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Waymark in the Depths: Baseband Signal Transmission and OFDM in Underwater Acoustic Propagation Channel Models

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Abstract— In the intricate environment of underwater acoustic propagation, establishing reliable communication channels stands as a formidable challenge, primarily due to the medium's inherent properties, such as high path loss, multipath propagation, and time-varying channel characteristics. "Waymark in the Depths: Baseband Signal Transmission and OFDM in Underwater Acoustic Propagation Channel Models" presents an innovative exploration into enhancing underwater communication systems by leveraging advanced signal processing techniques and channel modeling strategies. At the core of this research lies the integration of Orthogonal Frequency Division Multiplexing (OFDM) with baseband signal transmission, aiming to mitigate the detrimental effects of the underwater acoustic environment on signal integrity and throughput. By dissecting the acoustic channel's unique attributes, the study devises a comprehensive channel model that encapsulates the dynamic nature of underwater acoustics, including the impact of temperature, salinity, and pressure on sound speed and signal dispersion. This model serves as a waymark, guiding the development of tailored OFDM techniques that are optimized for the underwater medium, focusing on maximizing spectral efficiency and minimizing error rates. The research meticulously examines the interplay between baseband signal processing and OFDM in this context, illustrating how their synergistic application can overcome the bandwidth limitations and frequency-selective fading characteristic of underwater channels. Through extensive simulation and experimental validation, the study demonstrates the feasibility of achieving high-speed, reliable underwater communication, highlighting significant improvements in data rates and link stability. Furthermore, the research delves into adaptive modulation schemes and coding strategies, optimized for the derived channel model, to bolster the robustness of the communication link against the unpredictable underwater environment. This pioneering work not only sheds light on the complexities of underwater acoustic signal transmission but also charts a path forward for the next generation of underwater communication systems. By pushing the boundaries of current technological capabilities and offering a solid theoretical foundation, this research contributes significantly to the field of underwater acoustics and opens new horizons for marine exploration, environmental monitoring, and submarine communication networks. Through its comprehensive analysis and innovative approaches, "Waymark in the Depths" not only addresses the technical challenges of underwater signal transmission but also lays down a crucial waymark for future endeavors in the uncharted territories of the ocean's depths.

Key words : Waymark, Baseband , Underwater , Acoustic Propagation , Channel Model, Signal Transmission, OFDM.

I. INTRODUCTION

In the quest to conquer the vast and enigmatic realm of the underwater world, technological advancements have paved the way for remarkable feats in communication and exploration, with "Waymark in the Depths: Baseband Signal Transmission and OFDM in Underwater Acoustic Propagation Channel Models" standing as a testament to the innovative strides made in this domain. This research not only underscores the crucial role of acoustic signals in penetrating the aqueous veil that envelops our planet's submerged terrains but also delves into the intricacies of baseband signal transmission and Orthogonal Frequency-Division Multiplexing (OFDM) as pivotal techniques in enhancing the clarity, range, and reliability of underwater communication. The enigmatic underwater environment poses a myriad of challenges, including high propagation loss, multipath reflections, and Doppler spread, all of which significantly impair the efficacy of traditional communication methodologies. However, by harnessing the principles of acoustic propagation and meticulously tailoring channel models to the unique conditions of the aquatic milieu, researchers have been able to chart a course through these turbulent waters, offering new possibilities for subaquatic navigation, data collection, and remote sensing. The exploration of baseband signal processing, with its capacity to minimize the bandwidth of the transmitted signal without compromising its integrity, emerges as a cornerstone of this endeavor, providing a robust framework for the transmission of information across vast underwater expanses. Coupled with the adoption of OFDM, a technique revered for its resilience to frequency-selective fading and its ability to facilitate high-speed data transmission over multiple carrier frequencies, this research illuminates a path forward in the quest for efficient and effective underwater communication.

Through the meticulous construction of channel models that reflect the nuanced dynamics of acoustic propagation beneath the waves, this study not only amplifies our understanding of the underwater acoustic environment but also paves the way for the development of sophisticated technologies capable of overcoming the formidable obstacles posed by the deep. In essence, "Waymark in the Depths" serves as a beacon of innovation in the field of underwater communication, heralding a new era of exploration and interaction with the world's most uncharted territories. By weaving together the threads of baseband signal transmission, OFDM, and acoustic propagation theory, this research not only charts a course for future advancements in underwater technology but also encapsulates the relentless human spirit to explore, understand, and connect with the mysteries that lie beneath the surface.

For millions of years, in the vast oceans, some marine mammals like dolphins and whales have used acoustic waves as a way of communicating with each other. In recorded human history, around 350 years B.C., Aristotle noted that humans can hear sound in water as well as in the air [5]. In 1490, Leonardo da Vinci observed that the sound of ships can be heard at great distances underwater [6]. In 1743, Abbe J. A. Nollet conducted a series of trials, and verified that sound can travel underwater, even easier than that travels in the air [7].

It is not until the Second World War, for military purposes, the underwater wireless commu-nication technique started to develop [8], eliminating physical connection of tethers. After the War, underwater communications started to extend into commercial fields. In recent years, the demand for it has motivated extensive research in a growing number of oceanic applications, e.g., discovery of new resources, marine and oceanographic research, marine commercial operations, speech transmission between divers, remote control in off-shore oil.
industry, scientific data collection from ocean-bottom stations, control of surface vessels, un-manned or autonomous underwater vehicles (UUVs, AUVs), ocean floor mapping, pollution monitoring in environmental systems, and so on [9, 10]. Driven by these demands, the utili-sation of underwater communications will likely experience a surge in the near future.

Currently, for employing such wireless communications, three completely different underwater wireless waves are commonly used, which are: radio waves, optical waves, and acoustic waves. The radio waves are commonly used for communication in the air, due to their fast-speed propagation and wide available frequency spectrum as well as their capability of propagation without medium. The optical waves are commonly used for their small propagation delay and high possible data rates. However, the radio waves suffer from tremendous attenuation, i.e., require large antennas and high power for transmission, only over short distances (usually at ranges of just a few metres) underwater [9]. The optical waves are severely scattered in a few hundred metres in water mediums [9]. Acoustic waves, on the contrary, are attractive for underwater communications, due to their capability of propagating over distances as large as hundreds or even thousands of miles [9].

Even though the acoustic waves possess the significant merit in underwater communications, they also offer a great deal of challenges, due to issues like [10,15]:

1. Doppler effect, induced by the motion of the transmitter, the receiver, and the propa-gation medium with a low propagation speed of sound (normally 1.5 km/s);
2. Multipath propagation, induced by reflections on the sea surface and bottom, refraction of sound waves, scattering from inhomogeneities in the water column, resulting in intersymbol interference, signals spreading (typically tens of milliseconds) and frequency-selective signal distortion;
3. Time-variation, from the ocean surface waves, internal waves, turbulence, and tides;
4. Small available bandwidth, from roughly 1 to 100 kHz;
5. Ocean noise from numerous mechanisms, including weather, surface wave action, marine life, shipping, and off-shore industry;
6. Geometrical shadow zones, where no acoustic power is transferred to, bent by uneven speed of sound in a designated direction;
7. Strong signal attenuation, due to absorption, i.e., transfer of acoustic energy into heat, especially for high frequencies over long distances.

Underwater communication techniques are summarized as follows.

1. The Waymark UWA channel model [1], based on an approach for setting waymark sam-pling interval, is modified for acoustic signal propagation underwater, that processes signals in the baseband. The baseband model processes signals at a low sampling rate. Therefore, the computational complexity of the model is reduced. Moreover, the performance of it is comparable to that of a relatively mature UWA channel model VirTEX [16].
2. A multi-channel autocorrelation (MCA) method is proposed for Doppler estimation. The method can be used in communication systems with periodically transmitted pilot signals or repetitive data transmission. This method requires a small number of Doppler estimation channels, which provides low computational complexity, while providing accurate Doppler estimation.
3. Space-time clustering in UWA channels is illustrated, and space-time clusters com-bining is proposed to improve detection performance and reduce the computational complexity of a receiver. Based on the illustrated space-time clustering, a spatial filter is proposed for DOA estimation, beamforming and producing directional

signals. The angles for producing directional signals are based on the discrete space-time clusters, which usually results in a small number of diversity branches of the receiver. Based on the delay spread estimation of a directional signal, an equalizer length is optimized to reduce the computational complexity of each diversity branch. Moreover, due to the Doppler-delay spread of signals in a single cluster is smaller than that in multiple clusters, extra performance improvement can be achieved with a reduced complexity.

4. The time-varying UWA channels are exploited with DOA estimation, and a beamform-ing technique with DOA tracking is proposed to produce directional signals in time-varying UWA communication channels. In the channels, the DOAs are often varying rapidly within small angular intervals, which are usually produced mostly by moving boundaries (ocean surface), internal waves and drifting hydrophones/sensors. Based on the proposed beamforming technique with DOA tracking, a receiver shows capability of tracking the time-varying DOA and demonstrates better detection performance than that without DOA tracking.
5. Two sliding-window sparse recursive least squares (RLS) adaptive filters, based on di-agonal loading and homotopy, are proposed and used in UWA channel estimator. They are used for UWA sparse impulse response estimation. Sea trial results suggest that the two proposed sparse RLS adaptive filters achieve better performance than the classic and existing sparse RLS adaptive filters used for comparison.

II. RESERACH BACKGROUND

For underwater acoustic (UA) communication systems, adaptive modulation was studied to improve efficiency. UA channels and ambient conditions alter quickly, making high data rates difficult. A time-varying UA channel is ideal for a self-adaptive system, which can select the appropriate approach based on channel conditions to ensure continuous connectivity and excellent performance. This paper introduces a real-time OFDM-based adaptive UA communication system using NI LabVIEW and CompactDAQ. This study uses the received SNR as a performance metric to choose transmission parameters back to the transmitter for data transmission. This research develops a UA OFDM communication system using adaptive modulation schemes for a nonstationary UA environment to select subcarriers, modulation size, and power adaptively to improve communication reliability, connectivity, and data rate. The adaptive UA OFDM system's performance and superiority were confirmed by recent UA communication trials at Canning River, Western Australia. [1]

Su tesis doctorate propone técnicas para mejorar la viabilidad de un transceptor OFDM para transmisión submarina. Initialmente, se desarrolla y evalúa un banco de pruebas (simulador) acústico submarino basado sobre el transceptor OFDM (Orthogonal Frequency Division Multiplexing) de prefijo cíclico (CP). The simulator is Matlab-based. OFDM has longer guard intervals than retardation and uses a ZF (Zero-Forcing) equaliser, estimating the optimal canal. Additionally, the proposed system allows for several transmitter parameters and BER comparisons for various scenarios. El diseño propuesto permite evaluar diversos modulation schemes. The second contribution proposes a pilot-assisted channel estimation algorithm based on a minimum squared error (LSE) estimate. Additionally, two equalisers have been considered to improve the error performance of an OFDM-based submarine communication system. Both equalisers use pilot subporters to measure the underwater hydraulic canal. Two equalisers are used: one is a minimum squared (LS) equaliser and the other is a ZF equaliser. The third contribution of this work evaluates the performance of a GFDM (Generalised Frequency Division Multiplexing) transceiver for high-speed submarine transmission. Using simulations, the proposed GFDM transceptor's spectrum efficiency, PAPR, BER, and computational complexity were examined. Comparisons were made with CP-OFDM results. A GFDM-based model has been developed and evaluated for underwater communication. [2]

This article introduces orthogonal frequency division multiplexing (OFDM) for underwater acoustic (UWA) communication using discrete Hartley transform (DHT) instead of discrete Fourier transform. DHT-OFDM reduces pilot overheads associated with tracking UWA channel effects by 50%, increases carrier frequency offset robustness, and reduces system complexity. The suggested system uses DFT receivers instead of DHT to enable low-complexity estimation and equalisation jobs and overcome intercarrier coupling, which reduces DHT-OFDM data rate by half. The proposed underwater DHT-OFDM now works with index modulation for better spectral efficiency harvesting. Both simulation and real experiments show that the suggested techniques outperform the benchmarks in bit error rate, Doppler shift, spectrum efficiency, and system complexity. [3]

This paper introduces a deep learning-based underwater acoustic (UWA) OFDM communication system. After sufficient training, the deep learning-based UWA OFDM communication receiver interpreted as a deep neural network (DNN) can directly recover transmitted symbols, unlike the traditional receiver that performs channel estimation and equalisation. The DNN-based receiver estimates transmitted symbols in two stages: (1) training, where labelled data like known transmitted data and signal received in the unknown channel are used to train the DNN, and (2) test, where the DNN receiver recovers transmitted symbols from the received signal. We use an acoustic propagation model with a measured sound speed profile to train and test the DNN receiver and generate a lot of labelled and unlabeled data to illustrate the performance of deep learning-based UWA OFDM communications. The performance of deep learning-based UWA OFDM communications is evaluated using system characteristics including cyclic prefix length, pilot symbols, and others. Simulations show that the deep leaning receiver outperforms the UWA OFDM receiver.[4]

This page discusses underwater acoustics transceivers. Underwater acoustic transceivers use more power than RF ones. Underwater acoustic systems cannot use radio frequency techniques directly; they must be redesigned. New or improved orthogonal frequency divisional multiplexing methods are needed for reliable acoustic data transfer. Power usage depends on underwater acoustic signal propagation and transmission distances. Several subsurface acoustic applications require long-term sea monitoring. The battery-powered modems are severely affected. This can be solved by building an energy-efficient OFDM communication system. We explore peak-to-average power ratio in an OFDM system by eliminating its main drawback. This article uses Partial Transmit Sequences for underwater acoustic OFDM communication, which is simpler. Results improved underwater acoustic OFDM communication system performance.[5]

We propose a deep learning (DL)-based OFDM receiver for underwater acoustic (UWA) communications in this paper. Our approach precisely tailors complex UWA communications compared to DNN OFDM receivers with fully connected (FC) layers. For signal recovery, it uses a convolutional neural network with skip connections. Stacks of convolutional layers with skip connections can identify interesting information from received signals and reconstitute broadcast symbols. Demodulation follows using a multilayer perceptron. Strength of the measured-at-sea WATERMARK dataset is used to build training and testing sets to illustrate the proposed DL-based UWA-OFDM communication system. Experimental results reveal that the proposed model with skip connections outperforms traditional UWA-OFDM with least squares channel estimation and FC-DNN-based framework in accuracy and efficiency. This is especially true in tough UWA situations with high multipath spread and rapid time-varying features. [6]

The underwater (UW) acoustic channel faces coloured ambient noise, frequency-dependent attenuation, and doubly selective fading. A reliable underwater communication system can improve pollution surveillance, defence, and search/rescue efforts. Generalised frequency division multiplexing (GFDM), a non-orthogonal multicarrier technique recently researched for terrestrial wireless fading channels, is designed and tested for UW acoustic communication signals. Statistics are used to model UW noise, attenuation, and doubly selective fading. From simple additive white Gaussian noise (AWGN) and Rayleigh fading channels to a horizontally arranged UW channel, the suggested system's BER performance is tested. The performance is also compared to modern OFDM and FBMC systems.[7]

UAC system designers face the wide range of communication qualities of underwater acoustic channels, especially in shallow waters with highly fluctuating instantaneous conditions. Phase modulated signals cannot reliably transmit data across such a difficult channel. However, orthogonal frequency-division multiplexing (OFDM), a multi-carrier amplitude and phase modulation technology used in the current wireless communications standards, offers reliable transmission with an acceptable error rate. This study presents communication tests in shallow water in Wdzydze Lake using a laboratory OFDM data transmission system model.[8]

Limited bandwidth, significant propagation delays, extensive multipath, severe attenuation, fast time fluctuation, and large Doppler shifts make underwater acoustic channels difficult. Many underwater communication strategies have been developed to handle such complexity, however they are mostly tailored to specific application scenarios. For high-spectral-efficiency modulations, which are sensitive to channel parameters, environment-specific solutions are essential. Our software-defined modem can dynamically predict acoustic channel conditions, tune OFDM modulator settings as a function of the environment, or switch to a more robust JANUS/FSK modulator in difficult propagation conditions. Maximum delay spread and Doppler spread summarise channel behaviour temporal variability. We offer a fast method for determining these parameters and explain the OFDM modulator's limit conditions. We also tune the prefix length and sub-carriers to reduce inter-symbol interference and Doppler effect signal distortions. We use a specialised simulator for time-varying underwater channels, the Watermark simulator, and real field tests to evaluate our estimation and adaptation methods. Our results show that in many practical instances, a dynamic modification of the prefix length and number of sub-carriers can enable OFDM modulations in underwater communications, whereas JANUS can be employed in harsher environments. [9].

We propose a deep learning (DL)-based OFDM receiver for underwater acoustic (UWA) communications in this paper. Our approach precisely tailors complex UWA communications compared to DNN OFDM receivers with fully connected (FC) layers. For signal recovery, it uses a convolutional neural network with skip connections. Stacks of convolutional layers with skip connections can identify interesting information from received signals and reconstitute broadcast symbols. Demodulation follows using a multilayer perceptron. Strength of the measured-at-sea WATERMARK dataset is used to build training and testing sets to illustrate the proposed DL-based UWA-OFDM communication system. Experimental results reveal that the proposed model with skip connections outperforms traditional UWA-OFDM with least squares channel estimation and FC-DNN-based framework in accuracy and efficiency. This is especially true in tough UWA situations with high multipath spread and rapid time-varying features. [10]

The orthogonal time frequency space (OTFS) modulating and demodulating signal in delay-Doppler domain reduces multipath delay spread and Doppler spread combined. UACs fail because underwater acoustic channels have double dispersive features (multipath propagation and ubiquitously relative mobility). This research presents an OTFS-based UAC technique to reduce double dispersion in underwater environments. We first explain the OTFS signal pre-processing and post-processing methods, then describe the OTFS-based UACs. Through simulation research, we confirm the suggested scheme's reliability. Final simulations reveal that OTFS-based UAC outperforms OFDM and DFT-s-OFDM in time-varying multipath underwater acoustic channel. [11]

Deep learning (DL) applications for underwater acoustic

(UWA) OFDM communication have garnered attention in recent years. Performance and generality evaluations of the deep neural network (DNN)-based approach with the UWA environment mismatch are constantly needed. In this research, DNN-aided channel estimation for UWA-OFDM is first established. Under some conditions, the properly built DNN estimator can approach the minimum mean square error (MMSE) solution, as shown by theoretical analysis and satisfactory experimental findings. In testing with the at-sea-measured WATERMARK dataset, the suggested method showed near-optimal performance and more than 40% bit error rate (BER) improvements over the least square (LS) algorithm. Additionally, UWA channel statistics are mathematically represented. Experimental results help us understand the model performance-UWA environment link. When UWA environment mismatches occur, such results can guide model transfer/adjustment. Finally, experimental results show that model transfer is feasible, reducing BER by 69.8% between two UWA scenarios. [12]

This study proposes a low-multifaceted Doppler-shift pay for OFDM suitable for underwater acoustic communication (UWAC). This calculation employs the quantity and fragmented parts of the time extension/pressure estimated in a short portion of an example period in each OFDM to measure the Doppler-shift and carrier-frequency-offset. The proposed plan built throughput utilising a single trill beat, unlike square Doppler remuneration. To manage Doppler-shift variability in OFDM, a smoothing channel is used. The planned technique can achieve high distinctive impacts without preliminary goal information. Its minimal computing complexity makes it easy for equipment to execute and handle. The strategy's viability is tested by recreation. [13]

Underwater acoustic communication is best for underwater data transfer and navigation due to its tens of kilometres transmission range and 20 kbit/s data rate. However, the underwater acoustic route has many issues, including high multipath propagation. One solution is to use an underwater acoustic communication system, which uses OFDM and a phased antenna array based on coaxially located piezo ceramic cylinder antennas to steer the transmitting device's directional pattern. OFDM with high-rank subcarrier modulation has good data throughput, and beam steering (BS) reduces multipath effects by finding the ideal directional pattern inclination angle. The study covers system design, experiment settings, and outcomes analysis. [14]

We are unaware of any studies on nonorthogonal frequency-division multiplexing (NOFDM) in underwater acoustics (UWA) communication, despite the decade-long study of OFDM. Thus, we examine NOFDM for UWA communication across the doubly dispersive channel. NOFDM has higher spectral efficiency than OFDM due to its closer-packed subcarriers. This gearbox is plagued by intercarrier interference. When considering the doubly dispersive channel, multipath propagation causes intersymbol interference. Thus, the typical NOFDM receiver in the UWA channel is computationally difficult. To address this issue, we build a NOFDM receiver using the basis expansion model and orthogonal matching pursuit (OMP), which reduces computational complexity. Due to guard intervals, this approach causes considerable delay/Doppler spread in the real sea. We recommend a time-domain equaliser to reduce lengthy delay/Doppler dispersion. Simulation and experimental bit error rate results show that significant interference in our proposed receiver degrades performance. Instead, our receiver with OMP channel estimation outperforms OFDM in mean-square-error performance. Closely packed subcarriers increase spectral efficiency. [15]

OFDM is promising for many underwater acoustic (UA) communications applications. This paper describes the architecture of a UA OFDM communication system with a traditional transmitter and a modified receiver with a deep neural network. The DNN could immediately recover transmitted bits by replacing channel estimation, equalisation, and demodulation in typical receivers. The regression-based DNN has an LSTM layer. DNN training can be offline or online. The trained network recovers online sent data directly during testing. The offline training approach uses a huge data collection and maximum channel situations. However, online training uses a tiny data set and short training time. The regression-based DNN receiver outperforms earlier DNN receivers and the least-squares (LS) estimator-based receiver. [17]

Underwater acoustic channels have multipath due to reflections of the sea surface, seabed, and obstacles and ocean inhomogeneity. Multiple pathways interfere, causing significant amplitude and frequency selective fading. Multicarrier underwater audio communication data rate is reduced by a long guard interval, but it is an effective anti-multipath approach. Our research proposes a new anti-multipath multi-carrier communication method using orthogonal chirp division multiplexing (OCDM) and chirp signals for carrier modulation. OCDM uses multipath components for variety, improving system robustness. A data pick-based rake receiver improves communication even at small guard intervals in the novel technique. We implement and select parameters for the antimultipath OCDM system and compare its performance with orthogonal frequency division multiplexing (OFDM) using simulations. Under a severe multipath simulation condition (the delay spread is longer than the guard interval), the antimultipath OCDM achieves a bit error rate (BER) of 10 -6, while the OFDM has a BER floor of 10 -3. Simulations demonstrate the method's viability and anti-multipath effectiveness. [18]

In Unique Word Orthogonal Frequency Division Multiplexing, high redundant energy is a problem. This letter proposes a solution. The Low-Redundant Energy UW-OFDM (LRE-UW-OFDM) scheme is suitable for time-varying harsh channels like the Underwater Acoustic (UWA) channel, where inserting UW data in the time domain causes huge redundant energy and a dramatic BER degradation. The suggested LRE-UW-OFDM inserts UW in frequency domain to be any desired sequences in time domain with constant redundant subcarrier energy regardless of data subcarrier size and placement. Over a long-delay UWA channel, the suggested technique outperforms existing schemes in BER and mean symbol energy. [19]

Orthogonal frequency division multiplexing (OFDM) systems are severely hampered by the Doppler effect. Underwater acoustic (UWA) communication methods lose orthogonality across sub-carriers due to the underwater channel's unique properties. Channel estimation and ICI reduction are widely used to compensate Doppler shifts, phase noise, and multipath channels in realistic communication circumstances. However, channel estimation and FFT size affect accuracy, increasing receiver computational cost. A unique frequency domain pilot structure has been used to overcome channel impulse response (CIR) variation in a block period in the underwater communication environment to achieve this dual purpose. Initial coarse Doppler shift estimation uses the pilot signal. After that, the study uses non-uniform fast Fourier transform (NFFT) to choose sampling points to build a fast and reliable Doppler frequency Compensation Matrix-based NFFT (DCMN) to fine-compensate the Doppler phase shift. This study concludes that experimental measurements and simulations improve the proposed strategy. [20]

III. WAYMARK BASEBAND UWA PROPAGATION CHANNEL MODEL

It is difficult to model acoustic wave propagation underwater, due to distortions from severe Doppler spreading and multipath [64]. The relatively slow propagation of sound through wa-ter makes the Doppler effect significant in performance of UWA communications. This is especially apparent when the specific time-varying multipath propagation is taken into consideration due to the complicated motion of a transmitter/receiver. It is clearly desirable to be able to make a computer simulation of the propagation of an acoustic signal through the ocean, especially for testing signal processing algorithms for UWA communications. Not only are sea trials expensive and time consuming, but also the parameters are difficult if not impossible to control, therefore trying out different design ideas in similar conditions or environments becomes infeasible.

Currently, a number of approaches to deal with this problem have been presented in litera-tures, for example using a static channel impulse response obtained from acoustic field computation, or a model based on random fluctuations of complex amplitudes of eigenpaths. Some models approximate the Doppler effect by introducing frequency shifts in eigenpaths and statistical model for multipath amplitudes. Other approaches are based on direct replay using a measured time-varying channel response, random local displace-ments, and so on.

Among these approaches, a promising one for dealing with this problem is the ‘virtual’ signal transmission. For such a virtual signal transmission, i.e., the transmission that mimics a real sea trial, the VirTEX underwater propagation channel model was developed and used; this model is based on the Bellhop ray/beam tracing to compute the channel impulse response in different acoustic propagation environments. A similar approach was im-plemented in the Waymark model [1] developed in this research group to efficiently simulate the UWA signal transmission in long communication sessions, potentially allowing for less computation. However, the passband signal processing in the Waymark model developed in [1] can be replaced by baseband signal processing, which would potentially reduce the complexity further.

A new Waymark model described in this chapter with the aim to further reduce the compu-tational complexity is developed by my colleague Mr. Benjamin Henson. The new developed model uses baseband processing for modelling the signal transmission. The author verifies the new developed model with three simulations, and use the new model to model the signal transmission for designing UWA receivers in the following paragraphs.

Underwater Channel Simulation

A received signal in a time-varying linear channel may be described in the general case by without considering noise:

Z 1

y(t) = h(t;)s(t)d ; t 2 [0; Tsig]; (2.1)

where h(t;) is the impulse response of the channel, s(t) is the transmitted signal, Tsig is the signal duration. At time t the baseband channel impulse response may be represented as the sum of multipath components given by:

L Xp h(t;) = cp(t) (p(t)); (2.2)

where

cp = Ap(t)e j2 fc p(t); (2.3)

L is the multipath components, cp is the complex amplitude of path p, j = 1, p(t) is the time-varying delay for path p, Ap(t) is the time-varying complex amplitude for path p, fc is the signal carrier frequency. The delay p(t), would be affected by the path geometry, which would encompass any movement in the system ultimately representing the Doppler effect.

In the passband Waymark model [1], the impulse response are calculated for a set of points or waymarks along the transmitter/receiver trajectory. The relative delay in the impulse responses between these points is then estimated, allowing the shape of the impulse response and the delays to be interpolated separately, giving an improved result.

Different from the Waymark model, the VirTEX model [16] uses a regularly spaced grid to describe the water volume that the signal propagates through. The model interpolation is performed on the amplitude and time of arrivals of the multipath components. An interpo-lated point between the grid points is the weighted sum of the arrivals at the four surrounding points. So, for instance, if there were two multipath arrivals at each of the surrounding grid points then the interpolated point would comprise of eight multipath arrivals. The delays are adjusted according to the local speed of sound, the geometric distance and incident angle from the interpolated point to the grid point. The VirTEX system also includes an ocean surface wave model, however for our experiment it is set up as a flat surface.

In the chapter both the Waymark and VirTEX models use the Bellhop ray-tracing pro-gram to simulate the physics of the propagation. Other simulators could be used, how-ever the VirTEX model is restricted to a ray traced input. The Waymark model can use any model that can produce a frequency response. This would perhaps be more versatile for lower frequency signals and more complicated bottom profiles where normal-mode models such as KRAKEN may be more appropriate.

The original signal spectrum is shifted to centre around zero and a low pass filter (LPF) applied. The LPF chosen is a raised cosine filter. Once the signal has been moved to be the baseband equivalent then the sampling frequency may, with reference to the baseband bandwidth, be decimated from Ts to give a lower sample period Td.

Figure 1 shows a diagram of the system with the development from the original system in [1]. In this development the waymark impulse response is created in the baseband, in addition the input signal is converted to a downsampled baseband signal and passed through the time-varying delay and time-varying FIR filter. The splitting of the channel into these two components allows a more accurate interpolation of the channel impulse response for more details see between waymarks, thus increasing the waymark interval and consequently reducing the computation. However, the time-varying delay requires a phase correction when upshifting the signal as shown in Figure 1.

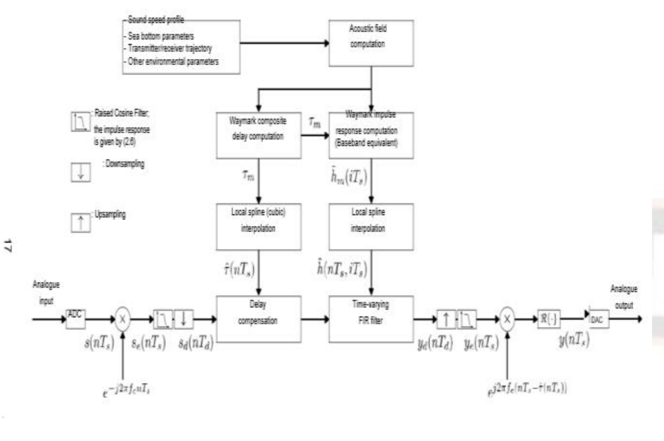


Figure 1: A block diagram of the UWA simulator as a development on the system presented in [1]. The link between the delay compensation for the impulse response and taking account for this in the upshifting can be seen represented with ^(nTs).

IV. SHALLOW WATER EXPERIMENTS

In order to compare the Waymark and VirTEX models, three experiments are performed. The first is with a flat sound speed profile (SSP), the second is in a summer environment, the third is in a winter environment.

In the three simulations, a pseudo-random binary sequence (PRBS) data signal is passed through the channel models, and a cross-ambiguity function (CAF) is computed. In or-der to obtain a fine resolution for Doppler and delay in the CAF, a PRBS is generated using an m-sequence of a length of 255. Five periods of the PRBS are generated at a bit rate of 1250 Hz. A square root raised cosine filter is used for pulse shaping the sequence, with a roll-off factor of 0.25, thus producing a signal with the bandwidth 1562.5 Hz. The carrier frequency is 5 kHz and the sampling frequency is 40 kHz. The transmitted signal duration is 100 s.

Flat sound speed profile
In this simulation, the environment is as follows.
Flat SSP at 1.5 km/s;
Flat bottom at 200 m. Sound speed in sea bed 1.6 km/s; Flat calm surface;
Transmitter and Receiver depth 100 m; Range 1000 + vct metres, (vc = 5 m/s);

Decimation factor 8, giving Td = 0.2 ms.

The decimation factor is 8, giving a large saving in the channel impulse response interpola-tion and convolution calculations (at least linear in the decimation factor) compared to the original Waymark model in [1].

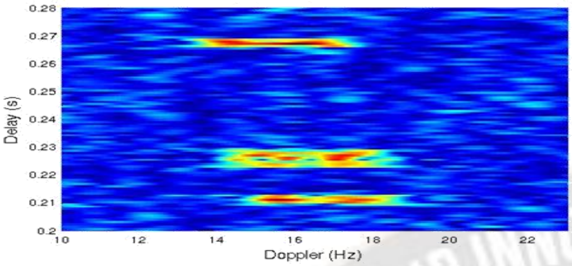
The waymark interval is 0.0512 s. For the Waymark model, two minutes of transmission time is simulated requiring 2344 field calculations, this number being proportional to the duration of the transmission time. As for the VirTEX model, to cover the whole area for ranges between 0 and 2 km and depths between 0 and 200 m with a resolution of 0.254 m, the same as that in the Waymark model, the VirTEX model would require 6:2 106 field computations; however this figure is constant for any transmission time. An estimate of the differential delay and Doppler shift between the generated PRBS signal and the demodulated sequences in the receiver a CAF was calculated using:

A(; f) = s1(t)s2(t +)e j2 ftdt; (2.8)

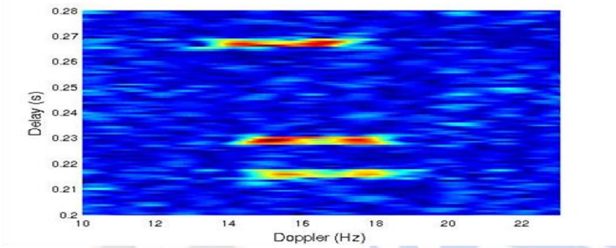
where s1(t) is the complex envelop of the generated PRBS, s2(t) is the complex envelop of the demodulated signal from the channel, is the multipath arrival delay, and f is the Doppler shift. Figures 2.2(a) and 2.2(b) show the CAF of the generated PRBS and demodulated sequence from the Waymark and VirTEX channel models.

One period of the signal is chosen for analysis. The images in Figures 2.2(a) and 2.2(b) show some similarities: both have three main paths (direct, and reflected paths from the surface and bottom) showing comparable excess delays. Also, both have similar Doppler shifts (around 16.67 Hz). The variation is considered to be due to the differences in the interpolation in the two models and a different processing window from the removal of the initial propagation delay for all paths.

In this simulation, the environment is as follows



(a) Waymark.



(b) VirTEX.

Figure 2: CAF for the two propagation models with a flat SSP.

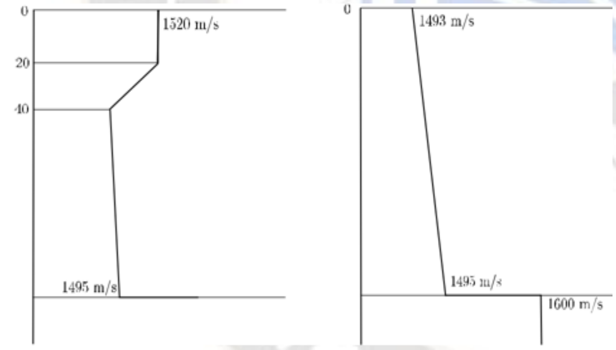
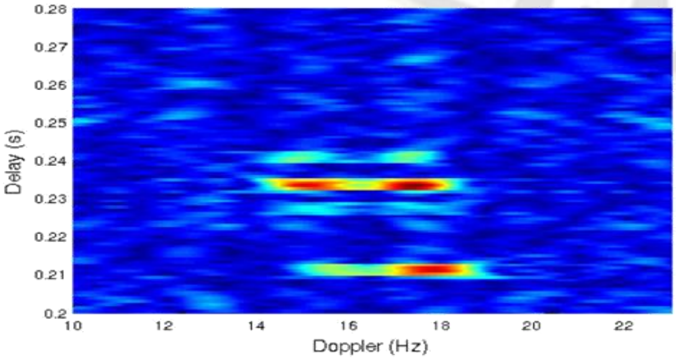
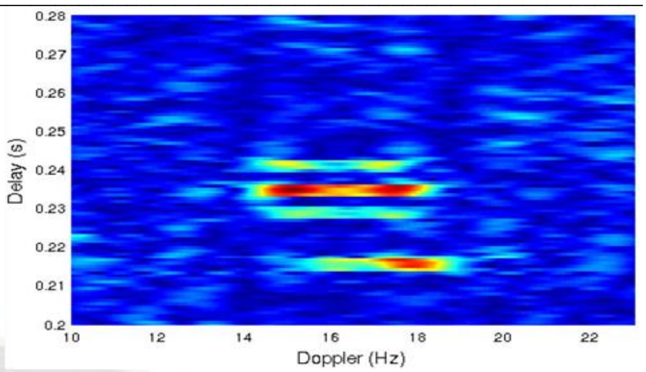


Figure 2.3: The canonical shallow water SSPs [2, 3] used in the simulation



(a) Waymark.



(b) VirTEX.

Figure 3: CAF for the two propagation models in the winter environment

V. CONCLUSION

the proposed Waymark baseband UWA propagation channel model requires a lower computational complexity than the Waymark passband UWA propagation channel model, and the performance of it is comparable to that of a relatively mature UWA propagation channel model (VirTEX). This chapter involves developing the channel model and signal representation at the baseband. This however represents a significant chal-lenge; the time-varying phase shift introduced into the upshifted signal at the channel output, should be perfectly synchronized with the time-varying delay introduced in the transmitted signal before the baseband time-varying convolution. This is in addition to the decimation process being taken into account. This challenge is similar to that in the baseband Doppler effect compensation in underwater acoustic modems. In this work, three experiments were considered, in which the Waymark and VirTEX models were compared. The results show similarity with a qualitative comparison, with the major feature such as the Doppler shifts and delays being the same. It is not expected that the results show perfect agreement, since different interpolation procedures are used in the models.

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