Poster Abstract: Enabling Concurrent Random Access in Underwater Acoustic Networks

Enqi Zhang[†], Lei Liang[†], Lizhao You[†], and Zhaorui Wang[‡]
[†]Xiamen University, [‡]The Chinese University of Hong Kong, Shenzhen

ABSTRACT

Uncoordinated random-access protocols are especially suitable for underwater acoustic networks with long propagation delays due to their simplicity. However, their performance is limited by severe collisions caused by uncoordinated access, and the current modulations cannot handle the collisions under the multipath environment. In this paper, we propose a new modulation and a new demodulation algorithm to resolve collisions. In particular, we adopt a Zadoff–Chu (ZC) sequence with cyclic shifts as the modulation, and assign users with different ZC sequences to minimize inter-user interference. To combat the multipath challenge, we leverage the insight that the multipath interference pattern is almost constant within the same packet and the modulated data only shifts the pattern, and develop a pattern-based demodulation algorithm. Trace-driven simulation results show that our new approach allows at least five users, and outperforms the existing approach by at least 8dB. In the future, we intend to develop a real-time system in a realistic environment.

1 INTRODUCTION

Underwater activities become more and more popular in recent years. One increasing demand is to collect data from underwater Internet of Things (IoT) to above-the-water gateways, such as in scuba diving and archaeological diving. However, high-rate underwater acoustic communication is very challenging. On one hand, the severe multipath effects limit the reliability. On the other hand, the propagation delay is non-negligible under the water (i.e., the acoustic signal travels at around 1500m/s underwater, much less than the speed in the air), and may lead to a high coordination overhead if the networking protocol is not carefully designed.

Uncoordinated random-access protocols (e.g., ALOHA) are especially suitable for the data collection application, and induce no protocol overhead. However, the performance of these protocols is limited by the severe collisions when users are not coordinated to transmit, and their signals may arrive at the receiver at the same time. The current systems with the orthogonal frequency division multiplexing modulation [1] and the chirp spread spectrum (CSS) modulation [2] are designed for point-to-point communication, and their demodulation methods cannot handle the collisions.

Recently, there exist some multi-packet reception algorithms (e.g., [3]) to resolve collisions for the CSS modulation in the wireless LoRa scenario. The key idea is to use the *peak-based* demodulation algorithm: locating the position of the highest peak in a demodulation window, and mapping the located position to the transmitted data. However, due to the existence of multiple paths with fractional delays (with respect to the sample duration), the highest peak may not correspond to the transmitted data.

Figure 1(b) illustrates an example under the simulation setup in Figure 1(a). The above figures show the individual received signals assuming the demodulation window of the target symbol, and the below figures show the superimposed signals. In this example, both user 1 and user 2 encounter seven paths, but with different delays and gains. We set three paths with fractional delays. In the first symbol, user 1 transmits data 0, and the multipath effect leads to several peaks. The fractional path delays weaken the peaks, making the decision of the highest peak vulnerable to noise. Thus, the superimposed signal does not exhibit the highest peak at the position corresponding to 0. In the second symbol, user 1 transmits different data, and user 2 also transmits different data, leading to different interference. The noise also makes the superimposed signal output a wrong peak position.

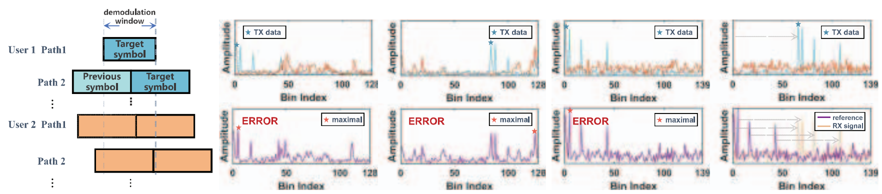
2 OUR APPROACH

The fundamental challenges to resolve collisions lie in a) *the non-negligible inter-user interference* and b) *the fractional path delays making peak decisions vulnerable to noise.* We address these challenges through the following two designs:

Zadoff-Chu(ZC) sequence-based modulation. Inspired by the design in 4G/5G random access, we adopt the ZC sequences to minimize inter-user interference. A ZC sequence has a length of N_{zc} (usually a prime) where its element has a constant amplitude and a phase. The phase is determined by the root index q and the element index. A ZC sequence can generate N_{zc} sequences by cyclically shifting the base sequence. The cyclic auto-correlation of a ZC sequence is zero for all nonzero shifts of the sequence. The normalized cyclic cross-correlation of two distinct ZC sequences (i.e., with roots q_1 and q_2, $q_1 \neq q_2$) is $1/\sqrt{N_{zc}}$.

We assign ZC sequences with different roots to different users so that their interference is minimized. For each user, a ZC sequence is a symbol. Each symbol modulates n bits, where $2^n \leq N_{zc} < 2^{n+1}$. For a given root q, we retain $N = 2^n$ sequences from N_{zc} sequences, and encode data $s \in \{0, 1, \dots, N-1\}$ into the corresponding sequence.

979-8-3503-6201-5/24/$31.00 ©2024 IEEE
DOI 10.1109/IPSN61024.2024.00039



(a) Simulation setup (b) Chirp signal (c) ZC sequence signal

Figure 1: The demodulation examples.

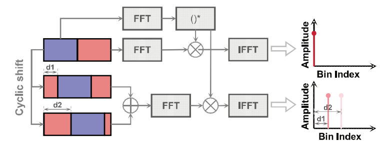


Figure 2: The ZC-seq-based mod./demod. approach.

To demodulate the received signal, we adopt the *FFT-based demodulation approach* similar to the dechirp approach in LoRa: 1) converting the time-domain received signal to frequency domain; 2) multiplying the frequency-domain signal with the conjugate of the base sequence in the frequency domain; and 3) converting the product signal to the time domain. In this way, the peak position corresponds to the encoded data. Figure 2 illustrates the ZC-seq-based modulation and demodulation approach, where different ZC sequences correspond to the peak positions encoded by the data.

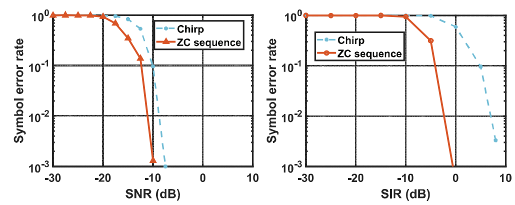
Pattern-based demodulation method. The above demodulation process applies to the single-path channel. In the multipath channel, there exist several peaks corresponding to different path delays. Furthermore, due to the existence of fractional path delays, the peaks may leak to neighboring bins, making the decision of the highest peak vulnerable to noise. Figure 1(c) illustrates an example with the ZC sequence signal assuming the same channels as in Figure 1(b). Although the inter-user interference is reduced by using ZC sequences, the noise may still cause the wrong decision.

We present a new demodulation approach to solve the problem. Although the position of the highest peak may not be accurate, the superimposed peak shape remains almost the same for all symbols within a packet except that the shape is shifted by the encoded data. Figure 1(c) illustrates the idea. In the second symbol, user 1 transmits different data, making the superimposed peak shape shift by exactly the number of bins corresponding to the encoded data. Given the insight, we can use preambles (e.g., the first symbol) to obtain the base shape, and demodulate the data that makes the shifted shape most matched with the received shape using the maximum likelihood approach.

3 EVALUATION

Simulation Setup. We evaluate the performance of the proposed signal and algorithm using the watermark channel NOF1 [4] collected from a shallow water area in Oslofjorden, Norway. The watermark channel is commonly used in underwater research, and it has severe multipath effects.

We compare the traditional linear chirp signal and the proposed ZC sequence signal. Both signals are generated with a center frequency of 14 kHz and a bandwidth of 6 kHz. We adopt the chirp signal with $SF = 7$, and the ZC sequence



(a) (b)

Figure 3: (a) SER results for single-user access; (b) SER results for multi-user random access.

of length $N_{zc} = 139$. To achieve the same rate, we retain 128 cyclic shifts of the ZC sequence. Given a transmission signal, we use the empirical channel to generate the received signal. To emulate different Signal-to-Noise Ratios (SNR), additive white Gaussian noise is added. We use the symbol error rate (SER) as the metric to compare their performance.

For the multi-user random access scenario, we simulate five users, and assign different ZC roots to these five users. There is one target user, and four interfering users. To emulate random access, we set the maximal time delay to be the duration of one symbol, and let the interfering users access the channel with a random delay. We define the Signal-to-Interference Ratio (SIR) as the ratio between the energy of the target signal and the total power of interference signals.

Simulation Results. Fig. 3(a) shows the SER results in the single-user access scenario. ZC sequence signal outperforms the chirp signal in SER due to the slightly longer symbol length and better auto-correlation property. Fig. 3(b) shows the SER results for the multi-user access scenario. Given the SER target 10^{-2}, the ZC sequence signal lowers the SNR threshold by around 8dB compared with the chirp signal.

REFERENCES

[1] S. Zhou and Z. Wang, *OFDM for underwater acoustic communications*. John Wiley & Sons, 2014.

[2] F. Steinmetz and B.-C. Renner, "Taking LoRa for a dive: CSS for low-power acoustic underwater communication," in *2022 Sixth Underwater Communications and Networking Conference (UComms)*. IEEE, 2022.

[3] Q. Chen and J. Wang, "AlignTrack: Push the limit of LoRa collision decoding," in *IEEE ICNP*, 2021.

[4] P. A. van Walree, F.-X. Socheleau, R. Otnes, and T. Jenserud, "The watermark benchmark for underwater acoustic modulation schemes," *IEEE Journal of Oceanic Engineering*, vol. 42, no. 4, pp. 1007–1018, 2017.