A Review of Single-Carrier Underwater Acoustic Communication Equalization Techniques

Ziyue Ding*

College of Future Technology, Harbin Engineering University, Harbin, China, 150001

*Corresponding author: 18209571858@163.com

Abstract. Single-carrier underwater acoustic communication equalization techniques play a significant role in marine environmental monitoring, environmental detection, and military defense. This paper provides a review of conventional and iterative equalization techniques in single-carrier underwater acoustic communication systems. First, conventional equalization techniques, including linear equalization and decision feedback equalization (DFE), are introduced, and their applications in low computational complexity and mild interference environments are discussed. Subsequently, the paper focuses on iterative equalization techniques, particularly Turbo equalization, iterative adaptive equalization, and MIMO systems, emphasizing their advantages in signal recovery under low signal-to-noise ratio conditions and their potential in handling time-varying channels and improving system capacity. Finally, this paper summarizes the limitations of existing technologies and envisions the future development of underwater acoustic communication equalization techniques through the integration of optimization algorithms and machine learning. It provides new research directions for the optimization of single-carrier underwater acoustic communication equalization techniques.

Keywords: Underwater Acoustic Communication, Equalization Techniques, Turbo Equalization, MIMO Systems, Signal Processing.

1. Introduction

Acoustic communication, as the core technology for underwater information transmission, has developed through a progression focused on overcoming the physical characteristics of underwater channels. As a fundamental supporting technology for ocean resource exploration, environmental monitoring, military defense, and underwater Internet of Things (Ocean-IoT) applications, the development of underwater acoustic communication systems has been constrained by the strong attenuation characteristics of electromagnetic and optical waves in underwater media, making sound waves the only viable long-distance information carrier. Since the mid-20th century, the development of underwater acoustic communication technology has undergone a paradigm shift, evolving from analog modulation to digital communication and from incoherent detection to coherent demodulation, forming a research framework with distinctive technical features.

In the early stages, underwater acoustic communication used analog techniques such as amplitude modulation (AM) and single-sideband modulation (SSB), primarily for short-range voice transmission. With advancements in communication technology, digital modulation techniques were introduced in the 1980s, and methods like frequency-shift keying (FSK) and differential phase-shift keying (DPSK) began to be applied to underwater acoustic communication, significantly improving communication reliability and anti-jamming capability[1-2]. In the 1990s, with breakthroughs in digital signal processing (DSP) technology, coherent communication became the focus of underwater acoustic communication research. During this period, the Stojanovic team at Northeastern University in the United States proposed a receiver structure based on decision feedback equalization (DFE) and phase-locked loops (PLL), which facilitated the realization of coherent single-carrier modulation underwater acoustic communication systems, opening a new chapter in the field[3].

However, despite significant advancements in bandwidth and anti-jamming capabilities, underwater acoustic communication still faces challenges such as multipath propagation, Doppler effects, and bandwidth limitations. These issues impose certain constraints on the system performance and reliability[3-4]. In recent years, although multi-carrier technologies such as orthogonal frequency-division multiplexing (OFDM) have been widely applied in underwater acoustic communication to address bandwidth and anti-jamming problems, single-carrier modulation technology, due to its inherent spectral efficiency advantages and peak-to-average power ratio (PAPR) characteristics, has once again become an important research direction for tackling time-varying multipath channels in complex marine environments[5]. In single-carrier architectures, equalization techniques can be classified into conventional equalization and iterative equalization, which differ fundamentally in algorithmic mechanisms and system complexity, both contributing to the transition of underwater acoustic communication from static compensation to dynamic cognition.

This paper focuses on the progress of equalization techniques in single-carrier underwater acoustic communication systems, and is organized as follows: Section 2 summarizes conventional equalization techniques and their applications, Section 3 discusses iterative equalization techniques, with a focus on Turbo equalization, adaptive iterative equalization, and MIMO system applications, and finally, Section 4 provides a summary and outlook.

2. Conventional equalization techniques

Conventional equalization is a widely used signal processing technique in digital communication systems, primarily aimed at mitigating inter-symbol interference (ISI). The basic principle of this technique is to perform inverse channel operations on the received signal through an equalizer at the receiver end, compensating for channel distortion and recovering the received signal as closely as possible to the original transmitted signal. In single-carrier communication systems, conventional equalization techniques primarily use linear equalization methods, such as Zero-Forcing (ZF) equalization and Minimum Mean Square Error (MMSE) equalization, or Decision Feedback Equalization (DFE). These techniques are often combined with channel estimation, phase-locked loop (PLL), spatial diversity, and other technologies to enhance the system's resistance to interference and phase tracking performance. Compared to iterative equalization techniques, conventional equalization does not require repeated iterations and typically relies on a single equalization calculation, resulting in lower computational complexity. However, in severe ISI and non-ideal channel environments, the performance of conventional equalization may be limited.

Tian Yanan et al. [6] employed multi-channel Decision Feedback Equalization (M-DFE) to combat multipath delay interference in complex channels under ice and compared the performance of two equalization algorithms: Improved Proportional Normalized Least Mean Square (IPNLMS) and Recursive Least Squares (RLS). Experimental results show that M-DFE effectively suppresses ISI, with RLS providing better equalization performance in the case of higher computational complexity, while IPNLMS, leveraging the sparsity of the channel, maintains good equalization performance with lower computational complexity.

To address noise robustness and Doppler frequency shift issues in single-carrier underwater acoustic communication, [7] proposed a Fast Kalman Adaptive Equalizer (FK), which, by incorporating phase tracking, effectively compensates for rotational delay in time-varying channels, improving noise robustness and resistance to Doppler frequency shifts. Compared to traditional equalizers, this method has lower complexity and superior bit error rate (BER) performance.

Xingbin Tu et al. [8] proposed an improved frequency-domain Decision Feedback Equalization (FD-DFE) method, which introduced explicit Interference-Free Information Cancellation (IFIC) strategies for two-step interference cancellation. First, Time Reversal (TR) processing is used to eliminate the primary Interference-Free Information (IFI), and then FD-DFE further eliminates the residual IFI. Additionally, a soft-symbol iterative reception method is used to continuously update IFI and channel estimates, further improving decoding performance. Experimental results indicate that the proposed method performs excellently in underwater acoustic communication experiments in the Gulf of Mexico, significantly reducing the Bit Error Rate (BER).[9] proposed a sparse direct adaptive equalization (Spares DAE) method suitable for single-carrier MIMO underwater acoustic communication, which used IPNLMS-DAE (Proportional Update, PU) to enhance convergence speed, and SZA-NLMS-DAE (Zero-Attraction, ZA) to improve sparsity. By combining both advantages, SZA-IPNLMS-DAE was introduced to optimize equalization performance and computational complexity. Furthermore, a Partial Tap Update (PTU) strategy was introduced, employing hard thresholding (HT) to select key equalization coefficients, reducing the computational load. Experimental results demonstrated that IPNLMS-DAE and SZA-IPNLMS-DAE outperformed SZA-NLMS-DAE, proving that the PU method is more suitable for underwater acoustic communication, and the PTU mechanism reduces computational complexity by 40%-70%, maintaining excellent equalization performance.

To address ISI in underwater acoustic channels, Abdelrahman Selim et al. [10] proposed a frequency-domain equalization technique based on SC-FDMA. By using frequency-domain preprocessing techniques, such as frequency-domain pre-equalization, the interference caused by multipath effects and channel attenuation is reduced. Subsequently, FD-DFE is applied to eliminate the remaining interference, optimizing the transmission process and enhancing system performance. Experimental results show that this technique significantly improves image transmission quality under different underwater channel conditions, especially in low signal-to-noise ratio (SNR) scenarios, effectively reducing noise enhancement issues and reducing Bit Error Rate.

3. Iterative equalization technology

Iterative equalization is a method based on soft information processing, typically achieved by introducing an iterative feedback mechanism within the receiver to continuously optimize the output of the equalizer, thereby reducing ISI and channel distortion. The core idea is to utilize Soft-Input Soft-Output (SISO) equalizers and soft-input soft-output decoders to exchange information, updating the confidence in the transmitted symbols during each iteration, progressively bringing the received signal closer to the actual transmitted signal. Compared to conventional equalization techniques, iterative equalization can leverage the soft information exchange between the decoder and the equalizer, significantly enhancing the detection reliability and anti-interference capability of single-carrier systems in severe inter-symbol interference or non-ideal channel environments.

3.1. Iterative equalization technique based on turbo equalization

One of the important applications of iterative equalization technology is Turbo equalization, which combines Turbo coding and the equalization process. By iteratively processing the signals, it significantly improves signal decoding and detection performance. In underwater acoustic communication systems, due to the time-varying nature and multipath fading characteristics of the underwater acoustic channel, conventional equalization methods alone cannot effectively recover the original signal. Thus, Turbo equalization has become a critical approach to address this issue. In contrast to traditional methods, this technique replaces hard decision-making with probability-based confidence transfer, fully exploiting redundant information for cooperative gain, thereby significantly improving reliability in low SNR scenarios. The Turbo Equalization Principle Block Diagram is shown in Figure 1. The signal first passes through SISO component decoder 1, where it is initially decoded using external information and prior information. It is then interleaved by an interleaver and passed to SISO component decoder 2 for further optimization. In each iteration, the decoders exchange prior information to refine the signal quality, and the signal is eventually processed by a deinterleaver and a hard decision module to produce the output. This iterative process effectively improves signal decoding accuracy in the complex underwater acoustic channel environment.

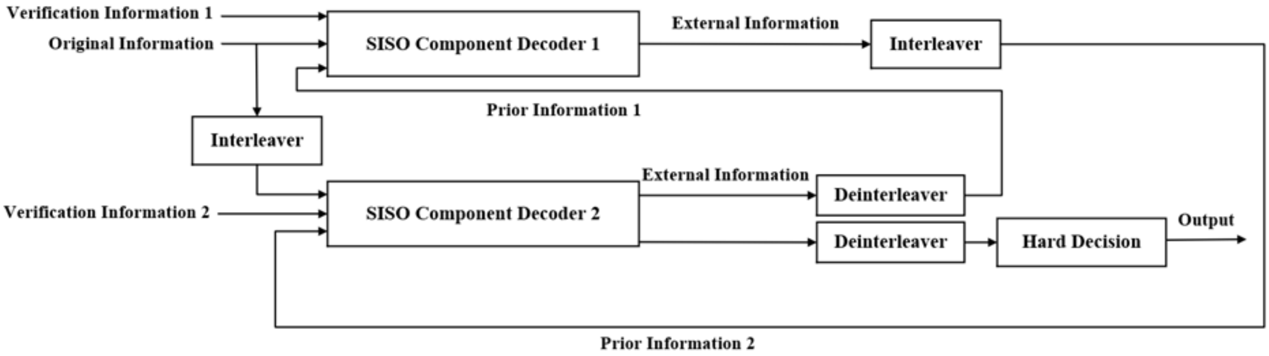

Figure 1. Turbo Equalization Principle Block Diagram

Yang Guang et al. [11] proposed a time-varying underwater acoustic channel estimation and equalization (ST-LTE) algorithm based on superimposed training sequences (ST) and low-complexity frequency domain Turbo equalization (LTE). By superimposing training sequences with symbols to improve channel information consistency, a least-squares (LS) algorithm is employed for channel estimation, while a frequency-domain LMMSE algorithm achieves low-complexity equalization. Turbo equalization further improves equalization performance through information exchange and the utilization of coding redundancy. In the MIMO underwater acoustic communication system, Xiangzhao Qin et al. [12] designed a Bayesian iterative algorithm-based MIMO underwater acoustic channel estimation (CE) and Turbo equalization (TEQ) scheme. They adopted the sparse Bayesian learning (I-SBL) algorithm for iterative MIMO underwater acoustic channel estimation and combined a space-time soft decision feedback equalizer (ST-SDFE) and successive soft interference cancellation (SSIC) for Turbo equalization.

Zhao Yanfeng et al. [13] proposed a low-complexity joint multipath cluster equalization method (MCW) for deep-sea long-range single-element underwater acoustic communication. The method implements sparse multipath cluster detection and synchronization using unprotected m-sequences, and uses the Proportional Fast A Posteriori Error Estimation Technique (PFAEST) to equalize each multipath cluster signal. Finally, delay alignment and maximal ratio combining are applied to achieve diversity gain, thus improving communication performance. Simulation and sea trial results indicate that the proposed method achieved 4000 bit/s error-free communication at a communication distance of 30 km, significantly outperforming traditional equalization methods.

3.2. Adaptive iterative equalization technology

By selecting the load prediction results of 403 and 411 lines. We can see that the actual values of the lines basically match the predicted values, but there are also some errors, especially in the peak period of electricity consumption, as shown in Table.1.

The adaptive iterative equalization method combines adaptive filtering technology and iterative processing mechanisms, dynamically adjusting the equalizer parameters to adapt to the fast changes in the underwater acoustic channel. In each iteration, the equalizer continuously optimizes the output based on the received information, aiming for more precise symbol recovery.

To address the symbol error rate (SER) issue in deep-sea vertical underwater acoustic communication, literature [14] proposed a sparse adaptive turbo equalization (Sparsity-Aware Adaptive Turbo Equalization, ATEQ) method. By improving the Inverse Proportional Normalized Minimum Symbol Error Rate (IPNMSER) criterion based on minimum symbol error rate (MSER) and the proportional normalization method, this approach enhances the convergence speed and adapts to sparse channel characteristics. Experiments in the Mariana Trench showed that IPNMSER outperforms traditional NMSER and other proportional normalization algorithms (such as IPNSA, IPNLMS, IPAPA), achieving zero-error detection at a communication distance of 10,500 meters.

Literature [15] introduced a new VP-DAE+PLL scheme, which dynamically adjusts equalizer step sizes and PLL coefficients using a recursive Gaussian-Newton method, offering better adaptability to rapidly changing underwater channel conditions. Compared to the SGD-based VP-DAE+PLL scheme, its performance is better, with lower complexity and reduced sensitivity to initial parameter settings. For single-carrier underwater acoustic communication, literature [16] proposed a delay-Doppler minimum mean square error adaptive equalizer (DD-MMSE-TEQ). By transforming the time-varying channel into a quasi-static channel using a delay-Doppler (DD) domain transformation, the method improves robustness and performance in dynamic environments. To tackle the challenges posed by impulsive noise interference, literature [17] proposed a joint impulsive noise suppression and sparse channel estimation algorithm, combining the Basic Expansion Model (BEM) and Sparse Bayesian Learning (SBL). Using the Variational Bayesian Inference (VBI) algorithm for iterative estimation of channel coefficients and impulsive noise, this method effectively improves channel estimation accuracy and suppresses impulsive noise.

3.3. Iterative equalization methods in MIMO systems

MIMO technology, which uses multiple antennas to enhance signal transmission capacity and reliability, has been widely applied in underwater acoustic communication systems. In MIMO underwater acoustic communication, the channel matrix's sparsity and multipath effects make the channel estimation and equalization processes more complex. The application of iterative equalization technology in MIMO systems can fully exploit their spatial characteristics, improving the system's anti-interference capability and signal recovery accuracy. The principle block diagram of MIMO technology is shown in Figure 2, where multiple antennas are deployed at both the transmitter and receiver ends. Multiple independent channels ($h_{11}, h_{12}, h_{21}, h_{22}$) are used to simultaneously transmit and receive multiple data streams, significantly increasing the capacity, transmission rate, and reliability of the communication system.

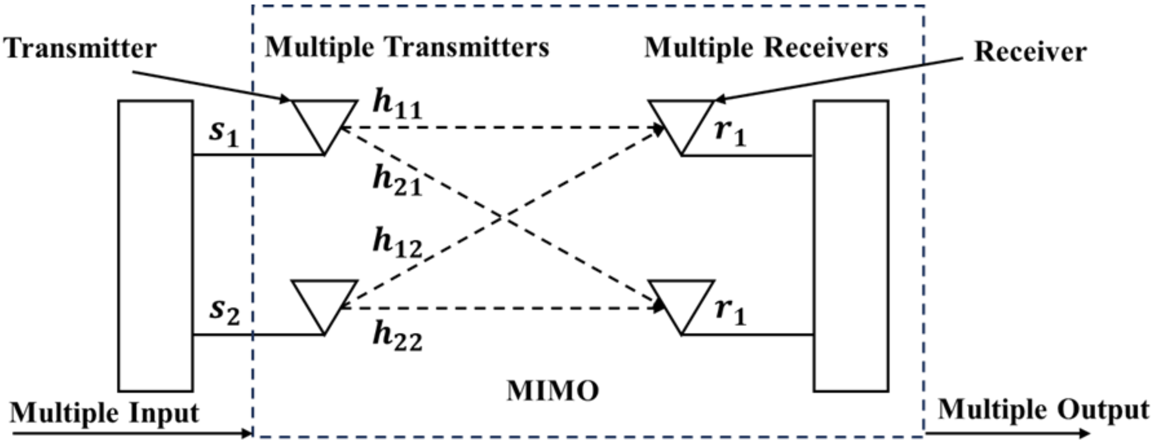

Figure 2. MIMO Technology Principle Block Diagram

Literature [18] proposed a scheme combining Adaptive Time Reversal (ATR) and Single-Channel DFE. ATR eliminates multipath interference and enhances signal focusing, while DFE further eliminates interference caused by imperfect focusing during the time-reversal process. Experimental results show that the SDM-MIMO communication with ATR-DFE scheme effectively improves data transmission rate over a communication distance of 12.5 km.

For single-carrier MIMO underwater acoustic communication, literature [19] proposed a frequency-domain equalization method combined with interference suppression, which is implemented in three steps: iterative least squares for channel estimation, interference suppression combined with interference rejection combining (IRC), and phase rotation compensation via a Digital Phase-Locked Loop (DPLL) and DFE. Experimental results show that this method significantly reduces BER and improves underwater acoustic communication performance.

4. Conclusions

The trend of mass data in power system provides a basis for load characteristic analysis and prediction model establishment, but the classical load forecasting method can not afford such a huge time and computing resource consumption. The problem of over fitting in large sample set will affect the prediction accuracy. In this paper, a power load forecasting model is built by using the BP neural network model, making full use of the powerful data processing function of Clementine and preventing the over fitting function. The experimental results show that the BP neural network model has good predictability and robustness, and has a certain practical application value.

This paper provides a comprehensive summary of recent advancements in equalization techniques for single-carrier underwater acoustic communication systems. Equalization in such systems can be broadly categorized into conventional and iterative approaches. Conventional methods, such as linear equalization and DFE, are favored for their low computational complexity and can perform well under certain environmental conditions. However, their effectiveness diminishes in scenarios characterized by severe channel distortion and high levels of interference. Iterative equalization techniques, particularly those based on Turbo equalization, leverage soft information processing to significantly improve detection reliability in low SNR environments. Nevertheless, their high computational demands hinder widespread practical implementation. Moreover, the application of MIMO technology in underwater acoustic communication remains at an exploratory stage. Despite its potential to enhance system capacity and interference resilience, the effective deployment of MIMO in oceanic environments presents significant challenges.

Future research should thus focus on several key areas. To address the computational intensity of iterative equalization, algorithmic optimization is essential to enhance real-time processing capabilities. The integration of MIMO in underwater systems requires further investigation, especially under deep-sea and multipath channel conditions, to fully exploit its spatial diversity gains for improved robustness and higher transmission rates. Furthermore, interdisciplinary approaches—such as incorporating machine learning into channel estimation and equalization—hold promise for overcoming existing technological limitations and advancing the field.

References

[1] Yang J, Wang J, Qiao G, et al. Overview of underwater acoustic communication and network technologies[J]. Journal of Electronics and Information Technology, 2024, 46(01): 1-21.

[2] Wang L. Key technologies and development discussion of underwater acoustic communication[J]. Acoustics and Electronic Engineering, 2024, (02): 68-71.

[3] Liu J, Leng X, Ji Q, et al. Research progress on channel estimation techniques in underwater acoustic communication[J]. Telecommunication Technology, 2024, 64(12): 2081-2090.

[4] Zhang Y, Wang H, Li C, et al. Progress in the intersection of channel estimation and machine learning in underwater acoustic communication[J]. Acoustic Technology, 2022, 41(03): 334-345.

[5] Zhang Y, Huang F, Lan H, et al. Overview of single-carrier modulation techniques for underwater acoustic communication[J]. Journal of Harbin Engineering University, 2019, 40(11): 1809-1815.

[6] Tian Y, Zhang A, Li L, Zhu G, Li W. Experimental study of single-carrier underwater acoustic communication under ice[J]. Acoustic Technology, 2022, 41(5): 648-653.

[7] Wu F Y, Yang H Z, Zhou Y, et al. A fast Kalman equalizer for single-carrier underwater acoustic communication[J]. IEEE Transactions on Industrial Informatics, 2024.

[8] Tu X, Xu X, Song A. Frequency-domain decision feedback equalization for single-carrier transmissions in fast time-varying underwater acoustic channels[J]. IEEE Journal of Oceanic Engineering, 2020, 46(2): 704-716.

[9] Tao J, Wu Y, Han X, et al. Sparse direct adaptive equalization for single-carrier MIMO underwater acoustic communications[J]. IEEE Journal of Oceanic Engineering, 2019, 45(4): 1622-1631.

[10] Selim A, Abdellatif H, Taha T E, et al. Efficient image transmission in high-degradation scenarios[J]. Journal of Optics, 2024, 53(3): 1689-1694.

[11] Yang G, Ding H, Guo Q, et al. Time-varying underwater acoustic channel estimation and equalization based on stacked training sequences and low-complexity frequency domain turbo equalization[J]. Journal of Electronics and Information Technology, 2021, 43(3): 850-856.

[12] Qin X, Qu F, Zheng Y R. Bayesian iterative channel estimation and turbo equalization for MIMO underwater acoustic communications[J]. IEEE Journal of Oceanic Engineering, 2020, 46(1): 326-337.

[13] Zhao Y, Tong F, Ma B, et al. Joint multi-path cluster equalization method for deep sea long-range single element underwater acoustic communication[J]. Acta Acustica, 2024, 49(4): 764-773.

[14] Xi J, Yan S, Xu L, et al. Sparsity-aware adaptive turbo equalization for underwater acoustic communications in the Mariana Trench[J]. IEEE Journal of Oceanic Engineering, 2020, 46(1): 338-351.

[15] Liu C, Tao J, Huang W. A recursive Gaussian Newton-based variable parameter adaptive receiver for single-carrier underwater acoustic communications[J]. IEEE Transactions on Vehicular Technology, 2024.

[16] Zheng T, He C, Jing L, et al. Delay-Doppler domain turbo equalization for single-carrier underwater acoustic communications[J]. IEEE Journal of Oceanic Engineering, 2025.

[17] Yu H, Liang Y, Ma H, et al. Joint impulsive noise mitigation and sparse channel estimation for mobile underwater acoustic communication[J]. IEEE Wireless Communications Letters, 2024.

[18] Kida Y, Deguchi M, Shimura T. Experimental demonstration on long-range time-reversal multiple-input/multiple-output underwater acoustic communication over tens of kbps in 12.5 km range[J]. Japanese Journal of Applied Physics, 2022, 61(SG): SG1057.

[19] Yin J, Ge W, Han X, et al. Frequency-domain equalization with interference rejection combining for single carrier multiple-input multiple-output underwater acoustic communications[J]. The Journal of the Acoustical Society of America, 2020, 147(2): EL138-EL143.