A Journey toward Modeling and Resolving Doppler in Underwater Acoustic Communications

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ABSTRACT

Underwater acoustic (UWA) communications is the only reliable method for long-distance communications underwater, and is widely used in commercial, scientific, and military scenarios. However, the UWA channel is most challenging due to its double dispersion property in both long time delay and large Doppler spread, resulting in severe multipath spread and time variation. Among these, Doppler spread is one of the most critical challenges, and researchers have proposed various models in order to resolve Doppler spread in UWA channels. In this article, an overview of Doppler modeling and resolving is provided, divided into four stages: the quasi-static model of the mid-1980s, the uniform Doppler shift model in the 1990s, the basis expansion model and uniform path speed models of the late 1990s, and the recently developed non-uniform path speed model. Furthermore, the UWA channel sparsity property utilized by each of those models will also be discussed.

INTRODUCTION

Underwater acoustic (UWA) communications are widely believed to be the only approach feasible for long-distance communications underwater, and are widely used in various scenarios. The need for high-quality underwater wireless communications arises in many military, scientific, and civilian applications, including communications among submarines, underwater security surveillance, scientific data collection at ocean bottom stations, off-shore oil explorations by autonomous underwater vehicles (AUVs), and data exchanges in underwater sensor networks for environmental monitoring. The 20th century witnessed the evolution of UWA communications from analog noncoherent techniques to digital coherent ones. However, as shown in Fig. 1, UWA communications is uniquely challenging due to the underwater environment and UWA propagation properties. A specific presentation of Fig. 1 is provided in the following three paragraphs.

On one hand, due to the low propagation speed at 1500 m/s of acoustic waves underwater, a relatively large number of arrivals could be distinguished at the receiver side in a shallow water scenario, which usually lasts for tens of milliseconds. This large multipath spread results in long time delay characteristic of the UWA channel and severe inter-symbol interference (ISI) when information from different arrivals collapse into each other, leaving channel equalization a demanding task for reliable UWA communications. Thus, multipath spread should be taken into account when modeling the UWA channel. In addition, the UWA channel also features significant Doppler effects due to platform and sea surface motion, causing large Doppler spread. The large Doppler spread may contaminate the communications, so it needs to be carefully mitigated. The reason the Doppler effect is difficult to solve lies in the fact that it could have different values for different frequencies throughout the bandwidth. Due to its nature, the Doppler effect is widely considered to be more difficult to accommodate than the multipath effect. Unfortunately, UWA channels have severe time variance, where the channel property may differ as time passes by. This explains why the UWA channel time-varying property is another important consideration in modeling. In general, due to long time delay and large Doppler spread, UWA channels are often characterized as doubly spread, especially in shallow water, while terrestrial RF channels are not unless the transceiver mobility is very high.

On the other hand, acoustic waves usually propagate at low frequencies, typically tens of kilohertz, compared to electromagnetic waves that propagate at gigahertz. The fractional bandwidth for a UWA communication system, defined as the ratio between bandwidth against carrier frequency, is usually 1000 times greater than that of terrestrial wireless systems. Thus, a UWA communication system is a typical wideband system. Due to the low propagation speed of acoustic wave at 1500 m/s in water compared to electromagnetic waves propagating at 3×10^8 m/s in air, Doppler spread for UWA communications will have much greater relative values than terrestrial RF communications. Furthermore, UWA communication systems have different Doppler spread values for different frequencies due to their wideband property, unlike narrowband systems where Doppler spread could be considered constant over the entire bandwidth.

The above discussions indicate that more severe challenges are present in UWA channels

The authors provide an overview of Doppler modeling, divided into four stages: the quasi-static model of the mid-1980s; the uniform Doppler shift model in the 1990s; the basis expansion model and uniform path speed models of the late 1990s; and the recently developed non-uniform path speed model.

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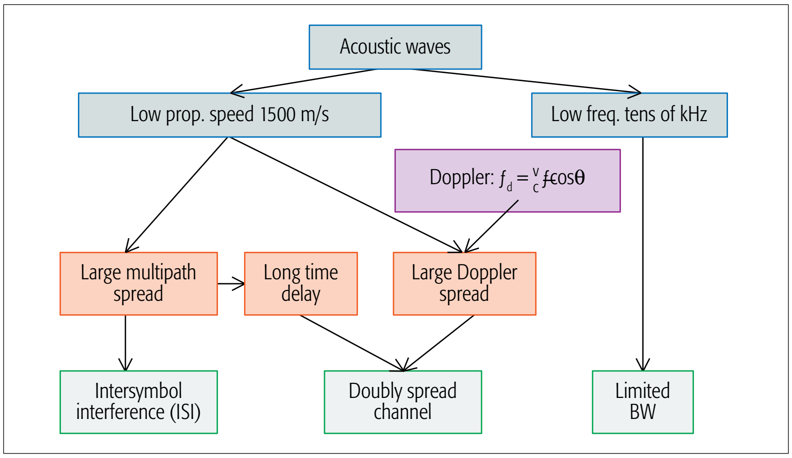

Figure 1. a) Uniform Doppler shift model; b) frequency compression.

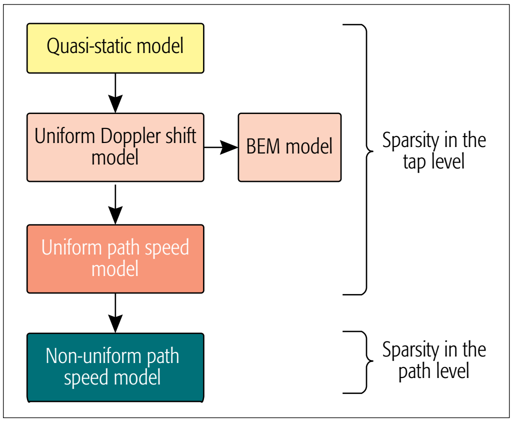

Figure 2. Doppler spread modeling in five stages.

than those in terrestrial RF channels. Several topics of interest have been focused on in UWA communications research in recent years, such as Doppler modeling and resolution, channel equalization for ISI cancellation, UWA channel doubly-spread mitigation in both time delay and Doppler scale, and bandwidth efficiency improvement. Among all these research interests, we believe that Doppler modeling and resolution is one of the most crucial aspects in present UWA communications, and also partly supports the physical layer research in UWA communications at the same time.

In this article, an overview of Doppler modeling and resolution is provided for ever better understanding of the nature of UWA communication channels, and through its development the progress of UWA communications research is also demonstrated. Unlike the distinguished review of UWA communications [1], where the major discussions about UWA communications are channel modeling, equalization, time reversal and passive phase conjugation, multicarrier system, and so on, this article mainly focuses on Doppler modeling and resolution, and tries to reflect the development of UWA communications via this approach. Throughout this article, the Doppler spread concept means that the exact Doppler value varies for different frequencies throughout the bandwidth, while for the term Doppler shift, which is a simplified version of Doppler spread, only a carrier frequency offset (CFO) is considered.

The modeling of Doppler spread can be divided into five stages in a chronological manner, which is shown in Fig. 2: quasi-static model, uniform Doppler shift model, basis expansion model (BEM), uniform path speed model, and non-uniform path speed model. In the mid-1980s, the quasi-static model considered UWA channels as time-invariant in a certain time interval, incapable of tracking channel time variation. The problem solving approach during that time was vague. Later, in the 1990s, a constant CFO (i.e., a uniform Doppler shift value throughout the bandwidth) was introduced into the uniform Doppler shift model, which can be compensated by frequency shifting at the receiver side. In the late 1990s, researchers started to use the BEM, which comprises a series of basis functions to fit UWA channel time variation, purely from the mathematical point of view and skipping its physical propagation properties. Around the same time as the BEM arose, the uniform path speed model started to be used in UWA communications, where a constant path speed is assumed. This model leads to the same Doppler expansion (or compression) ratio for various frequencies, and this expansion (or compression) could be compensated by resampling the received signal in the time domain. The most recent model, the non-uniform path speed model, which arose in the last few years of the 2000s, involves different path speeds for various paths. One possible approach to achieving the non-uniform path speed model is to parameterize both the amplitude and the time delay in a path-wise manner. Therefore, precise Doppler spread modeling, estimation, and compensation could be performed with high precision. UWA channel sparsity is also an important issue to be addressed, where the quasi-static model, uniform Doppler shift model, BEM, and uniform path speed model exploit the sparsity in the tap level, while the non-uniform path speed model utilizes the sparsity in the path level. The usage of sparsity is discussed later.

This article is organized as follows. The quasi-static and uniform Doppler shift models are discussed, respectively. BEM is given. We focus on the uniform and non-uniform path speed models, respectively. We give insight on UWA channel sparsity. Finally, we provide a summary and possible future prospectives.

Quasi-Static Model

In the early stage, around the mid-1980s, UWA communication systems were achieved with limited data rates, which were usually under 1000 b/s. Knowledge on the UWA channel itself was quite limited. The UWA channel was modeled as quasi-static, that is, time-invariant within a certain time interval. This approach was not able to track the variation of the UWA channel; a long channel coherence time is required to achieve reliable communications. Doppler spread is treated at the expense of lowering the data rate and bandwidth efficiency. In addition, the time reversal (TR) signal processing technique for UWA communications was also developed based on the quasi-static channel assumption, utilizing the principle of the TR mirror in the 1990s. TR signal processing is in fact a channel equalization technique utilizing the auto-correlation property of channel impulse response (CIR), where a Dirac-shaped impulse response will be generated at the receiver side, further enabling the matched filter processing [2]. From another point of view, TR signal processing for UWA communications could be considered as a time-space matched filter for CIR by taking advantage of the ocean itself.

Uniform Doppler Shift Model

Later on, in the 1990s, the quasi-static model developed into the uniform Doppler shift model, where a fixed Doppler shift Δf_d, that is, a carrier frequency offset (CFO) as indicated in Fig 3a, was assumed throughout the whole bandwidth. In the later processing stage of received signals, this offset would easily be removed by shifting the frequency band opposite to that CFO. For example, as in [3], a frequency-shift estimator combined with a time-scale interpolator is utilized to estimate the Doppler shift, remove the offset, and then interpolate to shift the timescale of the data. The uniform Doppler shift is estimated from the training data at the start of each received packet and is computed across the range of Doppler shifts to maximize the ambiguity function, which is a two-dimensional function of the time delay and the Doppler frequency. As the previous step removes coarse Doppler shift, further operation is dedicated to deal with the residual Doppler shift; still, the performance might not be perfect.

In multiple-carrier UWA communication systems, such as an orthogonal frequency-division multiplexing (OFDM) system, which is very sensitive to the Doppler spread since it destroys the orthogonality among subcarriers, a general CFO was often modeled and estimated for all subcarriers by means of the null-subcarriers-based approach. Due to the Doppler spread, there would be energy leakages to null subcarriers, and by minimizing the energy on those null subcarriers, a CFO estimate could be obtained [4]. However, some necessary and sufficient conditions on the number of null subcarriers and their placement should be considered cautiously, since they may relate to issues like CFO identifiability. In summary, as the uniform Doppler shift model considers static Doppler shift in a certain time interval throughout the whole frequency band, it could also be regarded as a generalized quasi-static model.

Basis Expansion Model

Apart from treating the UWA channel as a quasi-static or uniform Doppler shift model, the focus of BEM, developed in late 1990s, is to model the UWA channel's time variation purely from a mathematical point of view. Taking the assumption that Doppler spread for a certain time-variant UWA channel is limited and under some maximum value, a series of basis functions could be used to fit its time variance, and those basis functions actually span an orthogonal signal space. The basic idea for BEM is that it truncates CIR in the time domain while the remaining channel taps are negligible, and then selects a series of basis functions and estimates the correspond coefficients to model the UWA channel.

The advantage of BEM is that it reduces the degree of freedom of the UWA channel since it uses limited basis functions with their corresponding coefficients to fit the UWA channel. For example, in order to get the exact CIR, an N-points sample is required. But with the BEM method, when zero values are set for those channel taps with negligible magnitudes, typically K basis functions are assigned to model the CIR, where K is smaller than N. It could be concluded from this observation that the BEM approach exploits the sparsity in the time domain for channel taps. However, the drawback of BEM is that the construction of orthogonal space is essentially performing a truncation in the time domain. This will lead to model error and frequency leakage in the high frequency band, deteriorating the estimation accuracy [5].

A brief introduction to various BEM models is provided in [6]. The discrete Fourier transform (DFT) BEM model is a common BEM model that utilizes low-frequency components in an inverse DFT matrix as basis functions, and channel fitting may be performed based on least square (LS) or minimum mean square error (MMSE) criterion. However, DFT BEM actually uses a window function to truncate CIR in the time domain, and this induces non-existent high-frequency components, resulting in modeling bias. Other BEMs include discrete prolate spherical sequences (DPSS) BEM and Karhunen–Loève (KL) BEM. DPSS BEM uses the set of eigenvectors corresponding to the largest eigenvalues of the band-limited rectangular power spectrum signal (i.e., discrete prolate spherical sequence) as the basis functions for UWA channel fitting. Since DPSS BEM has a double orthogonality property over an infinite and a finite time interval, it takes fewer approximations compared to DFT BEM. In addition,

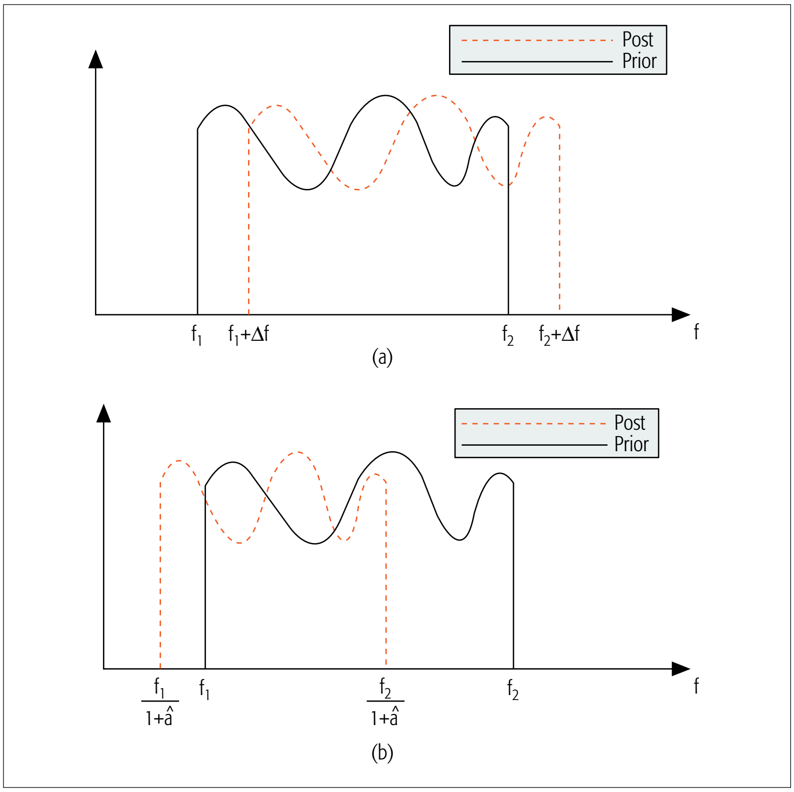

Figure 3. a) Uniform Doppler shift model; b) frequency compression.

As the uniform path speed model introduces a constant relative speed, the acceleration of transmitter or receiver platform is neglected. In fact, the constant relative speed is sufficient, because during a certain time block, the speed variation is quite limited, and the acceleration for transmitter or receiver platform, if any, is very little.

channel estimation could be performed with higher resolution by DPSS BEM since the matrix formulated by its basis function matrix is a uniform matrix the inverse of which could be calculated easily. The disadvantage of the DPSS BEM approach is that it influences the channel fitting bias distribution since it colors the noise, being worse than the DFT BEM approach. The tradeoff of DPSS BEM should relate to when to use it. KL BEM uses the eigenvectors corresponding to the largest eigenvalues of the covariance matrix of the channel as basis functions. However, a channel covariance matrix is usually not available when applying KL BEM. This yields limited usage for the KL BEM approach.

By catching the channel variation, BEM transfers the time-variant channel into its time-invariant equivalent, usually within a block time, further enabling two possible applications. One is to perform channel estimation based on BEM, since BEM reduces the number of coefficients to be estimated. DFT BEM is preferred, but the frequency leakage problem should also be considered. A possible solution is to design the window function with fewer sidelobes [5]. After the block-wise time-invariant equivalent channel model is obtained, another application is to apply differential coding at both the transmitter and receiver. By differential coding, the previously received symbols could be used as the channel reference for the current symbols, and channel estimation could be skipped.

Uniform Path Speed Model

The aforementioned model merely uses an average Doppler shift in the frequency domain to model the Doppler spread that UWA communications systems actually suffer from, and the BEM approach does not take advantage of the physical propagation property. Since the UWA communications system is a typical wideband system, where Doppler shifts each frequency component by a different amount, a more general Doppler spread should be considered. Therefore, researchers transformed the uniform Doppler shift model to the uniform path speed model for better performance.

In the uniform path speed model, for the dominant arriving paths, a constant relative speed between transmitter and receiver platform and a certain constant acoustic speed are assumed. And a complete time scaling, that is, the same ratio, throughout the frequency band is utilized to describe the Doppler expansion (or compression) in the frequency domain, which is shown in Fig 3b. In other words, the absolute Doppler spread values may differ from different frequencies, but these values share the same scaling ratio.

Therefore, a more realistic Doppler compensation strategy is to compress or extend the received signal in the frequency domain according to that ratio, which corresponds to upsampling or downsampling in the time domain. The advantage of resampling is that it could compensate for varying Doppler spread for different frequencies, which was widely used later on. As the uniform path speed model introduces a constant relative speed, the acceleration of transmitter or receiver platform is neglected. In fact, the constant relative speed is sufficient, because during a certain time block, the speed variation is quite limited, and the acceleration for transmitter or receiver platform, if any, is very little.

The example of resampling is to use a Doppler-insensitive signal, such as a linear frequency modulation (LFM) signal, placed before and after the transmitted data block, to calculate the ratio between the duration time at transmitter side T_{tx} and that at receiver side T_{rx}. By dividing T_{tx} by T_{rx}, the resample ratio $\hat{\alpha}$ can be obtained. Later on, the resampling method was extensively used in both single-carrier and multicarrier UWA communications systems, and hence became a dominant approach for average Doppler spread mitigation.

In a single-carrier UWA communications system, resampling is usually performed prior to symbol demodulation. In order to achieve high accuracy, sample rate conversion should be performed cautiously. This demanding task is usually accomplished by converting the sampling rate by a rational number [7] by which the received signal is interpolated in the first place, continued with a finite impulse receiver (FIR) filter, and finally decimated. Computational load should be improved by using linear interpolation to calculate each new sample.

Resampling has a similar application for average Doppler removal in multi-carrier UWA communications system. To achieve better perform- ance, some fine Doppler spread compensation strategy is required for more precise compensation. As shown in [8], the received signal for an OFDM communication system is resampled to remove average Doppler spread prior to being transferred to the baseband for fine compensation, converting the wideband problem into a narrowband problem. And the high-resolution uniform residual Doppler compensation is performed corresponding to the narrowband model for the best inter-carrier interference (ICI) reduction.

The application scenarios for uniform path speed model and resampling Doppler spread compensation are somehow limited, since it would lose effectiveness in shallow water scenarios when paths with excessive reflections exist, as shown in Fig. 4. For some paths (e.g., direct, surface-reflected, and bottom-reflected paths), the uniform path speed model may work well, since the difference between various arriving angles is little, yielding similar Doppler spreads. But for those with excessive reflections, a constant path speed is not adequate, and those paths need to be involved for reliable system performance. Therefore, a precise path-based Doppler modeling approach is required in addition to the uniform path speed model.

Non-Uniform Path Speed Model

The aforementioned methods (e.g., the uniform Doppler shift or uniform path speed model) use either a constant uniform Doppler shift or a constant speed to model the Doppler shift, and the BEM approach skips the channel propagation property. All three models are tap-based and unable to fully utilize the UWA channel propagation properties (the multipath effect, etc.). Thus, a new path-based approach for UWA channel modeling is required, emphasizing the channel physical propagation properties.

As shown in Fig. 4, the multipath effect of

UWA channels could be demonstrated as the effect of the direct path, the surface-reflected path, the bound-reflected path, the multi-reflected paths, and so on. The differences between these paths lay in the path variant amplitudes, time delays, and speeds, that is, Doppler spreads. The Doppler shift for the direct acoustic ray is $D_1 := fv/c$, and the Doppler shift for the acoustic ray with largest arriving angle θ is $D_2 : = fv/c \cdot \cos\theta$, so the Doppler spread is defined as $D_s := D_1 - D_2$, where v stands for the relative speed between the transmitter and receiver platforms, c is the sound speed, and f is the carrier frequency. Some insights could be obtained from the above expression when modeling Doppler spread for a specific path with path speed v, which provides the possibility of realizing the non-uniform path speed model. The UWA channels scattering function in the RACE08 sea trial is shown in Fig 5. RACE 08 was performed at Narragansett Bay near the University of Rhode Island with the help of WHOI. The water depth was 9 to 14 m, and the distance was 1000 m. Twelve hydrophones with 0.12 m spacing and three transducers were used in the experiment. Figure 5 indicates different Doppler spreads on different paths, where in good channel conditions the Doppler varies from approximately –0.2 Hz to 0.2 Hz, and it varies from approximately –1.5 Hz to 0.5 Hz in bad channel conditions. Furthermore, the sparsity property of UWA channels could also be exploited, together with compressive sensing. This is discussed in the next section.

In UWA related applications, some modeling approaches referring to physical propagation effects have been investigated (e.g., the ray-based acoustic scattering approach). In addition, the path-based UWA channel model is also investigated, in which the Doppler spread is modeled at the path level. The advantage of the path-based UWA channel model is that the Doppler spread could be treated as a mean Doppler spread that is the same for all the paths plus an individual residual Doppler spread for each path. The mean Doppler spread could be compensated by easily resampling to reduce computational complexity. And for the residual Doppler spread for each path, some advanced modeling and problem-solving approaches could be applied for better performance.

A prevalent method is to use polynomials to fit amplitude variation and time delay for different arrivals in UWA channels, first applied in terrestrial wireless communication systems and then transferred into UWA communications systems. Three coefficients are required to model each dominant ray: amplitude A, time-delay τ_p, and Doppler spread β. Specifically, as shown in [9], a polynomial up to N order is used to model the channel amplitude variation, and another one- or two-order polynomial is used to model the time delay for UWA channels. Usually, one-order polynomial is able to represent the constant speed of the transmitter and receiver platforms (i.e., the Doppler spread), while two-order polynomial is capable of modeling the linear acceleration for transmitter and receiver platforms, but additional application complexity is introduced as indicated by the theoretical analysis.

In the next step, UWA channel estimation is investigated. One possible approach is to simultaneously search in both the timescale and Doppler spread scale for estimating amplitude variation, time delay, and Doppler spread. This approach would introduce a relatively high computational load and application complexity. The computational complexity and communication overhead are traded off for achieving reliable UWA communications. When more coefficients are involved, the overhead is most likely to increase linearly depending on the transmission scheme, while the computational complexity may increase exponentially when a matrix inversion operation is required.

For further improvement, a two-stage UWA channel estimation method was proposed in 2013 [10], as shown in Fig. 6. In this approach, time delays (squares) are estimated in the timescale for each ray in the first place, and then the delay-Doppler two-dimensional grid is constructed based on the previous estimated time delay (circles). As in the two-stage approach, the estimations of two dimensions are done sequentially, and the total number of candidates for this approach is the sum of the number of candidates in each dimension. However, in the one-stage approach, as the estimation is done simultaneously in both the timescale and Doppler spread scale, the total number of candidates becomes the multiplication of the number of candidates in each dimension. Furthermore, the two-stage approach could achieve higher accuracy with the same amount of pilots or reduce the amount of required pilots to have the same accuracy as the one-stage approach.

In summary, the non-uniform speed path model exploits the propagation effect while modeling UWA channels and enables specific Doppler spread estimation on the ray-level, which are the two major contributions to UWA communications research.

Besides the difference in the approach for modeling the UWA channel for the aforementioned five models, they also vary in application scenarios. For quasi-static and uniform Doppler shift models, they are most applicable in calm sea environments with fewer water dynamics and little relative movement between the transmitter and the receiver, and the symbol duration is considerably less compared to channel coherence time. The uniform path speed model is suitable when distance between the transmitter and the receiver is large so that the reflection angle for acoustic rays is quite little. For BEM, since it is

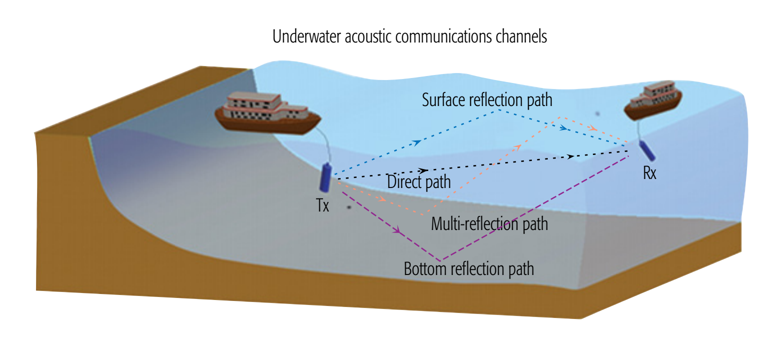

Figure 4. UWA channel multipath property.

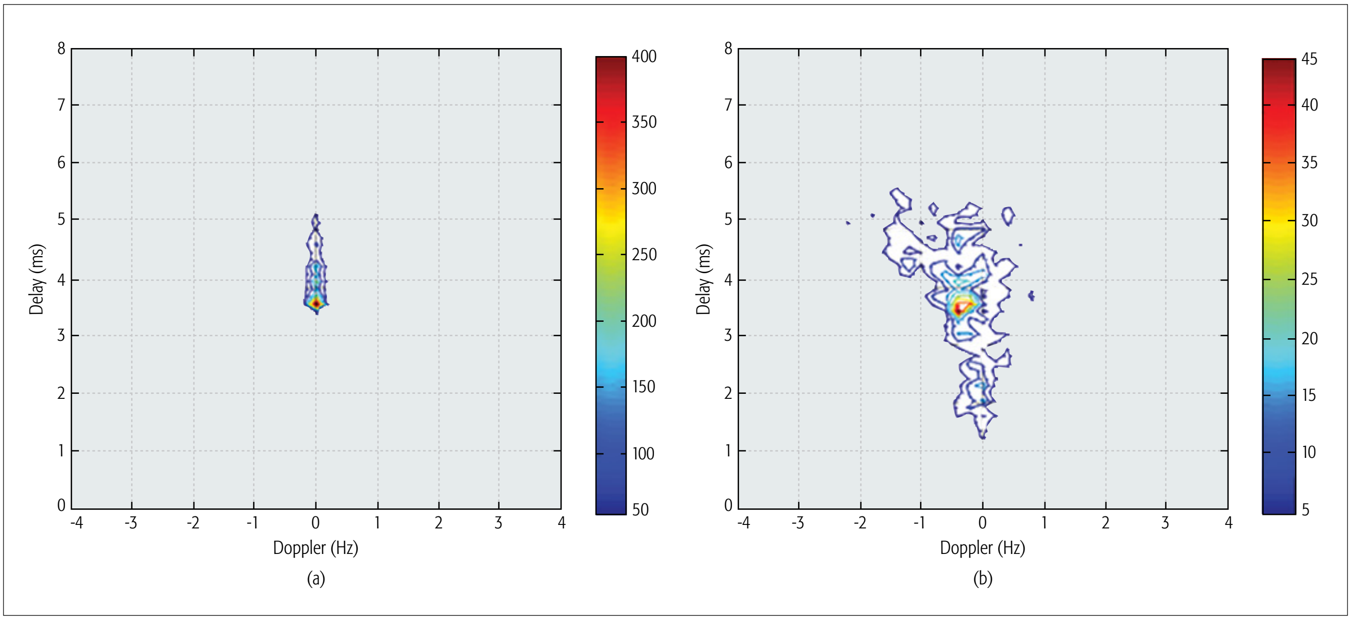

Figure 5. Scattering function for UWA channels in RACE08: a) for good channel conditions; b) for bad channel conditions.

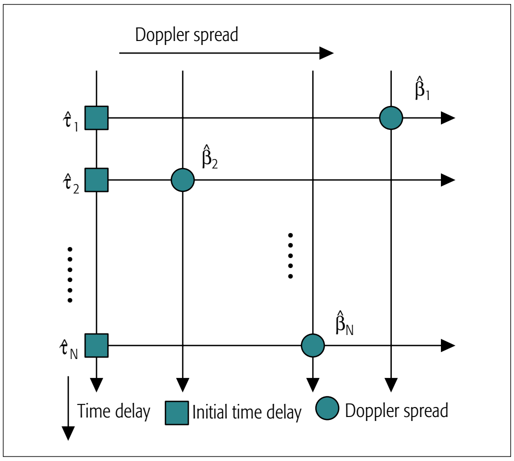

Figure 6. Search pattern for two-stage UWA channel estimation.

an approximation of a UWA channel's variation, it makes sense when the largest Doppler value is accessible. The non-uniform path speed model has the optimal performance in dynamic water circumstances with multiple paths.

UWA Channel Sparsity

From the previous sections, we see that throughout the development of UWA communications, researchers are always trying to obtain a more precise model to describe the Doppler spread, that is, the quasi-static, Doppler shift, uniform path speed, and non-uniform path speed models, and BEM, which uses basis functions to fit UWA channel time variation.

However, as more coefficients are involved in channel modeling, problems arise such as computational complexity and communication overhead. The model accuracy and the above expense seems a trade-off for achieving reliable UWA communications. One possible solution to this problem is to explore UWA channel sparsity and combine it into the demanding model task. The aforementioned models utilize the UWA channel sparsity to different extents, as discussed in the following parts.

The quasi-static and uniform Doppler shift model only utilize a constant uniform Doppler shift, which could be treated as the sparsest but least accurate modeling approach. Also, the uniform path speed model performs the Doppler modeling by means of a constant speed, so specific Doppler spread values for different frequencies are actually required for compensation, which increases its complexity but with better system performance. BEM uses a series of basis functions to fit the time variation of UWA channels, and it truncates the CIR with a certain window function, neglecting the rest of the channel taps. In one word, the above models utilize UWA channel sparsity at the tap level.

When it comes to the non-uniform path speed model, taking advantage of UWA channel sparsity becomes an important problem, since more coefficients are about to be involved, which are in two aspects: channel modeling and estimation.

First, given that there are multiple arriving acoustic rays due to reflections, a question arises naturally: Is it really compulsory to take every path into consideration? Generally, when more paths are involved, a more precise channel model is obtained, and better performance is thereby achieved with less modeling error and lower error rate. For convenience, the multipath effect of a UWA channel could be limited to some degrees about which only the dominant paths need to be concerned, while the rest could be neglected due to excessive reflections or low energy.

In the second stage, sparse channel estimation based on greedy algorithms for UWA communications could also be applied, especially when a UWA channel is modeled based in the path level. These methods include the basis pursuit (BP) and orthogonal matching pursuit (OMP) algorithms. When the UWA channel is modeled based on the non-uniform path speed model where each path is determined by amplitude variation, time delay, and Doppler spread, we could search for those optimal values within a predefined dictionary with the assistance of those greedy algorithms. The intention of those greedy algorithms is to iteratively search for the optimal estimation, while BP and OMP are two applications.

A certain sparse channel estimation is shown in [11] in which the sparsity property of UWA channels is investigated by analyzing channel scattering function, and several greedy-algorithm-based channel estimation methods are also performed. This combined non-uniform path speed model and sparse UWA channel estimation approach is also investigated in [10], where the estimations of time delay and Doppler spread are divided into two stages.

Summary and Prospects

For the past three decades, researchers have been concentrating on achieving a more precise model for Doppler spread, and performing problem-solving for Doppler estimation and compensation with higher accuracy. In this article, Doppler spread modeling and solution is categorized in five stages: the quasi-static model developed around mid-1980s, the uniform Doppler shift model of the 1990s, BEM and the uniform path speed model from the late 1990s, and the non-uniform path speed model developed recently. Throughout the development, we observe that efforts have been made in order to get a more precise model with fewer approximations to reflect the reality of UWA channels. In a chronological manner, the five models discussed in this article provide higher and higher accuracy to reflect the reality of UWA channels step by step, by carefully considering the hardware voltage responses, the computational complexity, and the necessary coefficients that must be involved. Fortunately, some remarkable milestones have been accomplished in this process, and these great contributions improve the reliability of UWA communications dramatically.

Based on the continuous investigation of UWA channel modeling, it is worthwhile for the next stage to look into the physical process that each path experiences (e.g., sediment property for bound reflect, surface wave analysis for surface reflect). This investigation could in turn enable a more precise model and problem solving for Doppler spread in UWA communications.

Based on the continuous investigation of UWA channel modeling, it is worthwhile for the next stage to look into the physical process that each path experiences. This investigation could in return enable a more precise model and problem-solving for Doppler spread in UWA communications.

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