Impact of Doppler effect on pilot augmentation techniques for channel estimation in UWA-OFDM systems

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Received 6 Aug. 2025; Revised 23 Sep. 2025; Accepted 10 Oct. 2025; Published 30 Oct. 2025.

DOI: https://doi.org/10.54939/1859-1043.j.mst.IITE.2025.99-106

ABSTRACT

This paper investigates the impact of the Doppler effect on pilot insertion techniques for channel estimation in Underwater Acoustic Orthogonal Frequency Division Multiplexing (UWA-OFDM) systems. Accurate channel estimation is critical for reliable data transmission in underwater acoustic communications, where the propagation environment is highly dynamic and susceptible to Doppler-induced distortions. To address this challenge, several pilot augmentation strategies are evaluated with the objective of enhancing the robustness and accuracy of channel estimation. The study provides a comparative analysis of these techniques under varying Doppler conditions, highlighting their effectiveness in compensating for frequency and time shifts caused by relative motion in the underwater environment. The results demonstrate the selection of appropriate pilot structures to mitigate Doppler effects and improve overall system performance.

Keywords: OFDM; Underwater acoustic; Channel estimation; Doppler effect.

1. INTRODUCTION

Communication in underwater acoustic environments encounters substantial difficulties due to distinctive channel characteristics, including fading, multipath effects, and absorption and reflection properties [1, 2]. The complexity of the underwater environment presents considerable demands and significant challenges to achieving efficient data transmission.

Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier modulation technique that offers high data rates and spectral efficiency, making it well-suited for underwater acoustic communication systems [3-5]. Its subcarriers are orthogonally synchronized, allowing channels to overlap without causing inter-carrier interference (ICI), thereby achieving high resistance to inter-symbol interference (ISI) and mitigating multipath effects [6, 7].

Channel estimation is a critical component that directly impacts the performance of underwater acoustic OFDM (UWA-OFDM) systems [8]. The transmitted signal is distorted due to the complex characteristics of the UWA channel, making it necessary to estimate the channel impulse response (CIR) to accurately recover the received signal. Pilot data known at the transmitter are typically sent along with the data symbol and are also known at the receiver for channel estimation purposes. Traditional channel estimation techniques are employed to evaluate the CIR in UWA-OFDM systems, such as the Least Squares (LS) algorithm and the Minimum Mean Square Error (MMSE) algorithm [9, 10].

Several research groups have proposed data-pilot aided (DPA) techniques with the aim of utilizing mapped data symbols as pilots for channel estimation. In [11], the authors introduced the Spectral Temporal Averaging (STA) method, which performs averaging of the estimated channels across both time and frequency domains to enhance system performance. The authors in [12] proposed the Constructed Data Pilot (CDP) approach to evaluate the reliability of channel estimates. The CDP method compares the correlation characteristics of the channels in two adjacent symbols and selects the appropriate channel updates. In [13], the research developed the

Time-domain Reliability-verified Frequency-domain Interpolation (TRFI) technique, with the core idea of verifying reliability by aligning previously received symbols with current OFDM symbols and interpolating the channel estimates when data subcarriers are detected to be erroneous.

The DPA techniques assumed the presence of cross-correlation between two adjacent data symbols and relied on the existence of two preamble symbols, as in the IEEE 802.11p structure. However, in UWA-OFDM systems, such assumptions are not valid due to the absence of these elements, making DPA techniques inapplicable for channel estimation. To mitigate the effects of underwater noise and address the aforementioned limitations, Pilot Enrichment (PE) was introduced in [14]. The PE technique enhances the pilot by extracting data symbols whose mapped constellation points lie within a predefined threshold T from the nearest ideal constellation point. The PE model typically outperforms MMSE in UWA-OFDM systems. However, pilot extraction in PE relies on a fixed threshold T, which may limit the selection of "good" data symbols as potential auxiliary pilots. The distance between received symbols and their respective constellation points can be influenced by environmental noise, modulation scheme, and other factors. Moreover, the PE technique employs a Least Squares (LS) estimator after pilot enrichment, which is generally less effective than MMSE.

To overcome these issues, the Suitable Pilot Search (SPS) method [15] was proposed, introducing a flexible threshold T_s and utilizing MMSE estimation after pilot enrichment. Simulations showed that SPS often achieves better performance than MMSE and PE. However, in some cases, pilots located far from their correct constellation points may be mistakenly classified into adjacent constellations, degrading the channel estimation quality. Future research could improve SPS-based estimation by identifying more reliable data symbols as pilots through multiple iterations and by automatically adapting the threshold.

To address the limitations of PE and SPS in UWA-OFDM systems, the Reliable Pilot Search (RPS) method [16] was proposed. The pilot extraction process is divided into multiple iterations, where previously extracted pilots assist the current extraction process. This iterative approach is guided by an adaptive threshold T_a, which selects received signals as reliable pilots if their distances to the nearest constellation points fall below T_a.

These pilot search techniques remain sensitive to environmental factors, particularly Doppler effects. This paper investigates the impact of Doppler on pilot-aided channel estimation methods in UWA-OFDM systems. Simulations are conducted to evaluate the performance of RPS in comparison to SPS, PE, and MMSE under varying Doppler conditions and modulation schemes, including 8PSK and 16QAM.

2. SYSTEM OVERVIEW AND PILOT AUGMENTATION TECHNIQUES FOR CHANNEL ESTIMATION

2.1. System overview

The block diagram in figure 1 illustrates the structure of the UWA-OFDM system. The system consists of a typical baseband OFDM transceiver with pilot-aided channel estimation to mitigate the challenges imposed by UWA channels.

At the transmitter, input binary data are passed through a modulator (Mod.), where modulation schemes such as 8PSK or 16QAM are applied depending on system requirements. The modulated symbols are then converted from serial to parallel form (S/P). Pilots are inserted at predefined subcarrier positions for subsequent channel estimation at the receiver. The symbols are transformed into time-domain signals via the Inverse Fast Fourier Transform (IFFT). The cyclic prefix (CP) is appended to each OFDM symbol to counteract ISI caused by multipath propagation. The signal is then converted back to serial format (P/S) and transmitted through the UWA channel, with additive white Gaussian noise (AWGN).

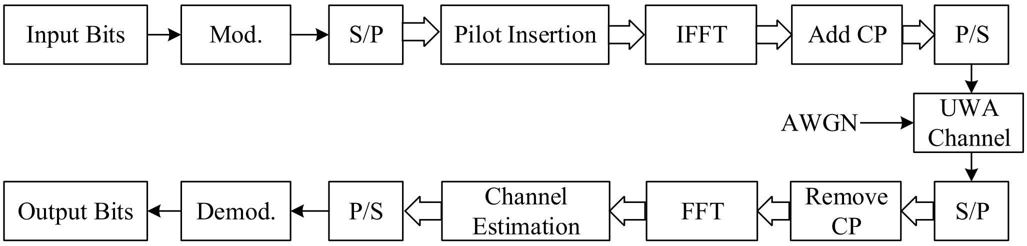

Figure 1. *UWA-OFDM system flow diagram.*

At the receiver, the signal is converted to parallel format (S/P), and the cyclic prefix is removed. The signal is transformed back to the frequency domain via the Fast Fourier Transform (FFT). Channel characteristics are estimated using the received pilot symbols through a channel estimator. The estimated symbols are then converted back to serial format (P/S) and passed through a demodulator to recover the original data bits.

This structure is well-suited to UWA environments, where multipath propagation and Doppler effects significantly degrade signal integrity. Pilot-based channel estimation and the use of a cyclic prefix help improve robustness and bit error performance in such challenging conditions.

2.2. Pilot augmentation techniques for channel estimation

In underwater acoustic orthogonal frequency division multiplexing (UWA-OFDM) systems, reliable channel estimation is crucial due to the presence of severe multipath propagation, time variation, and Doppler effects. Conventional pilot-aided channel estimation methods are often limited by sparse pilot allocation, which may lead to inaccurate channel estimates under fast time-varying or Doppler-distorted conditions. To overcome this limitation, several pilot augmentation techniques have been proposed to extract additional pilot information from the data symbols themselves, thereby enhancing estimation accuracy without increasing pilot overhead.

One of the approaches is the PE technique [14], which identifies potential pilot symbols by selecting data subcarriers whose received values fall within a predefined threshold distance T from the nearest ideal constellation point, described in Algorithm 1. These selected symbols are then treated as additional pilots. Although PE improves estimation performance compared to traditional methods, its effectiveness is sensitive to the choice of the threshold T, which may be affected by noise, modulation scheme, and Doppler-induced frequency shifts.

Algorithm 1: Potential pilot extraction

```
1. **Input:** Received symbols on subcarriers $X_l^*(k)$, and modulation scheme ('PSK'/'QAM').
2. Compute Euclidean distance $d_k$ from each received symbol $X_l^*(k)$ to all constellation points.
3. Select the nearest point and record the minimum distance $d_k$.
4. Threshold $T$: If modulation == 'PSK', then set $T = 0.1$ end.
                  If modulation == 'QAM', then set $T = 0.4$ end.
5. If $d_k < T$, then select $X_l^*(k)$ as a potential pilot.
6. **Output:** Set of additional pilots (original pilots and potential pilots).
```

To address the limitations of fixed-threshold pilot selection, the SPS method [15] introduces a flexible threshold mechanism and incorporates an MMSE estimator after pilot enrichment. To determine whether a received signal can be considered suitable, a flexible threshold T_s is defined. This threshold is modulation-dependent and influenced by environmental noise. The value of T_s is proportional to the average distance between the received symbol and its nearest constellation point. It is computed based on the minimum and maximum Euclidean distances D_l between the received symbols and their corresponding constellation points. Algorithm 2 demonstrates the selection of suitable signals as pilots. This method demonstrates better resilience under moderate Doppler conditions; however, it may still misclassify signals of other constellation points as pilots, thereby degrading estimation accuracy.

Algorithm 2: Search for suitable pilot

```
1. Input: Received symbols on subcarriers $X_l^*(k)$, distance vector $D_l$, and modulation-specific scaling factor $\gamma$.
2. Compute Euclidean distance $d_k$ from each received symbol $X_l^*(k)$ to all constellation points.
3. Select the nearest point and record the minimum distance $d_k$.
4. Threshold $T_s$: $T_s = \frac{\gamma}{2}.(minD_l + maxD_l)$ .
5. If $d_k < T_s$, then select $X_l^*(k)$ as a suitable pilot.
6. Output: Set of supplementary pilots (original pilot and suitable pilots).
```

The RPS method [16] applies a multi-iteration strategy in which pilot extraction is refined over several iterations. In each iteration, newly extracted pilots with extracted pilots of the previous iteration are used to estimate the channel. An adaptive threshold algorithm is proposed to extract reliable pilot symbols based on the distance vector D_l^i , which contains the distances of received symbols to their nearest constellation points, as presented in algorithm 3. The steps are as follows:

Algorithm 3: Adaptive threshold for reliable pilot extraction T_a^i

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1. Input: Distance vector $D_l^i$, modulation scheme ('PSK'/'QAM'), and tuning parameter $\beta$.
2. Initialize a constraint factor $d_{con} = 1.0$.
3. If modulation == 'PSK', then set $d_{con} = 0.5$ end.
4. Determine $d_{\max} = \max(D_l^i)$.
5. If $d_{max} > d_{con}$, then set $d_{max} = d_{con}$ end.
6. Output: Adaptive threshold $T_a^i = min(D_l^i) + (d_{max} - min(D_l^i)/ \beta$ .
```

In this algorithm, the adaptive threshold is calculated from the range of distance values, taking into account the modulation scheme and a tuning factor β. The constellation grid radius is d_{con}=0.5 for PSK modulation, while for QAM it is d_{con}=1.0; the value dcon is capped by constraint in step 5 to prevent unreliable pilots from being selected. As a result, only symbols located close to their ideal constellation points are searched as reliable pilots. Algorithm 3 ensures that the pilot selection process is adaptive and robust to varying channel conditions and modulation types. By capping the maximum distance and incorporating a factor β, the method helps the classification of reliable symbols as pilots. RPS has shown superior performance in highly dynamic underwater environments.

These pilot augmentation methods effectively enhance channel estimation performance, addressing more complex challenges such as Doppler-induced distortions in UWA-OFDM systems. As UWA channels are highly time-varying, especially under mobility or surface dynamics, the impact of Doppler shift becomes a critical factor that must be carefully considered in signal processing.

3. IMPACT OF DOPPLER EFFECT ON UNDERWATER ACOUSTIC CHANNEL

In UWA communication, the propagation environment is strongly affected by multipath and time-varying characteristics. One widely used approach to model such propagation is the Bellhop ray model, which represents the channel as a summation of discrete propagation paths, each with specific delay, attenuation, and Doppler properties.

The frequency response of the UWA channel based on the Bellhop model [17] is expressed as:

$$H(f) = H_0(f)\sum_p h_p \gamma_p(f) e^{-j2\pi f \tau_p} \tag{1}$$

where $H_0(f)$ is the reference transmission function, h_p is the gain of the p-th propagation path, τ_p is the delay, and $\gamma_p(f)$ represents the scattering coefficient for that path. The scattering coefficient is further defined as:

$$\gamma_p(f) = \frac{1}{h_p}\sum_{i\geq 0} h_{p,i} e^{-j2\pi f \delta\tau_{p,i}} \tag{2}$$

where $h_{p,i}$ and $\tau_{p,i}$ are the gain and delay associated with the i-th scattering component of path p, modeled as random variables due to the stochastic nature of scattering in underwater environments.

When motion is introduced, either by the transmitter, receiver, or the medium itself, the Doppler effect becomes significant. It manifests as a frequency shift characterized by the Doppler coefficient a_p, which can stem from drift (a_{dp}), vehicle motion (a_{vp}), or surface wave motion (a_{sp}).

The scattering coefficient under Doppler influence becomes:

$$\tilde{\gamma}_p(f,t) = \gamma_p(f,t) e^{j2\pi a_p f t} \tag{3}$$

As a result, the time-varying channel frequency response is expressed as:

$$H(f,t) = H_0(f)\sum_p h_p \tilde{\gamma}_p(f,t) e^{-j2\pi f \tau_p} \tag{4}$$

The Doppler effect is quantitatively evaluated through the Doppler spread B_{dp}, which reflects the spectral broadening of the received signal. A wider B_{dp} leads to higher time-frequency distortion, resulting in ICI in OFDM systems.

4. RESULTS AND ANALYSIS

To evaluate the effectiveness of pilot augmentation techniques for channel estimation, the simulation is conducted and benchmarked with MMSE, PE, SPS, and RPS approaches.

4.1. Setting experiment

The UWA channel used in the simulation is based on the Bellhop model [18]. The simulation also accounts for transmitter and receiver range and environmental factors, incorporating key underwater acoustic propagation characteristics such as multipath, surface and bottom reflections, and Doppler effects. Details of the UWA-OFDM system parameters used in the simulation are summarized in table 1.

Table 1. *The UWA-OFDM system parameters.*

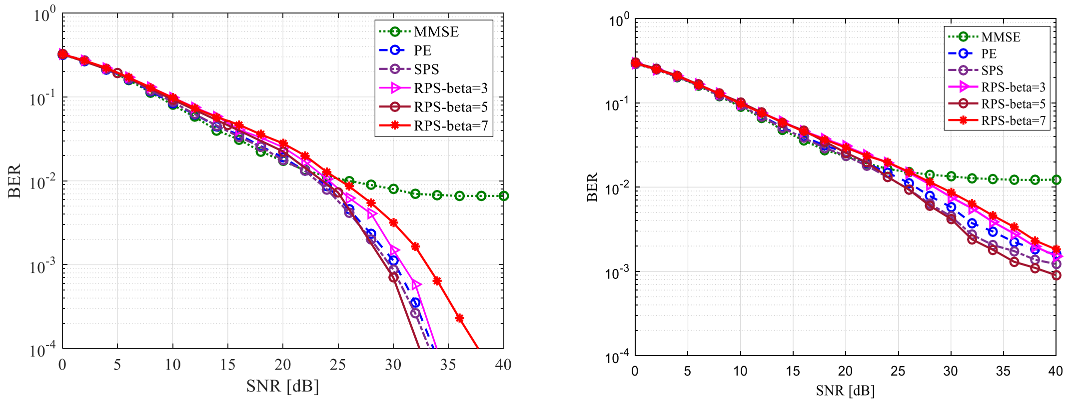
Parameters	Value
FFT length	256
Subcarrier Number	256
Cyclic prefix duration	64
Pilot spacing	8
Type of Modulation	8PSK, 16QAM
Channel	Bellhop

4.2. Simulator and analysis

Simulations are presented to evaluate the BER performance of the channel estimation methods, such as MMSE, PE, SPS, and RPS techniques. The assessment is conducted using a multipath channel model $N_{cir} = 32$, a pilot spacing of $ps = 8$, exploration of the scaling parameter β, and and various modulation schemes. The impact of Doppler effects on system performance is investigated.

**Investigating the tuning parameter β of the adaptive threshold T_a^i for the RPS method*

The values of the parameter β of the adaptive threshold T_a^i in the RPS method are evaluated on the UWA-OFDM system in Figure 2, considering modulation schemes of 8PSK and 16QAM, with a pilot spacing of $ps = 8$, a channel impulse response length of $N_{cir} = 32$, and a Doppler spread of $B_{\delta p} = 0.0005$ Hz. The results indicate that when β is small ($\beta = 3$), the adaptive threshold T_a^i becomes large, resulting in an excessive number of supplementary pilots. Consequently, some pilots may be incorrectly mapped to constellation points, leading to poor channel estimation quality and degraded BER performance. When β increases to 5, the adaptive threshold T_a^i decreases moderately, allowing for the extraction of a sufficient number of reliable pilots. This improves channel estimation quality and yields better BER performance compared with MMSE, PE, and SPS methods. However, when β is further increased ($\beta = 7$), the adaptive threshold becomes too small, reducing the number of supplementary pilots and thereby lowering BER performance. Overall, the scaling parameter is achieved at $\beta = 5$, which provides the best balance between pilot reliability and quantity.



a. 8PSK *b. 16QAM*

Figure 2. *BER of the UWA-OFDM system with 8PSK, 16QAM; $B_{\delta p}$=0.0005 Hz; β = 3; 5; 7.*

**Investigating the impact of the Doppler effect on system performance under different modulation schemes*

This analysis examines how Doppler-induced distortions influence the BER performance of UWA-OFDM systems. Comparative evaluations are conducted across various modulators under dynamic channel conditions.

Figure 3 reports BER–SNR performance for UWA-OFDM with 8PSK under Doppler spreads $B_{\delta p} = 0.0005, 0.005, 0.05, 0.5$ Hz. In low Doppler, all receivers improve with SNR; the ordering is stable RPS achieves the lowest BER, followed by SPS, PE, and MMSE. As the Doppler spread increases, all receivers deteriorate and the performance gaps widen. RPS maintains the steepest BER slope, achieving about 10^{-3} BER at high SNR, whereas PE and MMSE exhibit pronounced error floors, underscoring the advantage of Doppler-aware processing for phase-modulated signals.

Figure 4 presents the same study for 16QAM. Curves shift upward relative to 8PSK, indicating the higher SNR required by the denser constellation. With RPS, saturation typically occurs between 10^{-2} and 10^{-1} at high SNR. At a representative BER (e.g., 10^{-2}), 16QAM demands roughly 3–5 dB more SNR than 8PSK in mild Doppler, with a larger penalty as $B_{\delta p}$ grows.

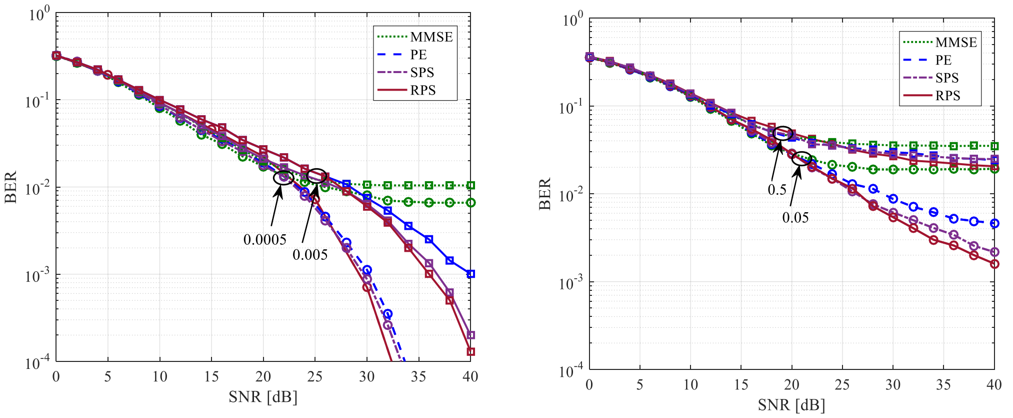


Figure 3. *BER of the UWA-OFDM system with 8PSK,*
$B_{\delta p}$ = 0.0005 Hz; 0.005 Hz; 0.05 Hz; 0.5 Hz.

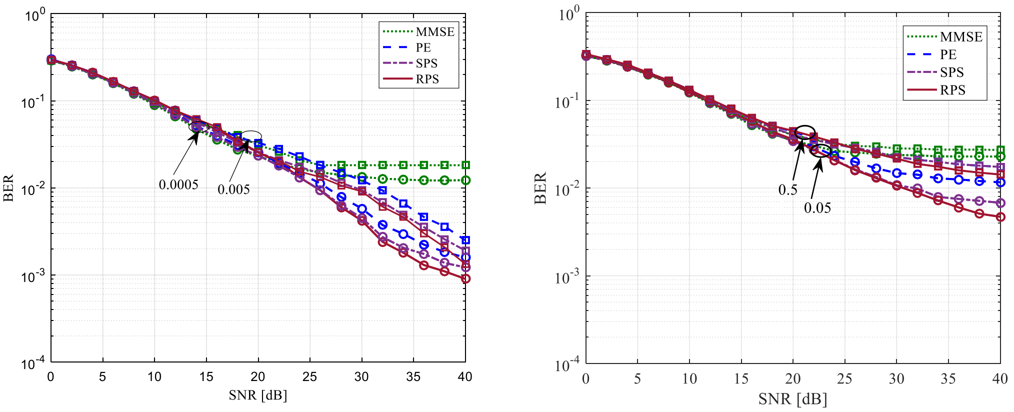


Figure 4. *BER of the UWA-OFDM system with 16QAM,*
$B_{\delta p}$= 0.0005 Hz; 0.005 Hz; 0.05 Hz; 0.5 Hz.

The analysis confirms that Doppler spread is a critical factor in UWA-OFDM performance. While the conventional estimation method (MMSE) degrades significantly, augmented pilot approaches (PE, SPS, RPS) provide substantial robustness. Among them, RPS delivers the best trade-off between pilot reliability and estimation accuracy, making it highly suitable for Doppler-impaired underwater acoustic channels.

5. CONCLUSIONS

This work has conducted an investigation into the influence of Doppler effects on pilot insertion techniques for channel estimation in UWA-OFDM systems. Given the time-varying and highly dispersive nature of UWA channels, particularly under relative motion, achieving accurate channel estimation remains a critical challenge. The evaluated pilot augmentation methods demonstrate enhanced robustness against Doppler-induced impairments, contributing to improved estimation precision and system reliability. The comparative results emphasize the significance of appropriately designing pilot structures in accordance with the channel fluctuations. Future research may focus on implementing advanced Doppler compensation techniques to enhance the efficiency and reliability of UWA-OFDM systems.

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TÓM TẮT

Ảnh hưởng của hiệu ứng Doppler đến các phương pháp bổ sung pilot cho bộ ước lượng kênh của hệ thống UWA-OFDM

Bài báo nghiên cứu ảnh hưởng của hiệu ứng Doppler đối với các phương pháp bổ sung pilot trong hệ thống UWA-OFDM. Các phương pháp bổ sung pilot được đề xuất nhằm cải thiện ước lượng kênh trong môi trường truyền sóng âm dưới nước. Hiệu ứng Doppler là một yếu tố quan trọng trong việc ảnh hưởng đến sự biến đổi của tần số và thời gian trên kênh truyền sóng âm. Bài báo phân tích và so sánh các kỹ thuật bổ sung pilot để tăng cường độ chính xác của ước lượng kênh trong các điều kiện ảnh hưởng của hiệu ứng Doppler. Các kết quả chứng minh việc lựa chọn các phương pháp bổ sung pilot phù hợp để giảm thiểu hiệu ứng Doppler và cải thiện hiệu suất tổng thể của hệ thống.

Từ khoá: OFDM; Thông tin dưới nước; Ước lượng kênh; Hiệu ứng Doppler.