IEEE ACCESS SPECIAL SECTION EDITORIAL: Underwater Wireless Communications and Networking

Underwater wireless communications (UWC) has been playing an important role in marine activities for the second half of the 20th century. From military purposes in its early stages to today's industrial and non-profit applications such as environmental monitoring, oceanographic data collection, disaster monitoring, and underwater resource exploration, there has been a growing interest in the realization of underwater wireless networks. However, practical applications often require significant data bandwidth. Such requirements are not always met by the design of current UWC systems, which are challenged by the unique and harsh conditions of underwater communication channels, including for example severe attenuation, multipath dispersion, and limited capability to exploit channel resources. Recently, many academic and industrial researchers have worked on the improvement of UWC systems by augmenting them with state-of-the-art information and communication technologies. There have been reports of new results and insight on the fundamental theories and practical implementations of UWC systems, i.e., UWC channel models and estimation, digital signal processing, advanced transceiver design, multiple access (MAC), and routing and upper-layer protocols, as well as successful cross-layer design implementations.

The objective of this IEEE *Access* Special Section on "Underwater Wireless Communications and Networking" is to offer a convenient and timely snapshot of the most recent advancement in UWC systems and underwater networks, so that the underwater communications and networking research community can find recent progress over state-of-the-art technologies as well as promising future research directions in the same venue. In this Special Section, we cover a broad range of techniques in this field, including but not limited to orthogonal frequency division multiplexing (OFDM), game theory, machine learning, localization, and software-defined transceiver design. Moreover, plenty of experimental results and field tests in our Special Section prove the feasibility of the proposed approaches, and catalyze the practical implementation of advanced UWC networks.

Our Call for Papers received an enthusiastic response with more than 80 high-quality submissions. Per the IEEE *Access* policy, it was ensured that the handling editors did not have any potential conflict of interest with the authors of the submitted articles. All articles were reviewed by at least two independent referees. The articles were evaluated for their rigor and quality, and also for their relevance to the theme of our Special Section. After a rigorous review process, we accepted 25 articles to form the Special Section.

1) First, our Special Section featured an article ''**On the Average Achievable Rate of QPSK and DQPSK OFDM Over Rapidly Fading Channels**,'' in which Aval *et al.*, argued that coherent receivers which rely on channel estimation can be outperformed by

differentially coherent receivers in rapidly time-varying wireless channels, as the latter do not require any channel estimation overhead. Here, the authors study the achievable data rates of some coherent and differentially coherent modulations in wireless underwater acoustic and radio channels, in the context of orthogonal frequency division multiplexing systems. Through analytical and numerical results, they study the trade-off between data rate and channel estimation cost in highly time-varying channels.

2) In the article "**Theoretical and Experimental Comparison of Off-Grid Sparse Bayesian Direction-of-Arrival Estimation Algorithms**," Das analyzes the theoretical bound of two off-grid sparse Bayesian learning (OGSBL) algorithms. OGSBL-based direction-of-arrival (DOA) estimates are hyperparameter-free, accurate and robust against offsets in the DOA. Two off-grid sparse estimation models are based on Taylor series expansion method (OGSBL-T) and linear interpolation method (OGSBL-I). The author derived the Cramer-Rao lower bound (CRLB) of the off-grid bias parameters for both the models for multiple snapshots. It is shown that the CRLB of the off-grid bias parameters for the OGSBL-T algorithm is significantly less than that for the OGSBL-I algorithm. Finally, the author demonstrates the application of the OGSBL-T algorithm for resolving the DOAs of multipath signals by analyzing data from the SWellEx-96 ocean acoustic experiment.
3) In the article "**Prefix-Free Frequency Domain Equalization for Underwater Acoustic Single Carrier Transmissions**," Tu, *et al*., proposed a prefix-free time-reversal (TR) frequency domain equalizer (FDE) in SIMO acoustic channel to avoid high prefix overhead and the resulting spectral efficiency loss in underwater acoustic channels, where the ratio between the multipath spread and the channel coherence time is large. The received prefix-free signals are partitioned into multiple overlapping blocks in order to perform block-by-block equalization. The proposed core receiver consists of mainly three processing blocks, TR processing, inter-block interference (IBI) cancelation, and prefix reconstruction before performing FDE. Further enhancements can be achieved by overlapping partitioning and iterative prefix reconstruction. The authors experimentally demonstrated the bit error rate performance of proposed FDE receiver through the field-test trials.
4) In the article "**A Blind Side Information Detection Method for Partial Transmitted Sequence Peak-to-Average Power Reduction Scheme in OFDM Underwater Acoustic Communication System**," Xing, *et al*., propose a blind side information detection method for the partial transmitted sequence (PTS) peak-to-average power ratio reduction (PAPR) method in underwater acoustic (UWA) orthogonal frequency division multiplexing (OFDM) communication systems. Simulation and field experiment results presented in this article demonstrate that the proposed scheme can differentiate the phase rotation

factor. Therefore, the quality of the UWA OFDM communication system is significantly enhanced.

5) In the article "**High-Frequency Acoustic Estimation of Time-Varying Underwater Sparse Channels Using Multiple Sources and Receivers Operated Simultaneously**," Kaddouri, *et al.*, propose a multiple-input multiple-output (MIMO) channel estimator by employing the orthogonal matching pursuit (OMP) algorithm to leverage the sparsity of underwater acoustic channels. This is achieved through a MIMO P-iterative OMP algorithm that iteratively searches for the closest matching projection of the received signals onto a dictionary comprised of transmitted signals. The authors showed from the selected simulation and controlled experiment that the proposed MIMO-OMP algorithm is robust to the time-varying nature and provides a significant RMSE improvement compared to a least square estimator.
6) In the article "**Soft-Decision-Driven Sparse Channel Estimation and Turbo Equalization for MIMO Underwater Acoustic Communications**," Zhang, *et al.*, develop a new soft-decision-driven sparse channel estimation and turbo equalization scheme in the triply selective MIMO UWA. The recently proposed Homotopy RLS-DCD adaptive algorithm is extended to adaptively estimate rapidly time-varying sparse MIMO channels. The proposed receiver has been tested by using the data collected from the SHLake2013 experiment. The results demonstrate that the proposed a posteriori soft-decision-driven sparse channel estimation based on the Homotopy RLS-DCD algorithm and turbo equalization offer considerable system performance improvements with respect to other turbo equalization schemes.
7) In the article "**Spatial and Time-Reversal Diversity Aided Least-Symbol-Error-Rate Turbo Receiver for Underwater Acoustic Communications**," Xu, *et al.,* propose a direct adaptation form of the bi-directional turbo equalizer (DA-BTEQ) under a least symbol error rate criterion. Turbo decision feedback equalization iteratively updates the symbol detector and channel equalizer to provide significant improvement over severe multipath propagation. Bi-directional equalization using both normal and time-reversed equalization effectively mitigates the error propagation effect. The multiple outputs of hydrophone array are equalized and combined by equal-gain combining in order to exploit spatial diversity. The authors evaluate the effectiveness of the proposed receiver structure through both computer simulation and field experiments.
8) In the article "**Robust Interference Cancellation of Chirp and CW Signals for Underwater Acoustics Applications**," Diamant looks into the problem of unwanted acoustic emissions which can act as strong sources of interference for desired signals in underwater environments. Since in-band interference can deteriorate the performance of underwater acoustic systems, it is of interest to have proper interference cancellation

algorithms in place. The author develops two interference cancellation filters and studies their performance using simulations and experimental data.

9) In the article "**Asynchronous Detection and Identification of Multiple Users by Multi-Carrier Modulated Complementary Set of Sequences**," Aparicio, *et al*., address the detection and demodulation of signals transmitted by multiple asynchronous users in underwater communication systems. The presence of multiple access interference, in addition to noise, Doppler shifts and other channel impairments, can further complicate the problem. In this article, the authors consider a direct-sequence code-division multiple access underwater system, where detection and user identification are accomplished using a combination of two sequences. The performance of the proposed method is evaluated using sea trials.

10) The continuous pursuit for higher-rate underwater communications is presented in the article "**A High-Rate Software-Defined Underwater Acoustic Modem With Real-Time Adaptation Capabilities**," by Demirors, *et al*. Here, the authors present the setup of a reconfigurable underwater acoustic transceiver that employed software-defined communications hardware, and explore the capability of a zero-padded orthogonal frequency division multiplexing (ZP-OFDM) modulation scheme to achieve high (order of 200 kbit/s) bit rates in intermediate-range shallow water communications in a lake. Adaptive modulation and coding schemes as well as chirp-based feedback are tested as part of the implementation.

11) Adaptive communications that adapt to the channel are the target of the article, "**Reinforcement Learning-Based Adaptive Transmission in Time-Varying Underwater Acoustic Channels**,**"** Wang, *et al.,* assume that the underwater channel has compound Nakagami-lognormal statistics, whose parameters vary according to a Markov process, which is observed only upon transmission. A reinforcement learning framework learns the model parameters and predicts future channel states. The performance achieved by the proposed approach is shown to be close to that enabled by perfect channel knowledge.

12) In the article "**Quality-of-Service Satisfaction Games for Noncooperative Underwater Acoustic Communications**," Pottier, *et al*., investigate decentralized resource sharing methods in multiple non-cooperative underwater acoustic communication links within the framework of game theory. The solution of generalized satisfaction equilibrium (GSE) problem is utilized to improve the reliability of point-to-point UWA communications facing interference in a non-cooperative environment. Assuming that the feedback of instantaneous channel information is irrelevant, the asynchronous satisfaction response algorithm (ASRA) based on feedback information of channel gain and interference plus noise power from the receiver is expected to yield satisfactory performance. A 1-bit

feedback blind satisfactory response algorithm (BSRA) was proposed to fit better to a limited bandwidth UWA feedback link. Two case studies using direct sequence spread spectrum (DSSS) and orthogonal frequency division multiplexing (OFDM) in shallow water UWA setup are considered.

13) In the article "**Underwater Localization Based on Grid Computation and Its Application to Transmit Beamforming in Multiuser UWA Communications**," Liao, *et al*., show that localization can act as a proxy to improve communications performance. They pre-compute the expected channel impulse response at several locations over a vertical plane using an underwater acoustic propagation model, and then drive a beamformer to cover a number of positions where the target is expected to be with higher probability. The localization system makes it possible to achieve this objective with a reduced amount of feedback information.
14) In the article "**Self-Localization of a Deforming Swarm of Underwater Vehicles Using Impulsive Sound Sources of Opportunity**," by Naughton, *et al*., the localization of a swarm of underwater drifters is enabled by uncontrolled sound sources that emit impulsive noise. The authors solve the problem of matching the reception of the sound emitted by the same source over different devices, and use this information to estimate the angle of arrival of each sound source and the geometry of the swarm. The technique compares similarly to an accurate acoustic localization solution.
15) In the article "**Low Probability of Detection for Underwater Acoustic Communication: A Review**," by Diamant, *et al*., the authors identify the main challenges for the design of low-probability-of-detection (LPD) underwater acoustic communication systems. The authors describe and classify common approaches for transmission, reception, and interception of LPD signals, and they discuss their advantages and weaknesses. They also present several methods to determine the LPD capability of a system, and suggest to adopt the range ratio test as a performance measure that captures both the effects of signal propagation through the underwater acoustic channel and the capabilities of the communication receiver and a signal interceptor.
16) In the article, "**Performance Evaluation of LOS and NLOS Vertical Inhomogeneous Links in Underwater Visible Light Communications**," Anous, *et al*., analytically model vertical underwater visible light communication (UWVLC) links by taking into consideration the inhomogeneity of the medium along the depth dimension. The changes in temperature, salinity and pressure as well as the variations of chlorophyll concentrations affect the radiative index profile and attenuation coefficient profile. The authors model the vertical link as a stratified multi-layer link and mathematically express the transmission and reflection efficiency between two layers by Fresnel's law and Snell's law. Path loss models

for LOS and NLOS links are mathematically derived, and the authors evaluate the bit error rate performance related to angular Rx position, transmit power and beam divergence.

17) In the article "**Revisiting Source Routing for Underwater Networking: The SUN Protocol**," Toso, *et al*., propose a reactive source routing protocol for underwater acoustic networks (SUN). Unlike the source routing paradigm suffering from high route discovery overhead and heavy maintenance in the terrestrial radio networks, SUN's design is tailored to the peculiarities of underwater acoustic channels. The protocol is designed to be independent of any specific underwater network topologies and is robust against the dynamics of underwater environments, such as network topology changes induced by channel variations and by the mobility of network nodes. Moreover, the proposed protocol does not require the knowledge of the network structure, of the locations of the nodes, and of the channel state. From the simulation using the DESERT framework for underwater network protocols and from experimental demonstrations, the authors conclude that SUN is a feasible option for dynamic underwater acoustic networks.

18) The article "**Relay Selection for Underwater Acoustic Sensor Networks: A Multi-User Multi-Armed Bandit Formulation**," by Li, *et al*., proposes a relay selection technique that works under the assumption that the nodes do not collect or feedback any channel state information. The problem is cast as a multi-armed bandit one, modified to be robust to fast underwater channel changes. Theoretical and simulation-based analysis shows that the proposed formulation achieves near-optimal performance and attains the degree of robustness sought.

19) Opportunistic routing is proposed to reduce energy consumption in multihop underwater network communications in the article "**EECOR: An Energy-Efficient Cooperative Opportunistic Routing Protocol for Underwater Acoustic Sensor Networks**," by Rahman, *et al*. The protocol chooses the relay that should forward a packet based on a mixture of energy consumption and forwarding probability information, and handles multiple access through a backoff mechanism. The best relay is obtained through a fuzzy-logic selection scheme. The simulation results show that the proposed algorithm achieves a lower packet delivery ratio, lower end-to-end delay and lower energy consumption with respect to the considered competitors.

20) In the article "**TDA-MAC: TDMA Without Clock Synchronization in Underwater Acoustic Networks**," Morozs, *et al*., investigate the application of underwater acoustic sensor networks for large scale monitoring of the ocean environment. The article presents two MAC protocols for underwater acoustic sensor networks, namely Transmit Delay Allocation MAC (TDA-MAC) and Accelerated TDA-MAC (ATDA-MAC), that can provide TDMA-based channel access to the network nodes without the need for centralized clock synchronization. The MAC functionality has a small footprint and the complexity related

to the control of the network operation is concentrated at the gateway node base station. These features make the proposed protocols a feasible networking solution for real-world cost-efficient UAN deployments.

21) In the article “**Minimum Symbol-Error Rate Based Adaptive Decision Feedback Equalizer in Underwater Acoustic Channels**,” Chen, *et al*., propose an adaptive decision-feedback equalizer (DFE), which is based on the minimum symbol-error rate (MSER) criterion. An optimization problem is formulated and solved to obtain the adaptive DFE that minimizes the sequential symbol detection error with a fast convergence rate. The simulation results demonstrate that the proposed MSER-based adaptive DFE outperforms the existing equalizers in terms of convergence speed and steady-state performance in underwater acoustic channels. The improved performance in terms of convergence rate comes at the price of higher computational complexity of the proposed algorithm.

22) The article “**Mobile Node Localization in Underwater Wireless Networks**,” by Zheng, *et al*., addresses the localization of mobile underwater acoustic nodes by considering time alignment and ray bending compensation. The Kalman filter is used to align different time instances utilizing timestamp information; in addition, ray tracing is performed to compensate for the stratification effect in the underwater channel related to sound speed variations with depth. A penalty convex-concave procedure (PCCP) is incorporated to minimize the localization errors. Using deep sea trial results, it is shown that the localization error for the mobile node is very small (1.44 m), which is a significant improvement compared to the existing state-of-the-art algorithms.

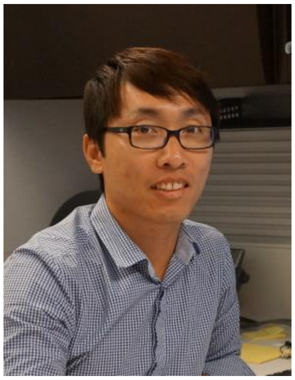
23) Similarly, in the article “**The Influence of MAC Protocol on a Non-Synchronous Localization Scheme in Large-Scale UWSNs**,” by Chen, *et al*., the authors consider the impact of the MAC protocol on localization in large-scale underwater wireless sensor networks. A multi-layer positioning model based on the underwater network architecture is first proposed. The authors then analyze the reason for packet collisions in non-synchronous localization schemes and propose the variable interval ALOHA (VI-ALOHA) protocol that reduces the collision by adding randomness in space and time. It is shown through simulation results that the MAC protocol has a significant influence on localization and the proposed VI-ALOHA protocol can improve the localization coverage and the packet loss by 20% compared to EI-ALOHA protocol.

24) In the article “**Performance Evaluation of Acoustic Model-Based Blind Channel Estimation in Ocean Waveguides**,” Feng, *et al*., propose a blind channel estimation (BCE) scheme based on acoustic models that exploits the acoustic propagation and the acoustic environmental information. The source is first localized with a matched-field processing algorithm that makes use of the physical model of the ocean waveguides to determine the channel impulse response. A performance comparison is carried out against artificial

time reversal and the ray-based synthetic time reversal methods, using the array data measured from the SWellEx-96 experiment. Simulation results are collected to evaluate the performance in terms of cross-correlation coefficient and normalized projection misalignment for different multipath channels, and demonstrate the effectiveness of the proposed scheme.

25) In the article "**Spread-Spectrum Techniques for Bio-Friendly Underwater Acoustic Communications**," Sherlock, *et al*., investigate techniques to mitigate the impact of acoustic communication signals on marine life, by minimizing the source level and by designing waveforms with characteristics proven to reduce animal discomfort in bioacoustics studies. High-ratio spread spectrum signaling is employed based on the families of near orthogonal pseudo-noise waveforms, generated by band-pass filtering of binary M-sequences. This enables the reception of data at very low SNR, over a range many times greater than the range of discomfort experienced by marine mammals. This article offers a way forward to more bio-friendly acoustic modem devices for operation in regions with sensitive fauna and/or increasingly strict environmental controls.

To conclude, we would like to sincerely thank all the reviewers who kindly volunteered their valuable time and expertise in constructively reviewing all the submissions, and for helping us handle the revision process successfully. Moreover, we kindly appreciate all the authors who submitted high-quality and timely articles to our Special Section. We would also like to thank the former IEEE Access Editor-in-Chief Professor, Michael Pecht, and other staff members of IEEE *Access* for their continuous support and guidance.



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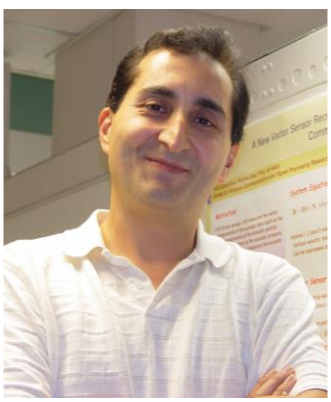

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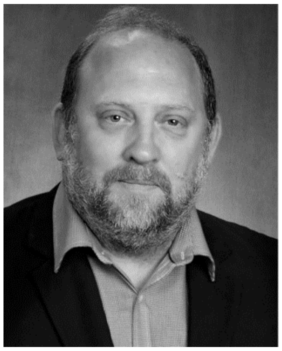

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