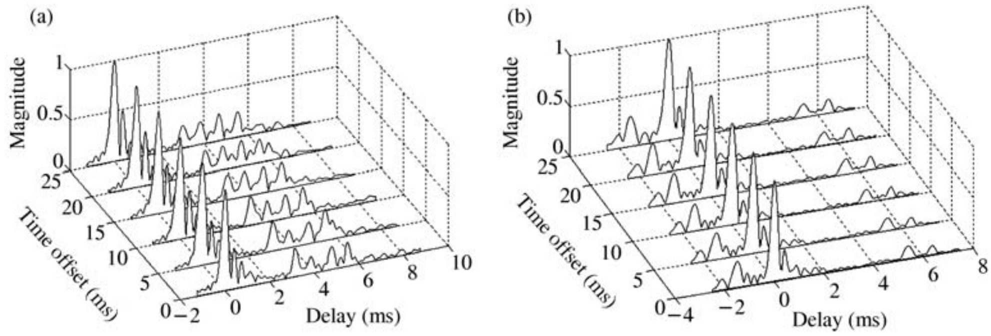

Figure 3 Time-varying channel responses in lake experiment. (a) At the range of 5 km; (b) at the range of 15 km.

4 Lake experimental results

4.1 Experiment description and system parameters

Our team performed experiments of this M-ary CDMA system on a lake in southern China during early 2005. The width of the lake is approximately 8 km, and the length is 25 km. The water depth was measured to be between 40–100 m. During the lake experiments, only two ships were deployed during transmissions. The receiver ship was anchored at one position and the transmitter ship moved to different desired positions for testing. The distance between transmitter and receiver ships varied in a range from 5 to 15 km. The source sensor was submerged from the transmitting ship to a depth of 22 m underwater. All signals were received using a single hydrophone, located 6 m below the receiver ship. The transmitted ship had a slow velocity due to water current. The transmission power was around 190 dB re μPa within 2 kHz bandwidth. The data block began with a synchronization sequence of length 511, followed by available message signal. The chip duration was 0.5 ms, corresponding to the chip rate of 2 kHz. All experimental data were first collected before being processed off-line. The parameters, such as the number of sequences, were chosen to increase the data rate without concerning the receiver complexity.

4.2 Channel characteristics

Channel responses were measured by applying matched filter to a chirp probing signal before the useful data. The responses are shown in Figure 3. The column in each figure contains six responses observed at different time separated by about 5 s. Each response is shown as a function of time delay. Figure 3(a) shows the channel response obtained during transmission at a distance of 5 km. The multipath spread spans about 6 ms, which means that it covers approximately 12 chips. Figure 3(b) shows the channel response obtained during transmission at a range of 15 km. Before the strongest path, there is a weaker multipath. The total multipath spread spans about 8 ms which corresponds to a delay spread of approximately 16 chips.

4.3 Synchronous M-ary CDMA lake experimental results

Synchronous M-ary CDMA signals for four users were generated at the transmitter before tests. Each user signal was generated with equal power before summing. Gold spreading codes of length 127 were used. Each user was given a set of 32 sequences such that each sequence transmission represented 5 bits. Under this setup, the available bit rate equaled 78.8 bps per user.

The average received SNR (signal-to-noise ratio) for the combined four-user signal using M-ary CDMA was 6.28 dB at 5 km. Naturally, each user had equal power interferences from all other three users. Therefore, the average SINR (signal to interference plus noise ratio) was 0.28 dB. Two chirp signals were also inserted at the beginning and the end of each data packet to measure the Doppler shift according to the method proposed in [15]. The Doppler shift measured was about −1.0 Hz. The output waveforms of correlation receiver for each user of 5 km are shown in Figure 4. These curves are akin to the traditional

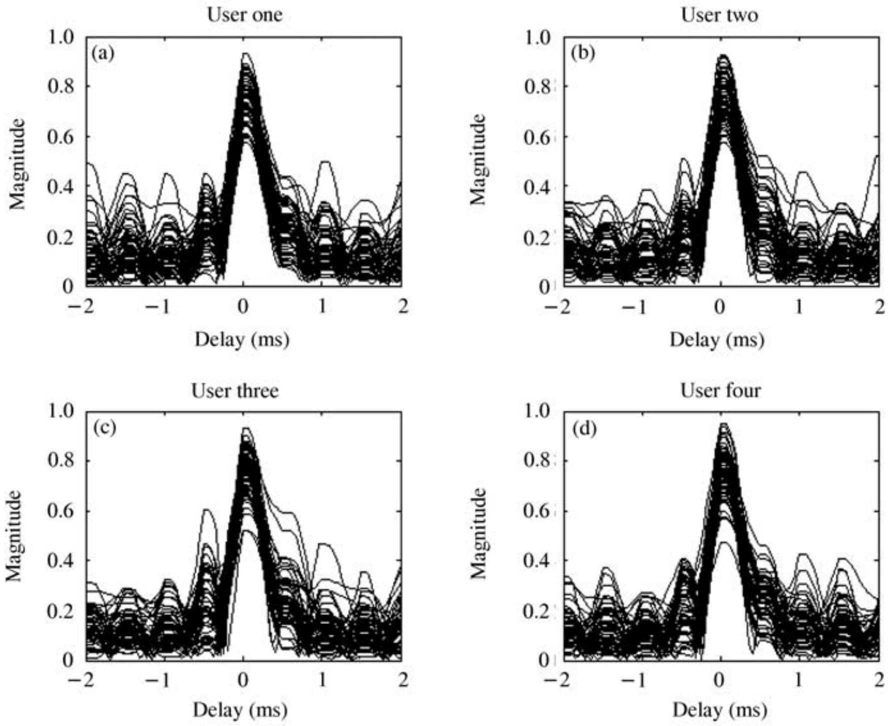

Figure 4 Outputs of correlator of four-user synchronous M-ary CDMA at 5 km showing open eyes.

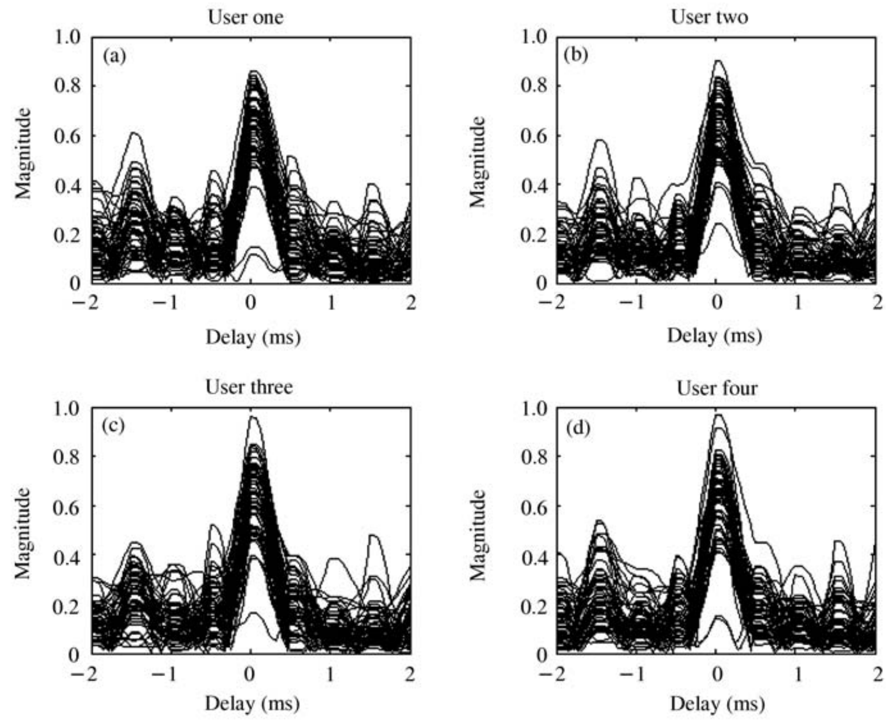

Figure 5 Open eyes at the outputs of correlator of four-user synchronous M-ary CDMA at 15 km.

eye diagram. The peaks in the middle of the correlation receiver output waveforms before sampling implies resistance to channel noise and interferences. Hence, a large peak means a large open eye.

The average received SNR for the combined four-user signal at the range of 15 km was 4.66 dB. Thus, given equal signal power, the average SINR for each user was −1.34 dB. The Doppler shift measured was about −2.1 Hz at 15 km. At the receiver, the correlation receiver output waveform for each user at

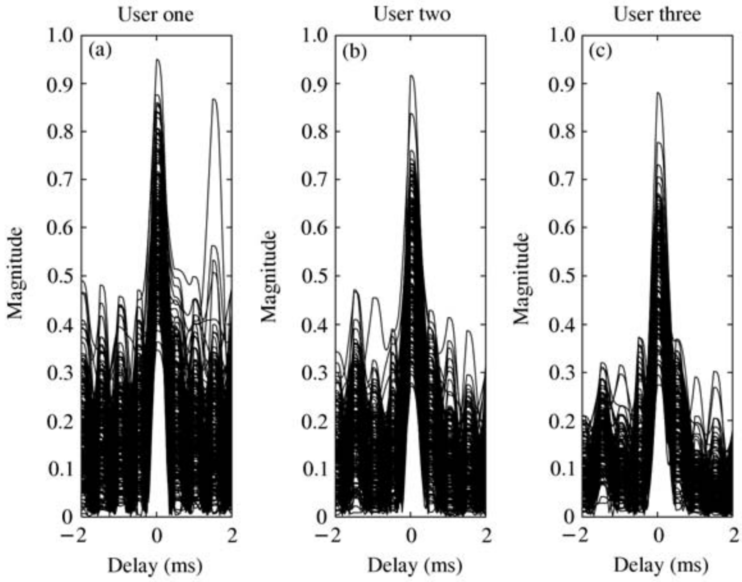

Figure 6 Open eyes at the outputs of correlator of three-user asynchronous M-ary CDMA.

15 km is shown in Figure 5. Again, open eyes were observed for all four users. The measured total average bit error rate (BER) for the four-user signal was 0 and 5.8×10^{-3}, at 5 and 15 km, respectively. Compared with coherent demodulation of DS-CDMA, the promising results showed that only one hydrophone was able to demodulate information successfully.

4.4 Asynchronous M-ary CDMA lake experimental results

For the asynchronous M-ary CDMA test, the received signals were constructed by superimposing recorded data from two locations. A special characteristic was that the M-ary CDMA system allows different users to use spreading sequences of unequal lengths. The received signals were recorded at the range of 5 and 15 km, respectively. Three-user asynchronous M-ary CDMA experiment was performed.

The average received SNR of user one signal was 7.1 dB from the recorded data of 5 km. The user one was given 32 Gold sequences of length of 31 to carry 5 bits of information. The Doppler shift was about −1.3 Hz. For user two, the average received SNR was 5.5 dB from the recorded data of 15 km. This user was given 64 Gold sequences. Hence, user two transmitted 6 bits information using a sequence twice as long as user one. The Doppler shift was about −2.2 Hz. User three was assigned 128 Gold sequences with a length of 127 to represent 7 bits of information from the recorded data of 15 km. The Doppler shift measured was about −2.2 Hz and the average received SNR was 5.5 dB. User two's signal and user three's signal were added to user one signal with a delay of 8 chips interval and 16 chips interval respectively in order to emulate the three-user asynchronous effect. The average SINRs for user one, user two and user three were 2.3, 0.7 and 0.7 dB, respectively. The output waveforms of correlation receiver for each user are shown in Figure 6. The waveforms again showed open eyes and forecasted BER performances. The higher the sidelobe of the correlation receiver output waveform, the worse the BER performance. The corresponding data rates were 322, 190 and 110 bps, respectively for the three users. The BER of user one and user two were 8.9×10^{-2} and 2.1×10^{-2}, and no error bit was observed for user three, suggesting that a very high sidelobe caused a high BER for user one as shown in Figure 6.

4.5 Performance in mobile condition

Limited by the practical environment of lake experiments, we only obtained the communication data with slight platform movement caused by water current. During each lake experiment, the transmitted ship was moving because of the water current. The drift speeds were about 0.15 m/s at 5 km, and 0.3 m/s at 15 km based on the estimated Doppler shifts. To evaluate system performance in mobile condition, UUV

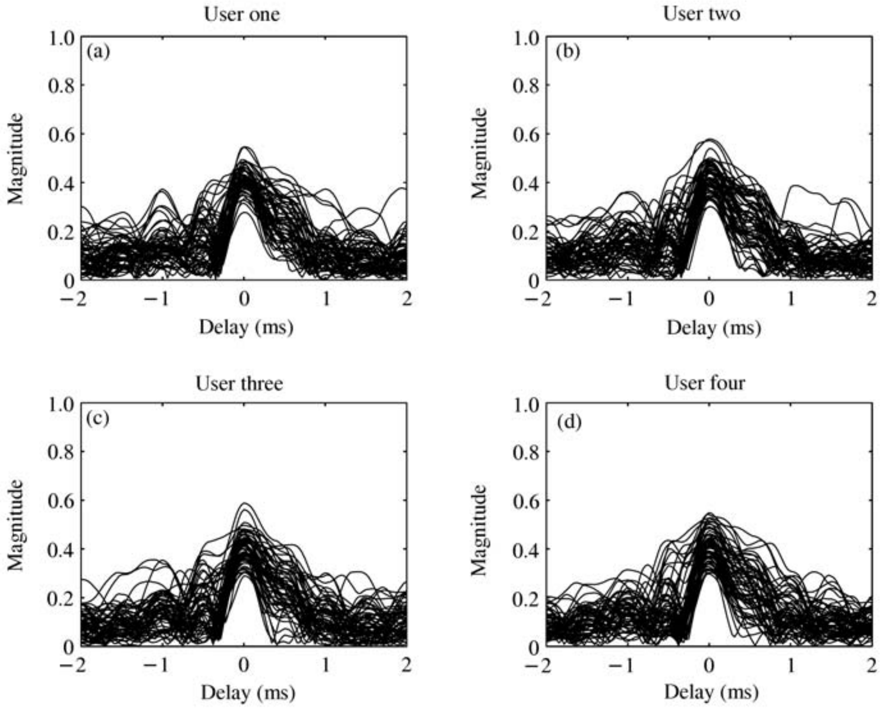

Figure 7 Open eyes at the outputs of correlator of four-user synchronous M-ary CDMA at 15 km with a speed of 3 m/s.

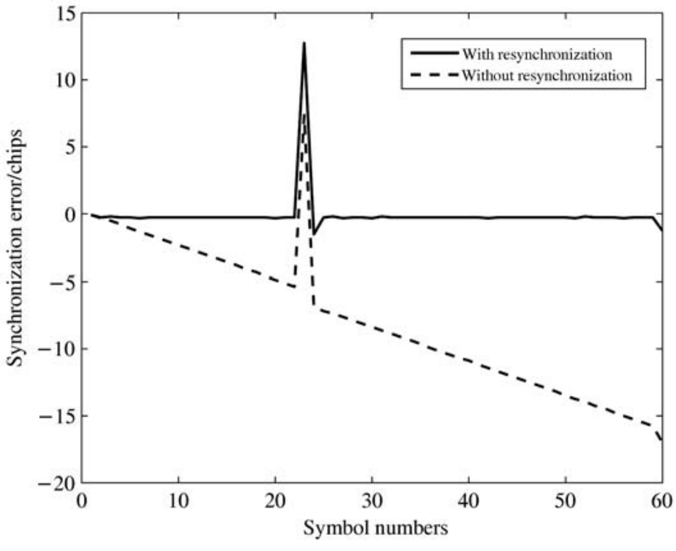

Figure 8 Synchronization error comparison.

platform speed was simulated by re-sampling the recorded data from lake experiment by a constant factor [15]. We chose the synchronous M-ary CDMA signals for four users at the range of 15 km. The constant speed was assumed to be 3 m/s (6 knots). At the receiver, the correlation receiver output waveforms for each user are shown in Figure 7. Compared with Figure 5, we found that the magnitude of Figure 7 was smaller than that of Figure 5 which was caused by Doppler effect. The measured total average BER was 6.25×10^{-3}, slightly worse than that of Figure 5.

The synchronization errors of using Doppler compensation method are shown in Figure 8. The vertical axis unit is chip that shows synchronization error value. For comparison, the synchronization errors without using Doppler compensation method are drawn as dotted lines. With Doppler compensation, there was a peak caused by the decision error, meaning that there was an error symbol. With Doppler compensation, the synchronization errors maintained a small value, unless error symbols existed. The synchronization errors only have slight fluctuation along with the increase in symbol numbers. However, along with the increase of symbol numbers, the synchronization errors became larger without using Doppler compensation. In this case, we could not demodulate the received signal correctly.

5 Conclusions

In this paper, we reported the design, implementation, and the testing of an M-ary CDMA communication. We applied reliable signal detection via correlator in shallow-water acoustic network. For four-user synchronous M-ary CDMA, each user could reach 78.8 bps within the bandwidth of 2 kHz at the range of 15 km. For three asynchronous M-ary CDMA users, the data rate could reach 322, 190 and 110 bps at 5 and 15 km, respectively. Compared with the existing DS-CDMA UWA communication systems, our experiments demonstrated significant improvement of communication range and bandwidth efficiency by adopting the M-ary CDMA system. Furthermore, the M-ary CDMA UWA communication transceivers were very simple and easy to implement. Our experiments showed that M-ary CDMA could support synchronous and asynchronous multiuser underwater acoustic communication networks. With the integration of advanced techniques such as diversity and adaptive equalization, further improvements of bandwidth efficiency and link accuracy are expected.

Acknowledgements

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