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2aUW9. An overview of underwater acoustic communication via particle velocity channels: Channel modeling and transceiver design

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Over the past few decades, the scalar component of the acoustic field, i.e., the pressure channel, has been extensively used for underwater acoustic communication. In recent years, vector components of the acoustic field, such as the three components of acoustic particle velocity, are suggested for underwater communication. Consequently, one can use vector sensors for underwater communication. The small size of vector sensor arrays is an advantage, compared to pressure sensor arrays commonly used in underwater acoustic communication. This is because velocity channels can be measured at a single point in space. So, each vector sensor serves as a multichannel device. This is particularly useful for compact underwater platforms, such as autonomous underwater vehicles (AUVs). Funded by the National Science Foundation, our research efforts focus on the research problems in two closely-related categories: channel modeling and transceiver design. Channel modeling research aims at characterization of those aspects of acoustic particle velocity channels such as delay and Doppler spread, transmission loss, etc., which determine the communication system performance. Transceiver design addresses optimal use of vector sensors and particle velocity for data modulation and demodulation, equalization, synchronization, coding, etc. (work supported by NSF).

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I. Introduction

Over 75% of the earth surface is covered with water, with lots of resources that human's life depends on. There are numerous naval and civilian applications that pose an increasing demand on high speed underwater wireless telemetry and data communication among sensors, autonomous underwater vehicles (AUVs), deepwater moored instruments, and surface ships. Examples include communication among AUVs for collaborative operations, harbor security and surveillance systems, oceanographic data retrieval from underwater sensors over geographically large areas, offshore oil and gas explorations, environmental monitoring, …

Since water strongly attenuates electromagnetic waves, acoustic waves are the appropriate carriers of information in underwater channels. For decades, underwater acoustic communication systems have been relying on scalar acoustic sensors, which measure only the pressure of the acoustic field. The idea in this paper is to take advantage of the vector components of the field, such as the three components of particle velocity, sensed by a vector sensor, for data communication. Application of vector sensors for information exchange over these degrees of freedom of the acoustic field has the potential to provide new opportunities for underwater acoustic communication and telemetry.

II. A Short Summary of Underwater Communication Techniques in Acoustic Pressure Channels

In general, underwater acoustic channels are seriously bandwidth-constrained and the bandwidth is range-dependent [1]. For distances from 10 km up to 100 km (long range), the available bandwidth is about few kHz, whereas in a 1-10 km medium range setup, the bandwidth is almost few 10 kHz. Only for very short ranges, say, smaller than 100 m, the bandwidth may exceed 100 kHz [2]. The harsh multipath, with delay spreads up to several hundreds of symbols for high data rates, and channel temporal variations due to the water surface fluctuations, internal waves, and turbulence, with Doppler spreads up to several 10 Hz, further complicates underwater communication. After the first generation of underwater (analog) modems, second generation (digital) modems in 80's used noncoherent techniques such as frequency shift keying (FSK) and differentially coherent schemes like differential phase shift keying (DPSK), which remained to be the mainstream for a decade [3]. Due to the need for higher spectral efficiencies over typical channels of interest, coherent systems with phase shift keying (PSK) and quadrature amplitude modulation (QAM) were considered as well, mostly in 90's. Comprehensive reviews of the past and present underwater communication and telemetry systems can be found in [2]-[4]. Spatial diversity (large arrays of hydrophones) and different types of equalization, beamforming, coding, channel estimation and tracking are also used for communication in pressure channels [3]. Underwater multiple-input multiple-output (MIMO) systems using spatially separated pressure sensors are also recently investigated [5]-[16].

Among the four types of underwater signals (control, telemetry, speech, video) [2], low data rates might be enough for control signals. However, for real-time transmission of telemetry, speech, and video signals over medium and long ranges, one needs high data rates and spectral efficiencies, specially for video signals.

III. A Brief Overview of Vector Sensors

Acoustic vector sensors can measure non-scalar components of the acoustic field such as the particle velocity, which cannot be sensed by a single scalar pressure sensor. Development of vector sensors may date back to 30's [17]. Over the past few decades, a large volume of research has been conducted on design and performance analysis of vector sensors [18]. They have been mainly used for target localization and SONAR applications. Examples include accurate beamforming and azimuth/elevation estimation of a source, avoiding the left-right ambiguity of linear towed arrays of scalar sensors, significant acoustic noise reduction due to the highly directive beam pattern, etc. [19]-[22].

There are two major types of vector sensors: pressure-gradient and inertial [18]. Pressure-gradient sensors use a finite-difference approximation to estimate the gradient of the acoustic field such as particle velocity. Inertial sensors truly measure the particle velocity by responding to the acoustic particle motion. Each sensor type has its own advantages and disadvantages. A brief summary of merits and limitations of these sensors can be found in [23]. More details and information on other types of sensors such as multimode vector sensors can be found in [18].

IV. Data Communication in Underwater Acoustic Particle Velocity Channels

A vector sensor measures the three orthogonal components of acoustic particle velocity, as well as the acoustic pressure, all at a single point in space. From this angle, one can think of a vector sensor as a compact multichannel device that can used for acoustic communication. This is particularly important for platforms such as small AUVs where large size array cannot be used. For example, the medium frequency 3 kHz receive array of a modem recently designed for the 21-inch diameter Bluefin AUV consists of four hydrophones and is 1.5 m long. Quoted from [24] " … Ideally a longer array would be used, but this is the largest that can be easily installed in the vehicle …" Even at high frequencies, the size of the array is an issue, if it is supposed to fit into the smaller 12.75-inch AUVs [24].

Research on data communication in particle velocity channels can be categorized into two closely related areas: channel modeling and transceiver design. Channel modeling research aims at understanding and characterization of particle velocity orthogonal components as communication channels. On the other hand, transceiver design research intends to determine how vector sensors, along with proper communication techniques and signal processing algorithms, can be used for successful transmission and reception of information via particle velocity channels. Possible differences between velocity channels and the acoustic pressure channel that are identified at the channel modeling stage can impose different constraints on system design. This raises the need to develop new communication and signal processing solutions, as well as perhaps new sensor types and technologies, for proper transceiver design.

V. Transceiver Design for Particle Velocity Communication Channels

The lessons learned from transceiver design in the acoustic pressure channel serve as useful guidelines for system design in particle velocity channels. However, due to the possible differences between velocity and pressure channels, a proper design should be able to utilize the special features of velocity channels. For example, some possible correlations among the velocity and pressure channels, or perhaps different delay spreads need to be included in the system design, the rate of change of velocity channels might be different and should be considered for system performance optimization, etc.

The schematic of a basic vector sensor communication system is shown in Fig. 1. There is one scalar pressure sensor at the transmit side which transmits the signal $s(t)$. The receiver is a vector sensor that measures the x, y and z components of particle velocity, in addition to the acoustic pressure. The measured signals are $r_x(t)$, $r_y(t)$, $r_z(t)$ and $r(t)$, respectively. The vector sensor is symbolically shown by three orthogonal dipoles and the single black dot at the center is the scalar pressure sensor. There are four possibly time-varying channels in the system, whose impulse responses are $v_x(\tau,t)$, $v_y(\tau,t)$, $v_z(\tau,t)$ and $p(\tau,t)$, as shown in Fig. 1. The first three represent x, y and z particle velocity channels, whereas $p(\tau,t)$ stands for the pressure channel.

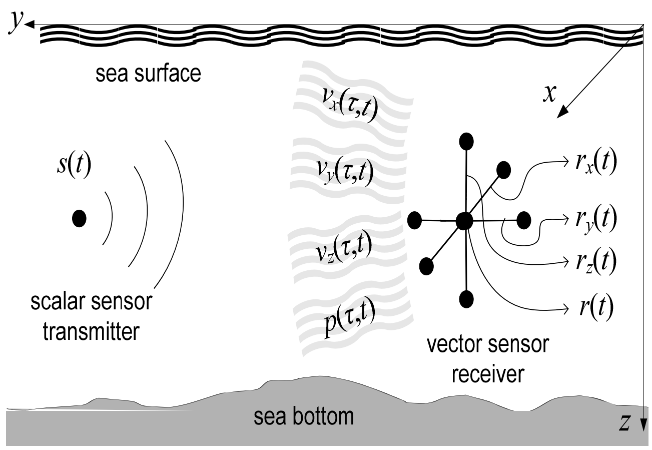

Fig. 1. A basic communication system in particle velocity and pressure channels. The transmitter is a single scalar pressure sensor whereas the receiver is a four-channel vector sensor.

The received signals can be written as

$$\begin{aligned} r_x(t) &= s(t) \oplus v_x(\tau,t) + n_x(t), \\ r_y(t) &= s(t) \oplus v_y(\tau,t) + n_y(t), \\ r_z(t) &= s(t) \oplus v_z(\tau,t) + n_z(t), \\ r(t) &= s(t) \oplus p(\tau,t) + n(t), \end{aligned} \tag{1}$$

where $\oplus$ is the convolution and $n_x(t)$, $n_y(t)$, $n_z(t)$ and $n(t)$ are noise components. These noise terms may include ambient noise, flow noise, structure-borne noise, etc. To recover the transmitted data $s(t)$ convolved with the frequency-selective channels $v_x(\tau,t)$, $v_y(\tau,t)$, $v_z(\tau,t)$ and $p(\tau,t)$, a multichannel equalizer is needed.

A. *Multichannel Equalization Using a Vector Sensor Receiver*

A multichannel equalizer is proposed in [23] and [25] to demonstrate the feasibility of inter-symbol interference (ISI) removal using vector sensors. The vector sensor receiver shows a competitive performance, compared to an equivalent array of scalar pressure sensors, as well as a single pressure sensor receiver. The impact of unbalanced noise powers in a vector sensor receiver is studied in [25]. Since perfect knowledge of the channels at the receiver is not available, the influence of channel estimation errors on the performance of a vector sensor receiver is investigated in [23]. Feasibility of multichannel equalization using a vector sensor is demonstrated in [26] using measured data.

B. *Signal Transmission and Reception Using Vector Sensors*

Since a vector sensor has a compact size, platforms such as small AUVs can significantly benefit from signal transmission using a vector sensor, in addition to signal reception. A system is proposed in [27] where both transmitter and receiver are vector sensors. In addition to particle velocity channels, particle acceleration type channels are also used in this system.

C. *Multiuser Communication Using a Vector Sensor*

Since it is demonstrated in [23] and [25] that a vector sensor can serve as a multichannel communication receiver for ISI cancellation in a single user system, it can be used in a multiuser system as well. Using space-time block codes, a multiuser system is developed in [28], where a compact vector sensor receiver is used for separating multiple users and also mitigating ISI for each user. Another advantage of the system in [28] is that to accommodate multiple users, it does not increase the bandwidth of users via spread spectrum and code division multiple access techniques. This is particularly important in highly bandlimited underwater channels.

VI. Particle Velocity Communication Channel Modeling

Underwater communication channels, especially in shallow waters, are stochastic multipath environments, due to the random roughness of sea bottom and its surface, multiple interactions of the signal with surface and the bottom, and also because of the presence of turbulence, internal waves, etc.

Modeling stochastic particle velocity channels as random linear time-varying filters is a system-theoretic methodology which provides those channel characteristics that directly affect system design and performance. Examples include space-time-frequency correlation functions in particle velocity channels, coherence time and frequency of such channels, level crossing rates and average fade durations, etc. All these are vital for the designer when choosing, say, sufficient element spacing in an array, proper number of taps for an equalizer, the updating rate of the equalizer taps, appropriate coding schemes which can handle deep fades of certain lengths, the maximum packet length over which the channel stays almost constant, …

In [29], [30] and [31], a ray-based stochastic framework for modeling particle velocity channels is developed, which includes those channel characteristics that directly affect the communication system performance. The parametric nature of the developed models makes them adaptable to a variety of underwater channels. In this approach, the channel is characterized using simple probabilistic models for the random components of the propagation environment. In this way, the statistical behavior of the channel can be imitated, and compact expressions for correlations and other related channel characteristics such as delay and Doppler spreads can be derived.

A. Particle Velocity Channel Correlations in Space, Frequency and Time

In general, correlations in a multiple-input multiple-output (MIMO) channel affect the system performance and channel capacity [32]-[35].

Consider the Fourier transforms of the particle velocity and pressure channels shown in Fig. 1, called $V_x(f,t)$, $V_y(f,t)$, $V_z(f,t)$, and $P(f,t)$, respectively. Spatial and frequency correlations between these channel functions are calculated in [29] for a single vector sensor, as well as a vertical array of vector sensors in shallow waters. Extension to an oblique array is addressed in [30]. Temporal channel correlations for a mobile receiver are derived in [30] and [36]. These particle velocity channel correlations are needed for proper communication system design, to achieve the required performance in the presence of some possible correlations.

B. Delay and Doppler Spreads in Particle Velocity Channels

In wireless multipath channels, the receiver receives the signal through multiple paths. Each path has a different delay (travel time), because of its different path length. Motion of the transmitter or receiver in a multipath channel also introduces different Doppler shifts. Delay spread and Doppler spread are two key channel parameters for system design in frequency-selective and time-varying wireless channels [37].

Using the particle velocity channel correlation functions developed in [29], analytical expressions for delay and Doppler spreads of particle velocity channels shown in Fig. 1 are derived [31]. Knowledge of delay and Doppler spreads in acoustic particle velocity channel is important for efficient design of underwater vector sensor communication system.

C. Simulation-Based Study of Particle Velocity Channels

Using the Bellhop simulator [38], impulse responses and frequency responses of particle velocity channels are simulated in [23] for different ranges and sediments. Some channel characteristics such as delay spreads, distribution of power among the particle velocity channels, channel condition numbers and channel eigenvalues are studied in [23] via simulation, whereas channel correlations are briefly investigated in [28].

VII. Conclusion

A vector sensor can be considered as a multichannel device that can be used for data communication in acoustic particle velocity channels. Research in this area entails the integration of the unique physics of underwater acoustic propagation, i.e., the acoustic particle velocity, into signaling techniques and data communication methods. An overview of communication in particle velocity channels is provided in this paper, and some topics in channel modeling and transceiver design are discussed.

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