A Survey of Underwater Acoustic Communication Systems Utilizing OFDM and OTFS Waveforms

www.surveyx.cn

Abstract

Underwater acoustic communication (UAC) systems are critical for various applications, including oceanographic data collection, exploration, and military operations. These systems face significant challenges such as multipath propagation, high attenuation, and the Doppler effect, which complicate signal transmission and reception. This survey examines the roles of Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Time Frequency Space (OTFS) waveforms in addressing these challenges. OFDM is effective in managing frequency-selective fading and multipath propagation, while OTFS offers resilience against Doppler shifts, making it suitable for high-mobility environments. The survey highlights advancements in channel estimation methods, including machine learning models and robust optimization algorithms, which improve the accuracy and reliability of UAC systems. Adaptive modulation techniques further enhance data transmission efficiency by dynamically adjusting to real-time channel conditions. Despite these advancements, challenges remain, necessitating further research into refining theoretical models, exploring additional waveform designs, and optimizing resource allocation strategies. Future research should focus on enhancing signal quality through advanced filtering techniques and optimizing the trade-off between estimation accuracy and complexity. By leveraging emerging technologies and optimizing current methodologies, future research can significantly advance the capabilities of underwater communication systems, ensuring robust and efficient communication in challenging aquatic environments.

1 Introduction

1.1 Significance of Underwater Acoustic Communication

Underwater acoustic communication (UAC) systems are essential for various applications, particularly in oceanographic data collection, where they facilitate the acquisition of vital information regarding ocean dynamics, marine life, and environmental conditions [1]. The growing need for effective marine resource management has highlighted the importance of advanced UAC technologies, which are crucial for reliable communication in challenging underwater environments [2].

Beyond scientific inquiry, UAC systems are integral to underwater exploration and military operations, supporting diverse activities such as submarine communication and mine detection [3]. They also play a significant role in environmental monitoring, delivering real-time data essential for resource management and environmental protection [4]. Nonetheless, UAC systems encounter substantial challenges, including high attenuation and multipath propagation, which complicate signal transmission and reception [5]. Additionally, path loss, influenced by transmission distance and signal frequency, presents further obstacles that must be addressed to improve the efficiency and reliability of underwater communication [6].

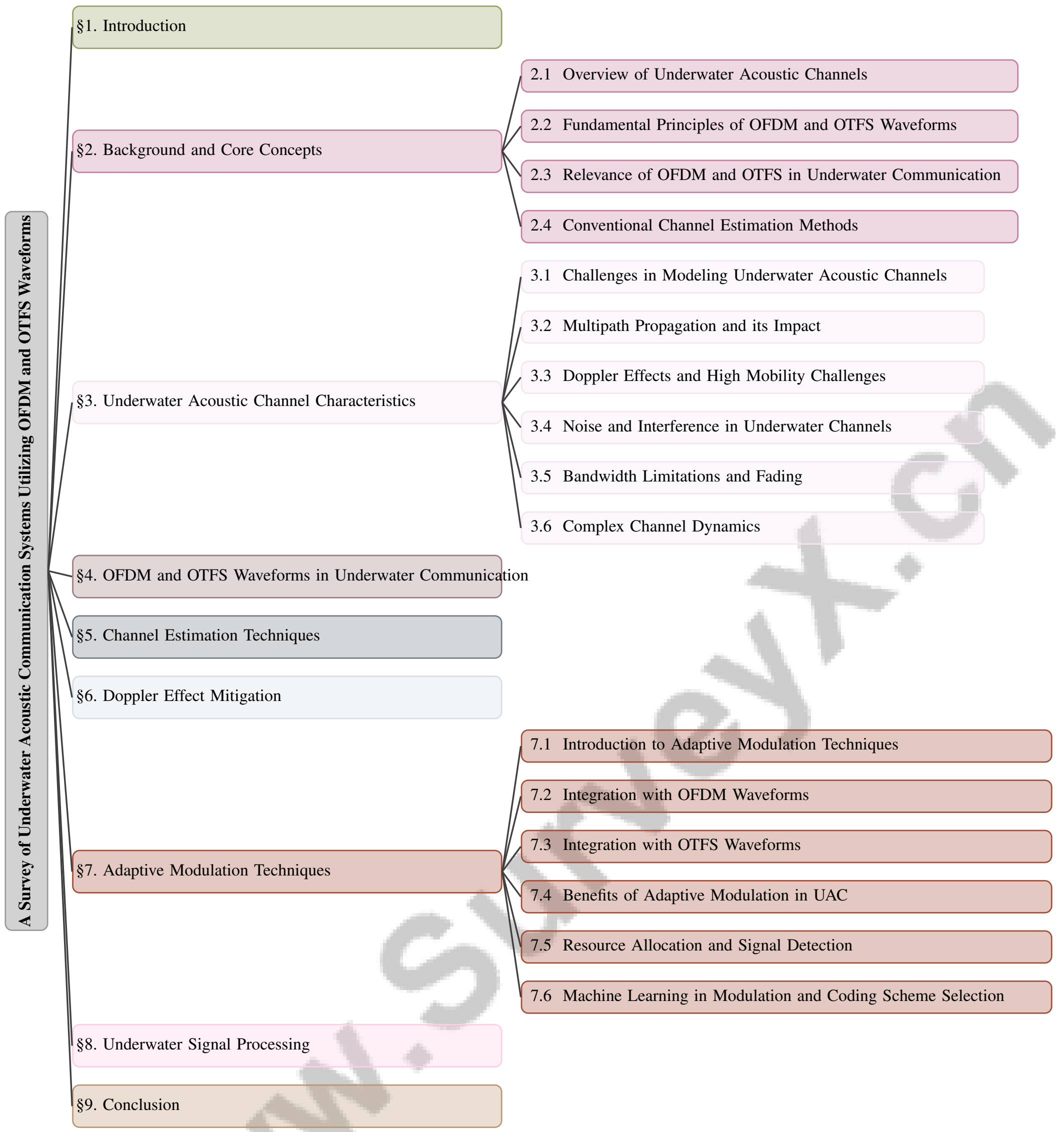

Figure 1: chapter structure

1.2 Challenges in Underwater Communication

The complexities of the aquatic environment impose numerous challenges on underwater communication systems. Multipath propagation, where signals reflect off surfaces such as the sea floor and water surface, results in overlapping signal paths that hinder reception and interpretation. High attenuation rates in underwater channels further diminish signal strength over distance, complicating reliable communication [1]. Path loss, affected by transmission distance and signal frequency, adds to the difficulties in efficient network design [6].

The Doppler effect poses significant challenges in high-mobility scenarios due to relative motion between transmitters and receivers, leading to non-uniform frequency shifts and inter-carrier interference (ICI) that degrade communication performance. Conventional modulation techniques, such as orthogonal frequency division multiplexing (OFDM), struggle to maintain effective communication under these conditions, while emerging technologies like orthogonal time frequency space (OTFS) modulation are designed to operate within the delay-Doppler domain, offering improved resilience to Doppler shifts and enhanced error performance in dynamic channels [7, 8, 9]. This limitation is particularly pronounced in scenarios involving underwater vehicles or marine life, where traditional

AI-generated, for reference only.

multicarrier systems like OFDM cannot sustain communication integrity due to severe Doppler spreads and ICI.

Furthermore, the reliance on accurate channel state information (CSI) complicates underwater communication systems. Outdated CSI in underwater acoustic (UWA) communication systems hampers the efficiency of adaptive communication technologies, necessitating more effective methods for obtaining and updating CSI [10]. Conventional adaptive modulation and coding (AMC) methods often fail to adapt dynamically to the unpredictable characteristics of underwater channels, highlighting the need for more efficient adaptive techniques [4].

Additionally, existing data processing methods struggle to manage large datasets efficiently, leading to increased processing times and resource consumption, emphasizing the necessity for advanced data processing strategies [11]. The nonconvex nature of optimization problems, particularly in balancing the trade-off between minimizing peak sidelobe levels and maximizing communication data rates under various constraints, remains a significant hurdle [12]. These challenges underscore the urgent need for innovative solutions and advanced technologies to enhance the reliability and efficiency of underwater acoustic communication systems.

1.3 Role of OFDM and OTFS Waveforms

Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Time Frequency Space (OTFS) waveforms are crucial in addressing the challenges faced by underwater acoustic communication systems. OFDM effectively manages multipath propagation and frequency-selective fading by partitioning the communication channel into multiple orthogonal subcarriers, thus improving signal clarity and reliability at the receiver [11]. However, OFDM's efficacy diminishes in high-mobility environments due to the Doppler effect, which generates ICI and adversely affects communication performance.

In contrast, OTFS has emerged as a robust alternative, particularly in environments with significant Doppler shifts. By operating in the delay-Doppler domain, OTFS leverages the time-frequency diversity of the channel, enhancing communication robustness in dynamic underwater conditions. This capability is particularly beneficial in scenarios where Doppler effects are prevalent, allowing OTFS to maintain low peak-to-average power ratios (PAPR) and simplify CSI estimation. Experimental evaluations have shown OTFS's superior performance over OFDM concerning bit error rates (BER) under high Doppler frequency shifts, underscoring its suitability for high-mobility environments [13].

Moreover, OTFS's integration into joint communication frameworks, such as the OTFS-based integrated sensing and communications (ISAC) system, optimizes both communication and sensing functionalities, which is critical for underwater applications requiring simultaneous environmental monitoring and data transmission [14]. This unified approach addresses the inefficiencies of traditional methods, including OFDM, by leveraging parallel processing capabilities to enhance overall system performance [6]. The survey emphasizes the importance of adaptive systems and technologies in improving performance in challenging underwater environments [3].

1.4 Structure of the Survey

This survey is structured to provide a comprehensive examination of underwater acoustic communication systems, focusing on the utilization of Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Time Frequency Space (OTFS) waveforms. The paper begins with an **Introduction**, elucidating the significance of underwater acoustic communication and the inherent challenges. This section also introduces the pivotal role of OFDM and OTFS waveforms in addressing these challenges.

Subsequently, the survey delves into the **Background and Core Concepts**, outlining the characteristics of underwater acoustic channels and explaining the fundamental principles of OFDM and OTFS waveforms, alongside conventional channel estimation methods like least squares, laying the groundwork for subsequent discussions.

The third section, **Underwater Acoustic Channel Characteristics**, analyzes the unique challenges posed by underwater channels, including multipath propagation, Doppler effects, and noise, and their implications for communication system design and performance. This is followed by a critical assessment of **OFDM and OTFS Waveforms in Underwater Communication**, evaluating their

AI-generated, for reference only.

applications, performance, advantages, and limitations in addressing underwater communication challenges.

In the fifth section, **Channel Estimation Techniques**, the survey reviews traditional and recent advancements in channel estimation methods, exploring alternative approaches and the potential of deep learning techniques for enhanced estimation accuracy. This leads to a focused discussion on **Doppler Effect Mitigation**, analyzing strategies for mitigating Doppler effects, particularly emphasizing the contributions of OFDM and OTFS waveforms.

The survey further explores **Adaptive Modulation Techniques**, highlighting their role in enhancing data transmission reliability and efficiency in underwater acoustic channels, discussing their integration with OFDM and OTFS waveforms.

The penultimate section, **Underwater Signal Processing**, addresses specific signal processing challenges and solutions pertinent to underwater communication systems, emphasizing advanced algorithms and technologies that improve system performance.

Finally, the **Conclusion** summarizes the key findings of the survey, reflects on the current state of underwater acoustic communication systems, and suggests future research directions to tackle existing challenges. This structured approach facilitates a thorough investigation of underwater acoustic communication technologies, particularly focusing on the challenges posed by the harsh oceanic environment. By integrating advanced machine learning techniques for adaptive modulation and coding, the exploration yields significant insights that can enhance the design and implementation of communication systems, benefiting both researchers and practitioners in the field [2, 15, 6].The following sections are organized as shown in Figure 1.

2 Background and Core Concepts

2.1 Overview of Underwater Acoustic Channels

Underwater acoustic channels present unique challenges for communication systems due to their high attenuation and variability, particularly at ultrasonic frequencies [5]. The non-stationary underwater environment, influenced by multipath propagation and impulsive noise, demands robust communication strategies [16]. Effective modeling of path loss, which varies with distance and frequency, is essential for optimizing network performance [1]. Environmental factors such as temperature, salinity, and water movement further complicate accurate modeling [17].

The broadcast nature of underwater acoustic networks makes them susceptible to jamming attacks, highlighting the need for enhanced security measures [18]. Research into channel capacity is critical, especially in environments with non-Gaussian noise and generalized fading, which complicate capacity optimization [19]. The growing prevalence of underwater activities necessitates effective communication systems to overcome these challenges [20]. Recent surveys advocate for advanced modeling and adaptive communication techniques to address the complexities of underwater environments [4]. Models offering closed-form approximations for power consumption, bandwidth, and capacity based on distance provide valuable insights for designing efficient systems [6]. Innovative solutions and adaptive technologies are essential to enhance communication reliability and efficiency in underwater acoustic channels [3].

2.2 Fundamental Principles of OFDM and OTFS Waveforms

Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Time Frequency Space (OTFS) waveforms are pivotal in enhancing communication efficiency in underwater acoustic channels. OFDM, a multicarrier modulation technique, effectively addresses frequency-selective fading and multipath propagation by dividing bandwidth into orthogonal subcarriers, thus simplifying receiver equalization [14]. Enhanced versions of OFDM employ advanced cyclic prefix design and pulse shaping to mitigate inter-symbol interference (ISI) and inter-carrier interference (ICI).

OTFS, operating in the delay-Doppler domain, offers significant advantages in high-mobility environments with severe Doppler effects [21]. Unlike OFDM, OTFS spreads data across the entire time-frequency grid, leveraging delay-Doppler characteristics to enhance robustness against time-variant impairments [22]. This capability ensures consistent performance in high-Doppler scenarios, such as underwater channels [9].

OTFS is defined as a two-dimensional signaling technique, multiplexing QAM information symbols over waveforms in the delay-Doppler representation [23]. This method embeds information in the delay-Doppler domain, converting it to a time-domain transmit signal, facilitating effective communication in high-Doppler fading channels [21]. Implementations of OTFS use transformations like the symplectic finite Fourier transform (SFFT) and discrete Zak transform (DZT) to enhance computational efficiency and reduce complexity [24].

Both OFDM and OTFS have distinct advantages depending on channel conditions. OFDM is effective in moderate mobility and frequency-selective environments but suffers in high-mobility scenarios due to significant Doppler shifts. OTFS, with its delay-Doppler domain operation, significantly enhances communication reliability in such conditions, making it suitable for next-generation applications, including 6G networks [8, 21, 25, 26, 23]. Selecting the appropriate waveform is crucial based on specific communication challenges and objectives.

2.3 Relevance of OFDM and OTFS in Underwater Communication

OFDM and OTFS waveforms are integral to addressing the challenges of underwater acoustic channels, including multipath propagation, Doppler effects, and noise. OFDM's division of the communication channel into orthogonal subcarriers effectively mitigates frequency-selective fading and simplifies receiver equalization, making it suitable for environments with prevalent multipath propagation [1]. However, its performance is limited in high-mobility scenarios due to susceptibility to inter-carrier interference (ICI) from Doppler shifts [27].

In contrast, OTFS excels in high-mobility underwater environments with severe Doppler effects. By operating in the delay-Doppler domain, OTFS enhances communication robustness and reduces detection complexity, relying less on channel state information (CSI) [10]. This capability makes OTFS particularly effective in managing Doppler shifts, enhancing spectral efficiency and reliability compared to traditional OFDM [9]. Experimental emulations have demonstrated OTFS's superior performance over OFDM in bit error rate (BER) under high Doppler frequency shifts, confirming its suitability for high-mobility environments [13].

Integrating OTFS with technologies like Non-Orthogonal Multiple Access (NOMA) enhances its applicability in underwater communication by combining time and frequency diversity, improving spectral efficiency and user experience in high-mobility scenarios [4]. The capacity of the underwater acoustic (UWA) channel can be effectively bounded using a GG noise model and an fading distribution, providing a more accurate representation of real-world conditions [19]. This modeling underscores the importance of effective waveform design, as highlighted by network coding-based approaches that optimize transmission power and performance in UWA systems [1].

The deployment of OFDM and OTFS waveforms significantly enhances underwater communication systems' ability to cope with unique environmental challenges. While OFDM addresses frequency-selective fading effectively, OTFS's superior performance in managing Doppler effects and its integration with advanced multiple access schemes position it as a promising solution for future underwater communication systems [23].

2.4 Conventional Channel Estimation Methods

Conventional channel estimation methods in underwater acoustic communication systems have primarily relied on linear algorithms, which often inadequately address the complex and dynamic nature of underwater channels [28]. These traditional approaches typically involve linear equalization techniques that assume a stationary channel environment, rarely present in underwater settings characterized by severe doubly-spread and time-variant characteristics [29]. The limitations of these methods are exacerbated by impulsive noise, which significantly affects the convergence and stability of linear equalizers [16].

To enhance channel estimation accuracy and reliability, researchers have explored advanced methodologies, including machine learning and deep learning techniques, such as Deep Neural Networks (DNN) and Long Short Term Memory (LSTM) networks, which outperform traditional linear models in complex underwater environments. Adaptive estimation frameworks utilizing l21 norms and novel equalization algorithms have been developed to address non-stationarity and impulsive noise challenges, thereby improving overall estimation performance [17, 10, 30, 31, 16]. Machine learning techniques, particularly DNNs and LSTMs, leverage real-world data to learn and predict channel characteristics, offering improved adaptability to dynamic underwater conditions.

Additionally, parallel computing strategies such as Parallel Data Processing Algorithms (PDPA) enhance channel estimation efficiency by distributing data processing tasks across multiple processors, significantly reducing computation time [11]. This approach is particularly beneficial for real-time processing of large datasets, common in underwater communication systems.

Simplified modeling techniques like the Approximate Model for Underwater Acoustic Communication (AMUAC) have been developed to streamline communication parameter estimation, offering a more tractable approach to understanding the relationship between transmission power and channel capacity [6].

While traditional channel estimation methods provide a foundational understanding of underwater acoustic channels, integrating advanced machine learning models and parallel computing techniques represents a significant advancement in addressing these conventional approaches' limitations. These innovations improve estimation accuracy and enhance the adaptability and robustness of underwater communication systems in complex and variable channel conditions [3].

3 Underwater Acoustic Channel Characteristics

3.1 Challenges in Modeling Underwater Acoustic Channels

Modeling underwater acoustic channels is complex due to their dynamic nature, influenced by environmental factors like ocean currents and depth variations, which lead to time-variant and doubly-spread characteristics. These conditions complicate communication system design, requiring advanced modeling techniques, including deep learning methods, to accurately capture channel dynamics [20, 32, 17, 6]. The rapid changes in channel state hinder reliable communication in underwater sensor networks, resulting in frequent routing failures.

Unique noise characteristics, particularly non-Gaussian noise in shallow waters, further complicate modeling. These noise characteristics deviate from standard Gaussian models used in terrestrial systems, complicating capacity evaluation and necessitating specialized models [19]. Environmental factors such as temperature gradients, salinity, and pressure variations contribute to the non-stationary nature of underwater channels, complicating predictions of channel behavior over time [17]. These complexities underscore the need for innovative modeling strategies that address the variable nature of underwater environments [3].

3.2 Multipath Propagation and its Impact

Multipath propagation challenges underwater acoustic communication due to reflections and scattering from surfaces like the seabed and submerged objects, resulting in overlapping signal paths that cause distortion and inter-symbol interference (ISI) [30]. This variability can degrade bit error rate (BER) performance, necessitating robust modulation and equalization techniques. OTFS waveforms, for instance, offer advantages over traditional OFDM by maintaining improved BER performance in environments with severe multipath effects [26].

Adaptive communication strategies, such as adaptive modulation and coding (AMC) and machine learning-based channel state information prediction, optimize bandwidth efficiency, reliability, and latency, enhancing system performance in harsh underwater environments [10, 2, 3, 23, 16]. Advanced equalization and channel estimation methods are crucial for mitigating the adverse effects of multipath propagation, ensuring high performance and reliability in underwater communication systems.

3.3 Doppler Effects and High Mobility Challenges

The Doppler effect significantly impacts underwater acoustic communication, particularly in high mobility environments. Relative motion between transmitters and receivers causes non-uniform frequency shifts, leading to inter-carrier interference (ICI) that degrades communication performance [33]. Fractional Doppler shifts further complicate detection processes and reduce error performance [34].

In underwater settings, moving targets introduce substantial Doppler shifts, impacting measurement accuracy and system performance [35]. These shifts can couple channel response with data symbols in the delay-Doppler domain, resulting in inter-carrier interference and diminished estimation accuracy [33]. OFDM systems are particularly susceptible to these challenges due to high sidelobes in their ambiguity function, which negatively affect sensing capabilities [36]. In contrast, OTFS waveforms operate in the delay-Doppler domain, effectively managing Doppler effects and maintaining robust performance despite RF impairments like non-linearity and Carrier Frequency Offset (CFO) [13]. This makes OTFS particularly suitable for underwater communication systems facing significant Doppler challenges.

3.4 Noise and Interference in Underwater Channels

Underwater acoustic communication systems encounter various noise and interference types, significantly challenging reliable data transmission. Noise is categorized into ambient and man-made noise. Ambient noise, generated by natural sources such as marine life and wave action, is typically low-frequency and varies with environmental conditions [28]. Man-made noise, arising from human activities like shipping and underwater construction, introduces sporadic interference, especially in high-activity areas. The broadcast nature of underwater acoustic networks exacerbates interference, as overlapping signals from multiple sources increase error rates [18].

Multipath propagation adds complexity, where signals reflecting off various surfaces create multiple paths that interfere with one another [30]. This interference is particularly problematic in shallow waters, leading to significant signal distortion and ISI. Impulsive noise, characterized by sudden amplitude spikes, further disrupts signal processing, increasing bit error rates [16]. The non-Gaussian nature of impulsive noise complicates mitigation efforts, necessitating advanced noise reduction techniques tailored to underwater environments [19]. The interplay of various noise sources and interference underscores the need for robust communication strategies capable of adapting to the dynamic underwater environment. Advanced signal processing techniques, such as adaptive filtering and noise cancellation, are crucial for improving the resilience of underwater communication systems [3].

3.5 Bandwidth Limitations and Fading

Bandwidth limitations and fading are critical constraints in underwater acoustic communication systems. High signal attenuation, particularly at higher frequencies, limits available bandwidth, necessitating efficient management strategies to optimize data transmission rates [5, 1]. Fading, primarily caused by multipath propagation, leads to fluctuations in signal amplitude and phase due to constructive and destructive interference [30]. Environmental factors such as water movement and temperature gradients exacerbate fading, particularly in shallow water environments where rapid channel state variations occur [17].

To combat fading, advanced modulation and coding schemes that adapt to changing conditions are essential. Techniques like adaptive equalization and diversity reception play a crucial role in maintaining performance despite fading challenges [3]. Moreover, limited bandwidth and fading necessitate efficient spectrum utilization techniques. Methods like OFDM and OTFS are effective in addressing these challenges by leveraging multiple orthogonal subcarriers and the delay-Doppler domain, respectively, enhancing spectral efficiency and robustness against fading. These strategies are vital for ensuring reliable communication among underwater vehicles and between vehicles and surface consoles, particularly in the face of varying acoustic propagation conditions [4, 2, 3, 1, 6].

3.6 Complex Channel Dynamics

The dynamic nature of underwater acoustic channels presents significant challenges for reliable communication. These channels exhibit rapid temporal variations and spatial heterogeneity influenced by environmental factors such as water currents and temperature gradients, complicating the design and operation of communication systems [28]. Advanced methods like Depth-Based Channel Aware Routing (DBCAR) leverage depth information and channel quality predictions to optimize routing paths, enhancing packet delivery ratios while managing energy consumption. This adaptability is crucial for improving system performance in dynamic underwater environments [28]. Additionally, the Dynamic Feedback-Based Adaptive Stochastic Recursive Mean Adaptive Estimator

(DFB-ASRMAE) method exemplifies the importance of adaptive techniques in managing rapid channel variations, effectively reducing prediction errors and enhancing tracking accuracy [37].

The intricate dynamics of underwater channels necessitate sophisticated models and adaptive communication strategies. To enhance the robustness of underwater acoustic communication systems, it is essential to consider the interplay between environmental factors—such as ambient noise and acoustic propagation loss—and channel characteristics, including transmission distance and signal frequency. Addressing trade-offs between bandwidth efficiency, reliability, and latency is vital for distinguishing underwater acoustic channels from terrestrial communication systems [3, 6].

In recent years, the exploration of advanced modulation schemes has gained significant attention in the realm of underwater communication. One notable approach is the use of Orthogonal Frequency Division Multiplexing (OFDM) and its extension, Orthogonal Time Frequency Space (OTFS). To elucidate the complexities of these waveforms, Figure 2 presents a detailed illustration of their hierarchical structure. This figure highlights fundamental concepts and performance comparisons, categorizing the primary features and innovations of each waveform. Furthermore, it emphasizes their roles in addressing the unique challenges posed by underwater communication, thereby providing a comprehensive overview of their respective advantages and applications.

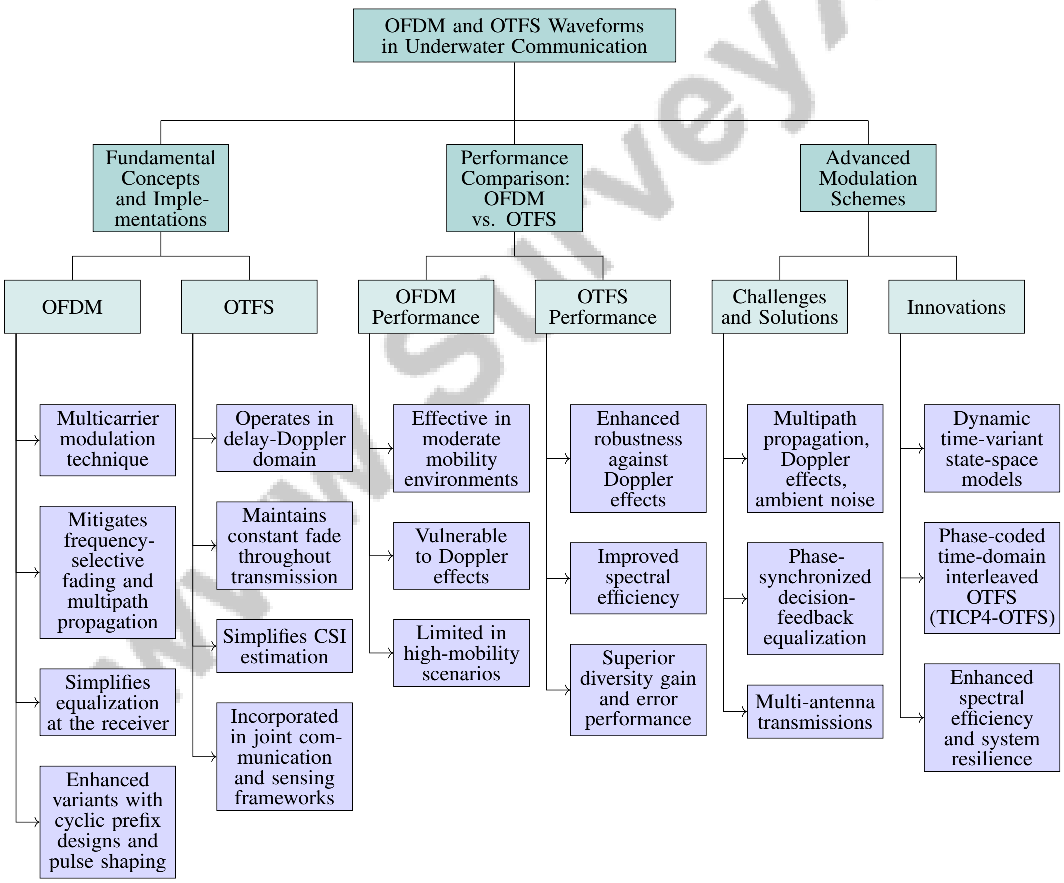

Figure 2: This figure illustrates the hierarchical structure of OFDM and OTFS waveforms in underwater communication, highlighting fundamental concepts, performance comparisons, and advanced modulation schemes. It categorizes the primary features and innovations of each waveform, emphasizing their roles in addressing underwater communication challenges.

AI-generated, for reference only.

4 OFDM and OTFS Waveforms in Underwater Communication

4.1 Fundamental Concepts and Implementations

Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Time Frequency Space (OTFS) waveforms are crucial for enhancing underwater acoustic communications by addressing environmental challenges. OFDM, a multicarrier modulation technique, divides the bandwidth into orthogonal subcarriers, each carrying a low-rate data stream, to mitigate frequency-selective fading and multipath propagation, thus simplifying equalization at the receiver. Enhanced OFDM variants with advanced cyclic prefix designs and pulse shaping further reduce inter-symbol interference (ISI) and inter-carrier interference (ICI) [12].

OTFS, operating in the delay-Doppler domain, excels in high-mobility environments by transforming signals into this domain, allowing symbols to maintain constant fade throughout a transmission frame [26]. This improves communication reliability and simplifies channel state information (CSI) estimation, making OTFS effective for underwater applications [38]. The sparse matrix structure in the delay-Doppler domain facilitates detection, a core aspect of RCP-OTFS [38].

Integrating OTFS with the Generalized Frequency Division Multiplexing (GFDM) framework through the EGFDM method enhances both modulation techniques [39], addressing underwater channel dynamics and bolstering system robustness. The Universal Analysis Framework for OTFS (UAF-OTFS) establishes upper bounds for the average bit error probability (ABEP) of SISO-OTFS and MIMO-OTFS systems using moment generating functions, offering insights into OTFS performance [22]. This framework is critical for optimizing OTFS in underwater contexts, ensuring reliable data transmission under adverse conditions.

OTFS is also incorporated into joint communication and sensing frameworks, such as OTFS-based integrated sensing and communication (ISAC) systems, which optimize resource allocation to enhance both communication and sensing capabilities [12]. This dual functionality highlights OTFS's versatility and transformative potential for underwater communication systems. The complementary strengths of OFDM and OTFS are evident, with OFDM addressing frequency-selective fading and OTFS managing Doppler effects and integrating with advanced multiple access schemes, positioning OTFS as a promising solution for future underwater communication systems [3].

4.2 Performance Comparison: OFDM vs. OTFS

The performance comparison between OFDM and OTFS waveforms highlights their respective strengths and limitations in underwater communication. OFDM effectively mitigates frequency-selective fading and multipath propagation by dividing the bandwidth into orthogonal subcarriers, suitable for environments with moderate mobility. However, its vulnerability to Doppler effects, causing inter-carrier interference (ICI), limits its performance in high-mobility scenarios [27].

In contrast, OTFS offers significant advantages in high-mobility communications, demonstrating enhanced robustness against Doppler effects and improved spectral efficiency over OFDM. By operating in the delay-Doppler domain, OTFS exploits the channel's time-frequency diversity, maintaining consistent performance despite Doppler shifts. Experimental evaluations confirm OTFS outperforms OFDM in bit error rate (BER), particularly under various RF impairments [13].

OTFS systems achieve superior diversity gain and error performance compared to conventional OFDM, especially in high-mobility contexts. This is due to OTFS's exploitation of the delay-Doppler domain, providing resilience against dynamic channel conditions common in underwater environments. Recent advancements in OTFS modulation underscore its potential as a next-generation solution for underwater communication, addressing traditional OFDM's limitations concerning bandwidth efficiency, reliability, and latency, crucial for applications in underwater exploration, resource extraction, and national defense [3, 23].

OFDM serves as a reliable modulation technique for frequency-selective fading in moderate mobility environments; however, OTFS, designed for the delay-Doppler domain, exhibits superior resilience to Doppler shifts and enhanced spectral efficiency, making it advantageous for high-mobility underwater communication systems [40, 25, 21, 26]. Ongoing research in OTFS technology continues to address challenges, further solidifying its role in advancing underwater communication.

4.3 Advanced Modulation Schemes

Advanced modulation schemes are essential for enhancing underwater acoustic communication systems by integrating with OFDM and OTFS waveforms. These schemes address complex underwater conditions, where multipath propagation, Doppler effects, and ambient noise affect communication quality. Optimizing bandwidth efficiency, reliability, and latency often requires trade-offs due to the unique characteristics of underwater channels, such as variable path loss with distance and frequency. Innovations like phase-synchronized decision-feedback equalization and multi-antenna transmissions are crucial for effective communication among underwater vehicles and surface consoles [3, 32, 4, 6].

Dynamic time-variant state-space models enhance tracking performance in nonstationary environments, improving modulation schemes' ability to maintain robust communication links despite changing conditions [37]. Phase-coded time-domain interleaved OTFS (TICP4-OTFS) demonstrates superior ambiguity function characteristics and enhanced performance in challenging scenarios [41]. TICP4-OTFS leverages the delay-Doppler domain to optimize signal processing, mitigating Doppler shifts and multipath interference, strengthening OTFS's robustness for high-mobility environments.

Integrating advanced modulation schemes with OFDM and OTFS enhances spectral efficiency and bolsters system resilience against aquatic challenges. By combining OFDM and OTFS advantages, these schemes improve reliability and efficiency in challenging underwater environments, addressing issues like bandwidth efficiency, latency, and Doppler shifts caused by currents and moving objects. This ensures robust data exchange essential for underwater exploration, resource extraction, and national defense [27, 3, 40, 14].

5 Channel Estimation Techniques

5.1 Advancements in Channel Estimation

Recent advancements in channel estimation for underwater acoustic communication have significantly enhanced accuracy and reliability under challenging conditions. Path-specific tracking using simplified sound models within a Kalman filter framework improves estimation by focusing on dynamic underwater parameters. Robust optimization algorithms, especially those utilizing the Alternating Direction Method of Multipliers (ADMM), excel in impulsive noise environments, leveraging compressed sensing to achieve accurate estimates with low computational complexity. These methods perform well against non-stationary, non-Gaussian noise, tackling severe multipath effects and large delay spreads [42, 37, 2, 30, 16].

In OTFS waveform contexts, channel estimation has progressed with methods like ED-OTFS, which mitigates Doppler shifts and reduces Peak-to-Average Power Ratio (PAPR), ensuring high estimation accuracy in high-mobility scenarios. OTFS modulation integration with advanced transceiver architectures enables precise handling of fractional Doppler interference, transforming doubly-dispersive channels into nearly non-fading channels in the delay-Doppler domain. This results in uniform impairments across transmitted QAM symbols, facilitating coherent combination across delay-Doppler diversity branches, crucial for optimal performance in high-mobility environments typical of 5G applications [21, 9, 26, 23, 7]. ODSS's nearly diagonal channel matrix simplifies receiver design, enhancing performance in wideband conditions.

Parallel Data Processing Algorithms (PDPA) have advanced channel estimation by efficiently handling larger datasets without increasing processing time, crucial for real-time processing in underwater systems due to variable path loss and frequency-dependent absorption [32, 17]. Adaptive modulation techniques are essential for reducing Bit Error Rate (BER) and improving communication reliability.

Deep learning models, particularly Long Short-Term Memory (LSTM) networks, have shown promise in modeling underwater acoustic channels by learning complex temporal dependencies, thereby enhancing channel estimation precision. CsiPreNet, combining CNN and LSTM architectures, exemplifies this trend by improving channel state information (CSI) prediction. The Adaptive Cyclic Minimization (ACM) method optimizes subcarrier selection and power allocation, enhancing performance and interference resilience, critical for designing interference-resilient OFDM waveforms in Integrated Sensing and Communications (ISAC) systems [11, 12, 36, 2, 18].

These advancements highlight the need for innovative approaches to tackle underwater acoustic communication challenges. Future research should focus on developing unified acoustic channel

AI-generated, for reference only.

models to refine estimation techniques [3], optimizing power allocation strategies, and exploring these techniques' performance in complex environments while integrating emerging technologies like reconfigurable intelligent surfaces (RIS) and backscatter communications to enhance channel estimation and overall system performance. Experimental emulation of OTFS waveforms provides insights into RF impairments' impact on waveform performance, guiding future designs [13].

5.2 Alternative Approaches for Improved Estimation

Enhancing channel estimation accuracy in underwater acoustic communication systems is crucial for improving reliability and performance. Advanced deep learning frameworks automatically extract high-level features from raw data, enhancing adaptive modulation and coding (AMC) performance in these systems [2]. These frameworks employ neural networks to learn complex temporal and frequency correlations in underwater channels, as demonstrated by the CsiPreNet model, which effectively captures these correlations to improve CSI prediction [10].

Dynamic tracking approaches, such as Kalman filter frameworks with simplified sound propagation models, provide robust means for estimating multipath channel parameters, adapting to underwater environments' time-variant characteristics [29]. Nearest neighbor regression for acoustic channel estimation, used in the Depth-Based Channel Aware Routing (DBCAR) protocol, enhances routing decisions in underwater sensor networks by improving estimation accuracy [28].

Optimizing transmitter and receiver windows is critical, particularly for OTFS systems, significantly enhancing estimation and detection performance in dynamic underwater environments [33]. Robust optimization algorithms, such as ADMM-based approaches, effectively handle impulsive noise and heavy-tailed noise distributions common in underwater channels [42].

Future research should focus on refining resource allocation algorithms and integrating them with machine learning techniques to enhance system performance [32]. Investigating existing models' adaptability in diverse underwater conditions could provide valuable insights for improving estimation methodologies [37]. Addressing long time-varying delay spreads and unpredictable high-energy fluctuations caused by oceanographic events can significantly advance estimation in underwater acoustic communication systems [30].

5.3 Deep Learning Approaches for Channel Modeling

Deep learning techniques in modeling underwater acoustic channels offer promising improvements in accuracy and adaptability in challenging environments. These techniques utilize deep neural networks, combining one-dimensional convolutional neural networks (CNNs) with long short-term memory (LSTM) networks, to identify and model intricate patterns in raw underwater data. This approach significantly enhances channel state information (CSI) prediction accuracy in adaptive communication systems, addressing challenges like severe multipath propagation and varying transmission speeds. Experimental results indicate these models outperform traditional methods, improving resource allocation and communication efficiency [20, 17, 10, 28, 2].

The OTFS-ISAC method illustrates the integration of sensing and communication functionalities, enabling more accurate channel predictions based on sensing parameters, thus enhancing overall performance [43]. Deep learning models' adaptability to time-variant channels is further demonstrated through path-specific tracking methods employing simplified sound propagation models within a Kalman filter framework, facilitating improved parameter estimation and performance in dynamic environments [29].

Robust optimization algorithms, particularly those based on the Alternating Direction Method of Multipliers (ADMM), address impulsive noise environments, enhancing reliability in underwater systems [42].

Mathematical frameworks integrating l21 norms with two-dimensional frequency domain analysis have been developed to enhance estimation accuracy, providing robust adaptation to unique underwater channel characteristics and improving performance amidst multipath and Doppler effects [30].

Integrating deep learning techniques, particularly Deep Neural Networks (DNN) and LSTM models, into underwater channel modeling marks a significant breakthrough in enhancing communication systems' effectiveness, often challenged by dynamic environments. Recent research shows these advanced methods can accurately model channels using real-world data from various aquatic settings, improving communication systems' design and performance in challenging conditions [17, 20]. By leveraging neural network capabilities and advanced mathematical frameworks, these approaches promise to significantly enhance estimation accuracy and reliability, paving the way for more robust and efficient underwater communication technologies.

6 Doppler Effect Mitigation

6.1 Waveform Design and Doppler Resilience

Waveform design plays a crucial role in enhancing Doppler resilience within underwater acoustic communication systems, where environmental dynamics present considerable challenges. Orthogonal Time Frequency Space (OTFS) waveforms have demonstrated significant potential in mitigating Doppler shifts by exploiting channel characteristics in the delay-Doppler domain, thereby improving channel estimation and data detection, and consequently enhancing overall communication performance [44]. OTFS effectively leverages time-frequency diversity, maintaining robust performance in high-mobility environments where Doppler effects are pronounced. This is further supported by advanced receiver techniques, such as Non-Orthogonal Multiple Access (NOMA)-OTFS systems, which address inter-carrier and inter-symbol interference efficiently [45].

The RCP-OTFS method illustrates the advantages of optimized waveform design, enhancing spectral efficiency through a single cyclic prefix to reduce overhead while preserving robust communication links amid Doppler effects [38]. This highlights the importance of waveform optimization in overcoming the unique challenges of underwater environments. Moreover, integrating sensing and communication functionalities within the OTFS framework offers additional benefits, such as reduced communication overhead and improved performance in high-mobility scenarios [43]. This integrated approach enhances Doppler resilience and optimizes resource allocation, ensuring reliable data transmission in complex underwater settings.

Strategic waveform design, particularly through OTFS, is vital for enhancing Doppler resilience in underwater acoustic communication systems. By utilizing the delay-Doppler domain and incorporating advanced receiver techniques, these designs provide promising solutions for maintaining robust and efficient communication in challenging underwater environments [14].

6.2 Signal Processing Techniques for Doppler Mitigation

Signal processing techniques are essential for mitigating Doppler effects in underwater acoustic communication systems, where high mobility and dynamic conditions pose significant challenges. A key strategy involves Orthogonal Time Frequency Space (OTFS) modulation, which demonstrates robust bit error rate (BER) performance in high-Doppler environments. OTFS's efficient channel estimation and low-complexity detection schemes make it particularly suitable for underwater communication [26]. The Non-coherent OTFS (N-OTFS) method operates effectively without requiring channel state information (CSI), reducing system complexity and enhancing performance in high-mobility scenarios [46], which is advantageous in underwater settings where rapid channel variations complicate accurate CSI acquisition.

Advanced power allocation strategies, such as the mercury/water filling method combined with a Dolph-Chebyshev window for the receiver, optimize channel sparsity and performance, enhancing transmitter and receiver windows to better address Doppler-induced impairments [33]. Adaptive filtering techniques, including LCLMA and LCLMS, have been proposed to mitigate impulsive noise associated with Doppler shifts, focusing on improving signal clarity and maintaining reliable communication links [16]. The Ak NN method further aids in Doppler mitigation by adapting to uncertainties in underwater channels without requiring an accurate channel model [2].

Integrating multiple signal processing strategies, such as indexing techniques like OFDM-HIQ-IM, enhances spectral efficiency and diversity through the joint utilization of I- and Q-components [15]. Future research should aim to optimize detection algorithms for MM-OFDM-IM and evaluate its performance amidst carrier frequency offsets and Doppler effects, which remain critical challenges in underwater communication systems [47].

Advancements in sophisticated signal processing techniques, such as adaptive filtering and equalization methods, are vital for effectively addressing Doppler effects in underwater acoustic communication systems. These methods enhance bandwidth efficiency, reliability, and latency while accommodating the inherent trade-offs of acoustic propagation, thus facilitating applications in underwater exploration and resource extraction [3, 16]. By leveraging innovative modulation schemes, power allocation strategies, and adaptive filtering approaches, these techniques significantly bolster the resilience and reliability of communication in dynamic underwater environments.

7 Adaptive Modulation Techniques

7.1 Introduction to Adaptive Modulation Techniques

Adaptive modulation techniques are pivotal for improving the performance and reliability of underwater acoustic communication (UAC) systems, which face unique challenges due to dynamic underwater environments. By adjusting modulation schemes in real-time based on channel conditions, these techniques optimize data transmission rates while maintaining error performance, aiming to maximize spectral efficiency amidst multipath propagation, Doppler effects, and noise [2].

Underwater channel conditions fluctuate significantly due to water movement, temperature gradients, and salinity changes. Adaptive modulation tackles these variations by selecting suitable modulation schemes that balance data rate and error performance. Higher-order schemes are used under favorable conditions to boost data rates, whereas lower-order schemes ensure robust communication in adverse conditions [2].

Implementing adaptive modulation typically involves advanced algorithms and signal processing techniques that continuously monitor channel state information (CSI) to adjust modulation parameters. Machine learning approaches, particularly deep learning frameworks, enhance adaptability and efficiency by identifying complex patterns in channel data, enabling precise predictions and adjustments of modulation schemes [10].

Combining adaptive modulation with power control and error correction coding further enhances system performance, ensuring reliable communication even amidst severe channel impairments. The development of robust adaptive modulation techniques is crucial for advancing underwater communication technologies and overcoming environmental challenges [2].

Adaptive modulation is a vital component of modern UAC systems, significantly improving data transmission efficiency and reliability. As research progresses, integrating advanced machine learning techniques and novel adaptive algorithms is expected to enhance adaptive modulation and coding (AMC) systems, enabling reliable communication in extreme underwater conditions. Innovations such as attention-aided k-nearest neighbor algorithms and the CsiPreNet model for CSI prediction exemplify how emerging technologies can optimize communication among underwater vehicles and sensor networks [2, 10, 4, 16].

7.2 Integration with OFDM Waveforms

Integrating adaptive modulation techniques with Orthogonal Frequency Division Multiplexing (OFDM) waveforms marks a significant advancement in underwater acoustic communication systems. OFDM effectively handles frequency-selective fading and multipath propagation, providing a robust platform for adaptive modulation [9]. By adjusting modulation schemes in response to real-time channel conditions, adaptive modulation enhances the spectral efficiency and reliability of OFDM-based systems.

In underwater environments characterized by variable channel conditions due to multipath effects, Doppler shifts, and noise, this integration enables more resilient communication. Systems can employ higher-order modulation schemes in favorable conditions to increase throughput while switching to lower-order schemes in adverse conditions for robustness [2]. The ability to adaptively select optimal modulation schemes based on CSI is crucial for maximizing OFDM system performance.

Advanced algorithms, including machine learning techniques, play a pivotal role in this integration by providing efficient methods for predicting channel conditions and selecting appropriate modulation schemes [10]. These algorithms analyze historical and real-time channel data to continuously optimize modulation parameters.

Furthermore, integrating adaptive modulation with OFDM is often complemented by power control and error correction coding techniques, enhancing system reliability in the face of severe channel impairments [2]. This combined approach addresses the unique challenges of underwater environments, improving data transmission efficiency and reliability.

The integration of adaptive modulation with OFDM waveforms enhances flexibility and efficiency, allowing real-time adjustments to modulation schemes based on the dynamic characteristics of the underwater environment. By employing machine learning algorithms, such as attention-aided k-nearest neighbor and sophisticated channel state prediction models, these adaptive systems optimize performance in response to challenges like multipath propagation and varying signal latency, ultimately improving communication reliability and throughput in underwater sensor networks [2, 11, 10].

7.3 Integration with OTFS Waveforms

The integration of adaptive modulation techniques with Orthogonal Time Frequency Space (OTFS) waveforms significantly enhances underwater acoustic communication systems, providing improved performance and reliability in challenging underwater environments. OTFS operates in the delay-Doppler domain, effectively managing dynamic conditions typical of underwater channels, such as multipath propagation and Doppler effects [43].

When combined with OTFS, adaptive modulation leverages time-frequency diversity to adjust modulation schemes based on real-time channel conditions, optimizing data transmission rates while maintaining desired error performance. This adaptability is crucial in underwater environments with rapid changes due to water movement, temperature gradients, and salinity variations [2]. By selecting suitable modulation schemes, OTFS systems maximize spectral efficiency and ensure robust communication links despite severe channel impairments.

Advanced algorithms and machine learning techniques enhance the integration of adaptive modulation with OTFS by providing accurate methods for predicting channel conditions and selecting optimal modulation parameters [10]. These algorithms utilize historical and real-time channel data to continuously optimize modulation schemes, ensuring reliable communication.

Additionally, combining adaptive modulation with OTFS can be complemented by power control and error correction coding techniques, further enhancing system performance and reliability. This integrated approach ensures that underwater acoustic communication systems maintain high performance levels, even under challenging conditions [2].

Overall, integrating adaptive modulation with OTFS waveforms offers a flexible and efficient solution for managing the complexities of underwater channels. As research progresses, incorporating advanced algorithms and techniques—such as adaptive filtering inspired by online learning methods and machine learning-based AMC—will significantly enhance OTFS-based system performance. These innovations are vital for improving reliability, bandwidth efficiency, and latency management in the challenging underwater environment, characterized by non-stationary conditions and impulsive noise, thereby facilitating critical applications in underwater exploration and resource management [2, 3, 16].

7.4 Benefits of Adaptive Modulation in UAC

Adaptive modulation techniques offer substantial benefits in underwater acoustic communication (UAC) systems by dynamically adjusting modulation schemes to match prevailing channel conditions, optimizing data transmission rates, and enhancing reliability. A key advantage is maximizing spectral efficiency while maintaining desired error performance, crucial in underwater environments characterized by multipath propagation, Doppler effects, and noise [2].

Channel conditions can vary significantly due to factors like water movement, temperature gradients, and salinity changes. Adaptive modulation addresses these variations by selecting appropriate modulation schemes to balance data rate and error performance. Higher-order modulation schemes increase data rates under favorable conditions, while lower-order schemes ensure robust communication in adverse conditions [2].

Implementing adaptive modulation in UAC systems involves advanced algorithms and signal processing techniques that continuously monitor channel state information (CSI) and adjust modulation parameters accordingly. Machine learning approaches, including deep learning frameworks, enhance adaptability and efficiency by identifying complex patterns in channel data, enabling accurate predictions and adjustments of modulation schemes [10].

Moreover, adaptive modulation techniques are often combined with power control and error correction coding strategies to further enhance system performance. This integrated approach ensures reliable communication links even amidst severe channel impairments, making robust adaptive modulation techniques essential for advancing underwater communication technologies and addressing underwater challenges [2].

Adaptive modulation is a critical component of modern UAC systems, significantly improving data transmission efficiency and reliability. As research progresses, integrating advanced machine learning techniques and novel adaptive algorithms is expected to bolster the performance of adaptive modulation and coding (AMC) systems, enabling reliable data transmission in extreme underwater conditions. Recent developments, such as attention-aided k-nearest neighbor algorithms and the CsiPreNet model for channel state information prediction, illustrate how emerging technologies can effectively address the unique challenges of underwater channels, facilitating better exploration and management of marine resources [2, 10, 4, 16].

7.5 Resource Allocation and Signal Detection

Resource allocation and signal detection are critical components in optimizing underwater acoustic communication (UAC) systems, where efficient management of limited resources is necessary due to dynamic underwater environments. Effective resource allocation strategies are essential for optimizing bandwidth utilization, power distribution, and time-slot assignments, ensuring high performance and reliability despite the constraints of underwater channels [32].

Advanced resource allocation techniques often integrate machine learning algorithms, providing adaptive and predictive capabilities for real-time resource management. These algorithms analyze historical and current channel data to predict future channel states, enabling dynamic adjustments to resource allocation that optimize system performance. By leveraging machine learning, UAC systems can achieve more efficient resource utilization, reducing interference and enhancing communication reliability [2].

Signal detection mechanisms are equally important in UAC systems, ensuring accurate interpretation of received signals amidst noise and interference. Advanced signal processing techniques, such as adaptive filtering and noise cancellation, enhance signal clarity and reduce bit error rates, which are crucial for maintaining reliable communication links in environments characterized by multipath propagation and Doppler effects [16].

Integrating resource allocation and signal detection strategies with adaptive modulation techniques further enhances UAC system performance. By dynamically adjusting modulation schemes based on real-time channel conditions, these integrated approaches optimize data transmission rates and improve communication reliability. The combined use of advanced resource management and signal detection techniques represents a significant advancement in underwater communication technologies, providing robust solutions for the unique challenges of underwater environments [2].

The development of innovative resource allocation and signal detection mechanisms is essential for advancing UAC capabilities. As research progresses, integrating emerging technologies such as machine learning and advanced algorithms is set to improve the efficiency and reliability of these systems, ensuring robust performance even in challenging oceanic conditions. Notable innovations, including adaptive modulation and coding frameworks, deep learning models for channel modeling, and sophisticated equalization techniques, are being developed to enhance communication capabilities and facilitate effective underwater exploration, resource extraction, and national defense operations [4, 17, 2, 3, 18].

7.6 Machine Learning in Modulation and Coding Scheme Selection

Machine learning (ML) has emerged as a transformative tool in selecting modulation and coding schemes for underwater acoustic communication (UAC) systems, addressing challenges posed by the complex underwater environment. Advanced ML techniques, such as attention-aided k-nearest neighbor algorithms and Long Short Term Memory (LSTM) networks, enable the development of adaptive modulation and coding (AMC) frameworks that enhance communication reliability and efficiency. These ML-driven approaches improve UAC system performance by overcoming channel modeling uncertainties and facilitating continuous self-improvement through online learning capabilities, leading to robust communication solutions in harsh oceanic conditions [2, 17, 20].

Integrating ML algorithms into UAC systems allows for the automatic selection of optimal modulation and coding schemes based on real-time channel conditions, enhancing communication reliability and efficiency. One key advantage of using ML is its ability to learn complex patterns in channel data, enabling predictions of channel states and adaptive adjustments of modulation and coding parameters to optimize system performance. This adaptability is crucial in underwater environments, where rapid changes occur due to multipath propagation, Doppler effects, and noise [2].

Advanced ML techniques, including deep learning and reinforcement learning, show significant promise in this domain. Deep learning models utilizing neural networks can automatically extract high-level features from raw data, enabling accurate predictions and adjustments of modulation and coding schemes. These models effectively handle the non-linear and time-varying characteristics of underwater channels, providing robust solutions for maintaining reliable communication links [10].

Reinforcement learning offers a framework for continuous learning and adaptation, allowing systems to learn optimal strategies for modulation and coding scheme selection through interaction with the environment. This approach enables UAC systems to dynamically adjust strategies based on feedback from the channel, continuously optimizing communication parameters to match prevailing conditions [2].

The integration of ML in modulation and coding scheme selection is further enhanced by advanced signal processing techniques and resource allocation strategies. By combining ML with these techniques, UAC systems achieve more efficient resource utilization and improved signal detection, further enhancing communication reliability and performance [16].

The application of machine learning in selecting modulation and coding schemes represents a significant advancement in underwater acoustic communication. As research continues, integrating innovative ML algorithms and techniques is set to improve the performance and reliability of UAC systems, addressing the unique challenges posed by the harsh underwater environment characterized by non-stationary conditions and impulsive noise. Recent developments, such as attention-aided k-nearest neighbor algorithms and deep learning models like LSTM networks, demonstrate superior capabilities in accurately modeling underwater acoustic channels and adapting to varying operational scenarios. These ML-driven approaches promise robust and efficient communication even in demanding underwater conditions, facilitating enhanced exploration and management of marine resources [2, 17, 4, 16].

8 Underwater Signal Processing

8.1 Optimization Techniques for Signal Processing

Optimization techniques are crucial for enhancing underwater acoustic communication systems, addressing challenges like channel estimation, noise reduction, and data detection. Advanced methods, such as adaptive filtering with logarithmic cost functions, improve convergence and stability under non-stationary conditions affected by impulsive noise. Strategies including sparse channel estimation and turbo equalization advance bandwidth efficiency, reliability, and latency, supporting applications like underwater exploration and resource extraction [3, 4, 16].

Channel estimation utilizes algorithms such as compressed sensing and deep learning models, including Deep Neural Networks (DNN) and Long Short-Term Memory (LSTM) networks, to manage dynamic underwater channels. These techniques address severe multipath effects, large delay spreads, and impulsive ocean noise, enhancing communication performance [42, 37, 17, 30, 16]. Kalman filtering and robust optimization further refine channel estimation accuracy in impulsive, time-variant environments.

Noise reduction is vital in underwater signal processing, where ambient and man-made noise can obscure signals. Techniques like advanced noise cancellation and adaptive filtering, including LCLMA and LCLMS, mitigate impulsive noise effects, ensuring reliable communication [16].

Data detection benefits from optimization techniques that enhance the robustness and efficiency of detection algorithms. Machine learning models, particularly deep learning and reinforcement learning, improve detection accuracy and reliability. DNNs and LSTMs effectively model complex underwater channels, overcoming challenges posed by harsh environments, as demonstrated by experimental results showing their superiority over traditional methods [2, 17, 20].

Moreover, optimization often involves resource allocation strategies to maximize limited resources. Algorithms for power distribution, bandwidth management, and time-slot assignments enhance performance and reliability [32]. By dynamically adjusting resource allocation based on real-time conditions, these techniques improve efficiency and resilience in underwater communication systems.

Recent advancements in algorithms, including compressed sensing and adaptive filtering, have significantly improved channel estimation and equalization. The alternating direction method of multipliers (ADMM) shows promise in accurately estimating underwater channels under impulsive noise, while novel adaptive equalizers enhance stability and convergence. Machine learning approaches, such as attention-aided k-nearest neighbor algorithms, are utilized to improve adaptive modulation and coding, addressing oceanic signal propagation complexities [2, 42, 30, 16].

8.2 Tracking and Adaptation in Dynamic Environments

Effective tracking and adaptation in dynamic underwater environments are critical for acoustic communication systems, particularly in rapidly time-varying channels influenced by impulsive noise and environmental conditions. Techniques like model-based subspace channel tracking and robust adaptive equalization address model mismatch and non-stationarity, enhancing system stability and convergence. These innovations facilitate reliable communication among underwater vehicles and support applications in exploration, resource extraction, and defense [3, 37, 4, 16].

Advanced filtering techniques, such as the Kalman filter, efficiently estimate and predict channel state information (CSI) in real-time, particularly effective in rapidly changing environments [29].

Machine learning models, especially deep learning frameworks, enhance tracking and adaptation capabilities by learning complex temporal and spatial patterns in channel data. These models optimize modulation and coding schemes, power allocation, and other parameters to maintain robust links in dynamic environments [10].

Integrating adaptive modulation with Orthogonal Time Frequency Space (OTFS) waveforms offers advantages in tracking and adaptation. OTFS, operating in the delay-Doppler domain, provides a robust framework for managing time-frequency diversity, improving resilience to Doppler effects and other dynamic impairments [43].

Developing advanced tracking and adaptation methods is vital for advancing underwater acoustic communication systems. Incorporating cutting-edge algorithms and emerging technologies, particularly those leveraging machine learning, will significantly improve adaptability and efficiency. Innovations such as the attention-aided k-nearest neighbor (Ak NN) algorithm enhance adaptive modulation and coding strategies, providing robust performance and self-improvement in response to varying acoustic conditions, crucial for sustainable resource exploration and management [2, 3].

8.3 Adaptive Filtering Techniques

Adaptive filtering techniques are essential for underwater acoustic communication systems, addressing challenges posed by dynamic and noisy environments, including non-stationary conditions and impulsive noise. Recent advancements in adaptive algorithms, particularly those utilizing relative logarithmic cost functions, enhance channel equalization performance and stability. Mathematical frameworks employing l_{21} norms for channel estimation improve accuracy and reduce execution times, while dynamic state-space models combined with Kalman filtering show significant improvements in tracking performance for rapidly varying channels, especially in rough sea conditions [37, 30, 4, 16].

The Least Mean Squares (LMS) algorithm, known for minimizing mean square error between desired and actual signal outputs, is a primary adaptive filtering method used in underwater communication. Its adaptability makes it suitable for time-varying channel conditions [16].

AI-generated, for reference only.

The Recursive Least Squares (RLS) algorithm offers improved convergence rates and tracking capabilities, excelling in scenarios with rapid channel variations, providing timely updates to filter coefficients [2].

Integrating machine learning models into adaptive filtering processes shows promise in enhancing performance. Deep learning frameworks learn complex patterns in channel data, enabling effective adaptation to changing conditions and improving signal processing efficiency [10].

Adaptive filtering techniques are crucial for advancing underwater acoustic communication systems. By continuously adjusting to dynamic and noisy conditions, these techniques enhance signal clarity and reliability. Recent developments in robust adaptive algorithms for channel equalization, utilizing innovative cost functions inspired by online learning methods, enhance stability and convergence in non-stationary environments. The application of l_{21} norms in channel estimation reduces algorithm complexity while improving mean square error (MSE) and execution time, promising robust and efficient solutions for communication challenges [30, 16].

8.4 Experimental Validation and Technological Integration

Benchmark	Size	Domain	Task Format	Metric
UAC-WB[5]	13	Underwater Acoustic Communications	Channel Estimation	Coherence Time, Coherence Bandwidth

Table 1: This table presents a benchmark dataset for underwater acoustic communication systems, detailing its size, domain, task format, and evaluation metrics. The dataset, UAC-WB, is specifically designed for channel estimation tasks and evaluates performance using coherence time and coherence bandwidth as key metrics.

Experimental validation and technological integration are pivotal for advancing underwater acoustic communication systems. The intricate nature of underwater environments necessitates extensive testing and validation to ensure resilience against challenges like multipath propagation, Doppler effects, ambient noise, and potential jamming attacks. These factors influence performance metrics such as coverage probability, average data rate, and energy efficiency, which vary with transmission distance and frequency. Designing underwater acoustic networks involves navigating trade-offs between bandwidth efficiency, reliability, and latency, as the acoustic channel imposes distinct constraints differing from terrestrial systems [3, 32, 18, 6]. Experimental validation provides insights into real-world performance, allowing researchers to identify weaknesses and areas for improvement. Table 1 summarizes a benchmark dataset utilized for experimental validation in underwater acoustic communication systems, highlighting its relevance in assessing channel estimation performance.

Integrating new technologies into communication frameworks is essential for enhancing capabilities and addressing limitations. Advanced algorithms and emerging technologies, such as machine learning and adaptive modulation techniques, significantly improve adaptability and efficiency. Machine learning models offer robust solutions for predicting channel states and optimizing communication parameters, enhancing performance in dynamic environments [32].

Testing communication frameworks in cloud environments demonstrates potential for scalable and efficient deployment across various settings. Cloud-based testing facilitates comprehensive performance assessments across different scenarios and configurations, yielding insights that enhance communication strategies. This approach is beneficial in complex environments, where jamming interference and fluctuating acoustic channel quality impact performance metrics. Techniques like machine learning-based adaptive modulation and coding enable dynamic evaluations, accounting for underwater environment challenges, leading to robust and efficient communication protocols [2, 18, 28].

The importance of experimental validation and technological integration cannot be overstated. By systematically evaluating and incorporating advanced technologies, researchers can create sophisticated communication systems tailored to underwater environments, addressing varying acoustic propagation conditions and potential jamming threats. These systems are essential for applications like exploration, resource extraction, and defense, addressing key performance metrics while navigating trade-offs imposed by acoustic channels [3, 18]. Ongoing integration of innovative technologies will further enhance capabilities and reliability, paving the way for effective deployment in aquatic applications.

9 Conclusion

This survey explores the intricacies of underwater acoustic communication systems, emphasizing the critical contributions of Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Time Frequency Space (OTFS) waveforms. These technologies address the unique challenges of underwater environments, such as frequency-selective fading, multipath propagation, and Doppler effects. OFDM is proficient in handling frequency-selective fading and multipath propagation, while OTFS excels in mitigating Doppler shifts, thereby enhancing overall communication performance. Notably, OTFS demonstrates superior performance compared to OFDM in doubly dispersive channels, particularly in terms of bit error rate and peak-to-average power ratio, making it highly suitable for high-mobility scenarios.

The survey highlights the importance of advanced channel estimation techniques, including machine learning models and robust optimization algorithms, which are effective in capturing the dynamic complexities of underwater channels. These methods, alongside adaptive modulation strategies, play a crucial role in optimizing resource allocation and improving signal detection, ensuring reliable communication in challenging conditions. Continued exploration of these approaches is vital for enhancing communication robustness and efficiency.

Despite significant advancements, several challenges remain, necessitating further research and development. Future work should focus on refining theoretical models to better capture practical constraints in dynamic environments and exploring new waveform designs to enhance performance. Key research areas include optimizing the trade-off between estimation accuracy and complexity, improving signal quality through advanced filtering techniques, and investigating reservoir computing as a promising modeling approach to achieve improved performance with reduced computational demands.

Moreover, optimizing the balance between robustness and latency, along with refining mathematical derivations for practical implementations, is essential for advancing communication technologies. Future research should also aim to balance out-of-band power with error performance and enhance detection algorithms for practical applications. By harnessing emerging technologies and optimizing current methodologies, future research can drive the development of more robust and efficient communication systems capable of navigating the complexities of underwater environments.

References

[1] Daniel E. Lucani, Muriel Médard, and Milica Stojanovic. Underwater acoustic networks: Channel models and network coding based lower bound to transmission power for multicast, 2008.

[2] Lihuan Huang, Qunfei Zhang, Weijie Tan, Yue Wang, Lifan Zhang, Chengbing He, and Zhi Tian. Adaptive modulation and coding in underwater acoustic communications: a machine learning perspective. *EURASIP Journal on Wireless Communications and Networking*, 2020:1–25, 2020.

[3] Aijun Song, Milica Stojanovic, and Mandar Chitre. Editorial underwater acoustic communications: Where we stand and what is next? *IEEE Journal of Oceanic Engineering*, 44(1), 2019.

[4] Lokesh Bommisetty, Samskruthi Gaddam, Nomula Prakash Reddy, Shaik Basharath, and Bharath Are. Cdma for underwater acoustic communication, 2021.

[5] Jesús López-Fernández, Unai Fernández-Plazaola, José F. París, Luis Díez, and Eduardo Martos-Naya. Wideband ultrasonic acoustic underwater channels: Measurements and characterization, 2024.

[6] Daniel E. Lucani, Milica Stojanovic, and Muriel Médard. On the relationship between transmission power and capacity of an underwater acoustic communication channel, 2008.

[7] Zhiqiang Wei, Shuangyang Li, Weijie Yuan, Robert Schober, and Giuseppe Caire. Orthogonal time frequency space modulation—part i: Fundamentals and challenges ahead. *IEEE Communications Letters*, 27(1):4–8, 2022.

[8] Weijie Yuan, Shuangyang Li, Zhiqiang Wei, Yuanhao Cui, Jiamo Jiang, Haijun Zhang, and Pingzhi Fan. New delay doppler communication paradigm in 6g era: A survey of orthogonal time frequency space (otfs). *China Communications*, 20(6):1–25, 2023.

[9] Patchava Raviteja, Khoa T Phan, Yi Hong, and Emanuele Viterbo. Interference cancellation and iterative detection for orthogonal time frequency space modulation. *IEEE transactions on wireless communications*, 17(10):6501–6515, 2018.

[10] Lei Liu, Lin Cai, Lu Ma, and Gang Qiao. Channel state information prediction for adaptive underwater acoustic downlink ofdma system: Deep neural networks based approach. *IEEE Transactions on Vehicular Technology*, 70(9):9063–9076, 2021.

[11] Yanling Yin, Sumit Roy, and Payman Arabshahi. A modified csma/ca protocol for ofdm underwater networks: Cross layer design, 2016.

[12] Qinghui Lu, Zhen Du, and Zenghui Zhang. Interference-resilient ofdm waveform design with subcarrier interval constraint for isac systems, 2023.

[13] Abdelrahman Abushattal, Salah Eddine Zegrar, Ayhan Yazgan, and Huseyin Arslan. Experimental emulation for otfs waveform rf-impairments, 2022.

[14] Orthogonal time frequency space.

[15] Miaowen Wen, Binbin Ye, Ertugrul Basar, Qiang Li, and Fei Ji. Enhanced orthogonal frequency division multiplexing with index modulation. *IEEE Transactions on Wireless Communications*, 16(7):4786–4801, 2017.

[16] Dariush Kari, Muhammed Omer Sayin, and Suleyman Serdar Kozat. A new robust adaptive algorithm for underwater acoustic channel equalization, 2015.

[17] Oluwaseyi Onasami, Damilola Adesina, and Lijun Qian. Underwater acoustic communication channel modeling using deep learning. In *Proceedings of the 15th International Conference on Underwater Networks & Systems*, pages 1–8, 2021.

[18] Waqas Aman, Saif Al-Kuwari, and Marwa Qaraqe. Performance analysis of underwater acoustic channel amid jamming by random jammers, 2024.

[19] Mustafa A. Kishk and Ahmed M. Alaa. On the capacity of the underwater acoustic channel with dominant noise sources, 2014.

[20] Oluwaseyi Onasami, Damilola Adesina, and Lijun Qian. Underwater acoustic communication channel modeling using deep learning, 2022.

[21] Saif Khan Mohammed. Derivation of otfs modulation from first principles. *IEEE transactions on vehicular technology*, 70(8):7619–7636, 2021.

[22] Shuo Li, Lixia Xiao, Yangyang Liu, Guanghua Liu, Pei Xiao, and Tao Jiang. Performance analysis for orthogonal time frequency space modulation systems with generalized waveform. *China Communications*, 20(4):57–72, 2023.

[23] Ronny Hadani and Anton Monk. Otfs: A new generation of modulation addressing the challenges of 5g. *arXiv preprint arXiv:1802.02623*, 2018.

[24] Arman Farhang, Ahmad RezazadehReyhani, Linda E Doyle, and Behrouz Farhang-Boroujeny. Low complexity modem structure for ofdm-based orthogonal time frequency space modulation. *IEEE wireless communications letters*, 7(3):344–347, 2017.

[25] Ruilin Liu, Gaoze Mu, Jiandi Hu, Ye Gong, Yanzhao Hou, Qimei Cui, Xiaofeng Tao, and Whai-En Chen. Ed-otfs: A new waveform design for orthogonal time frequency space modulation in high-speed mobile communication scenarios. In *2024 IEEE 99th Vehicular Technology Conference (VTC2024-Spring)*, pages 1–5. IEEE, 2024.

[26] K R Murali and A Chockalingam. On otfs modulation for high-doppler fading channels. In *2018 information theory and applications workshop (ITA)*, pages 1–10. IEEE, 2018.

[27] Orthogonal delay scale space mod.

[28] Boyu Diao, Chao Li, Qi Wang, Zhulin An, and Yongjun Xu. A channel-aware routing protocol with nearest neighbor regression for underwater sensor networks, 2021.

[29] Xiuqing Li, Wei Li, Xinlin Yi, Qihang Huang, Yuhang Wang, and Chenzhe Ye. Path-specific underwater acoustic channel tracking and its application in passive time reversal mirror, 2021.

[30] Amer Aljanabi, Mohanad Abd Shehab, Osama Alluhaibi, Qasim Zeeshan Ahmed, and Pavlos Lazaridis. Underwater acoustic channel adaptive estimation using l21 norms, 2021.

[31] Weijie Yuan, Zhiqiang Wei, Jinhong Yuan, and Derrick Wing Kwan Ng. A simple variational bayes detector for orthogonal time frequency space (otfs) modulation. *IEEE transactions on vehicular technology*, 69(7):7976–7980, 2020.

[32] Daniel E. Lucani, Muriel Médard, and Milica Stojanovic. Capacity scaling laws for underwater networks, 2009.

[33] Zhiqiang Wei, Weijie Yuan, Shuangyang Li, Jinhong Yuan, and Derrick Wing Kwan Ng. Transmitter and receiver window designs for orthogonal time-frequency space modulation. *IEEE transactions on communications*, 69(4):2207–2223, 2021.

[34] Shuangyang Li, Weijie Yuan, Zhiqiang Wei, and Jinhong Yuan. Cross domain iterative detection for orthogonal time frequency space modulation. *IEEE transactions on wireless communications*, 21(4):2227–2242, 2021.

[35] ISHII Toru, Yukiko Yoshikawa, Shintaro Izumi, and Hiroshi Kawaguchi. Subcentimeter precision ranging system for moving targets with a doppler-effect-compensated ultrasonic direct sequence spread spectrum. *IEEE Transactions on Instrumentation and Measurement*, 70:1–8, 2020.

[36] Silvia Mura, Dario Tagliaferri, Marouan Mizmizi, Umberto Spagnolini, and Athina Petropulu. Optimized waveform design for ofdm-based isac systems under limited resource occupancy, 2024.

[37] Qihang Huang, Wei Li, Weicheng Zhan, Yuhang Wang, and Rongrong Guo. Dynamic underwater acoustic channel tracking for correlated rapidly time-varying channels, 2021.

[38] Patchava Raviteja, Yi Hong, Emanuele Viterbo, and Ezio Biglieri. Practical pulse-shaping waveforms for reduced-cyclic-prefix otfs. *IEEE Transactions on Vehicular Technology*, 68(1):957–961, 2018.

[39] Ahmad Nimr, Marwa Chafii, Maximilian Matthe, and Gerhard Fettweis. Extended gfdm framework: Otfs and gfdm comparison, 2018.

[40] Ali J Ramadhan and Ali TaeiZadeh. The orthogonal time frequency space (otfs) technique in 6g wireless communications. In *BIO Web of Conferences*, volume 97, page 00128. EDP Sciences, 2024.

[41] Jiajun Zhu, Yanqun Tang, Chao Yang, Chi Zhang, Haoran Yin, Jiaojiao Xiong, and Yuhua Chen. A phase-coded time-domain interleaved otfs waveform with improved ambiguity function, 2023.

[42] Tian Tian, Agastya Raj, Bruno Missi Xavier, Ying Zhang, Feiyun Wu, and Kunde Yang. A robust admm-based optimization algorithm for underwater acoustic channel estimation, 2023.

[43] Weijie Yuan, Zhiqiang Wei, Shuangyang Li, Robert Schober, and Giuseppe Caire. Orthogonal time frequency space modulation—part iii: Isac and potential applications. *IEEE Communications Letters*, 27(1):14–18, 2022.

[44] Zhiqiang Wei, Weijie Yuan, Shuangyang Li, Jinhong Yuan, Ganesh Bharatula, Ronny Hadani, and Lajos Hanzo. Orthogonal time-frequency space modulation: A promising next-generation waveform. *IEEE wireless communications*, 28(4):136–144, 2021.

[45] Aritra Chatterjee, Vivek Rangamgari, Shashank Tiwari, and Suvra Sekhar Das. Nonorthogonal multiple access with orthogonal time–frequency space signal transmission. *IEEE Systems Journal*, 15(1):383–394, 2020.

[46] Chao Xu, Luping Xiang, Shinya Sugiura, Robert G Maunder, Lie-Liang Yang, Dusit Niyato, Geoffrey Ye Li, Robert Schober, and Lajos Hanzo. Noncoherent orthogonal time frequency space modulation. *IEEE Transactions on Wireless Communications*, 2024.

[47] Miaowen Wen, Ertugrul Basar, Qiang Li, Beixiong Zheng, and Meng Zhang. Multiple-mode orthogonal frequency division multiplexing with index modulation. *IEEE Transactions on Communications*, 65(9):3892–3906, 2017.

Disclaimer:

SurveyX is an AI-powered system designed to automate the generation of surveys. While it aims to produce high-quality, coherent, and comprehensive surveys with accurate citations, the final output is derived from the AI's synthesis of pre-processed materials, which may contain limitations or inaccuracies. As such, the generated content should not be used for academic publication or formal submissions and must be independently reviewed and verified. The developers of SurveyX do not assume responsibility for any errors or consequences arising from the use of the generated surveys.

AI-generated, for reference only.