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Underwater Distributed Antenna Systems: Design Opportunities and Challenges

Zhaohui Wang, Shengli Zhou, and Zhengdao Wang

The authors examine both theoretical and system design issues pertaining to the underwater DAS, including operation strategies, communication algorithms and mobile node positioning, and pinpoint future research directions to fully realize its potentials.

Abstract

Underwater systems for ocean exploration and monitoring consist of a mix of geographically distributed stationary infrastructure and mobile units. The stationary infrastructure could be bottom-anchored nodes and surface buoys that are connected to a control center via cables and in-air radio links. Both the stationary and mobile units can be equipped with acoustic communication modules for underwater wireless data transmission. With the backbone (cable or radio) connection, those acoustic communication modules naturally form an underwater DAS. Similar to the DAS in terrestrial radio networks, the underwater DAS supports larger acoustic communication coverage and higher network throughput compared to the CAS. Furthermore, the characteristics of underwater acoustic channels, such as the frequency-dependent signal absorption loss and the low sound speed in water, lead to unique design challenges and unforeseen opportunities in the underwater DAS. This article examines both theoretical and system design issues pertaining to the underwater DAS, including operation strategies, communication algorithms and mobile node positioning, and pinpoints future research directions to fully realize its potentials.

Introduction

The distributed antenna system (DAS) is a wireless communication architecture. It consists of multiple geographically distributed wireless transmission and reception antenna elements that are connected to a central station via secondary links, such as fiber and coaxial cables. The DAS architecture was originally proposed in the 1980s to increase the coverage of indoor wireless communication systems [1]. Since then, it has drawn considerable attention in the wireless research community. Relative to the centralized antenna system (CAS), where the antenna elements are closely spaced at the base station, DAS provides higher throughput for the network with nomadic users [2]. Various research topics on terrestrial radio DAS, especially DAS in cellular systems, have been explored. They can be divided into three categories:

- Theoretical limits, such as capacity and spectral efficiency analysis.
- Deployment of distributed antenna elements (DAEs) and resource management.
- Coordinated multipoint transmission and reception, such as dynamic transmission (reception) point selection, joint transmission (reception), and coordinated transmit scheduling and beamforming.

Compared to terrestrial radio networks, research on underwater wireless networks has been progressing slowly. The water world is an extremely dynamic and harsh physical environment, requiring a mix of *in-situ* and ad-hoc infrastructures for observing the evolution or changes across various spatiotemporal scales. Along with spatially distributed stationary infrastructure, autonomous underwater vehicles (AUVs) and unmanned underwater vehicles (UUVs) are playing an increasing role in underwater systems. The stationary infrastructure elements and underwater vehicles are often equipped with acoustic communication capabilities. From the communication perspective, they naturally form an underwater DAS. However, the concept of underwater DAS has not been formally laid out, and the corresponding design challenges and opportunities have not been systematically studied.

A general underwater DAS architecture is depicted in Fig. 1, where the DAEs could be surface buoys equipped with radio frequency modems for high-data-rate in-air communications or bottom-anchored nodes connected via fiber-optic links.[1] The two types of DAEs could co-exist in a hybrid system where they are ultimately connected at the control center. Each DAE is equipped with an underwater modem for wireless communication with submerged system clients, for example, AUVs, UUVs, gliders, or standalone stationary instruments. Due to the high attenuation of radio waves in water, acoustic waves are used as the carrier for long-range underwater wireless information transfer. Typically, the DAEs have virtually unlimited power supply, strong infrastructure support such as multiple transmitters/receiving hydrophones, and high processing capability. The underwater clients are energy-constrained, and are usually equipped with a smaller number of transmitters and receivers. For presentation convenience, in this article we use AUVs to refer to all types of underwater clients.

Two operational testbeds with the DAS architecture include a network deployed and operated by the Atlantic Underwater Test and Evaluation Center (AUTEC) [3] and the Ocean Technology Test Bed (OTTB) [4] developed by the University

[1] In the shallow water, the DAEs can be surface buoys and/or bottom-anchored nodes. In the deep water, due to the high deployment and maintenance cost of bottom-anchored nodes, surface buoys are more viable. Depending on applications, the distances among DAEs in both scenarios vary from hundreds of meters to a few kilometers.

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Zhaohui Wang is with Michigan Technological University; Shengli Zhou is with the University of Connecticut; Zhengdao Wang is with Iowa State University

of Victoria. The AUTEC network is located around Andros Island near the Tongue of the Ocean, Bahamas, and developed for testing, evaluation, and underwater research [3]. It has 96 stationary nodes that are fiber-connected, covering an area of 30 km × 30 km with a water depth of about 1.5 km to 2 km [3]. Acoustic communications are in extensive daily use between stationary nodes and various underwater vehicles. The OTTB is a multi-functional underwater test facility to serve military, academia, government, and industry needs [4]. It is located off the coast of Vancouver Island, Canada, and resides in 80 meters of water. The testbed contains five centrally-managed towers that are cabled together and communicate via fiber optics, and covers two square kilometers of the seafloor.

Compared to the underwater communication system with centralized antennas, the underwater DAS requires higher deployment and maintenance cost. However, similar to the DAS in terrestrial radio networks, the underwater DAS supports larger acoustic communication coverage and higher network throughput. The unique features of underwater acoustic channels enable further throughput improvement and other system functions, such as communication secrecy and mobile node localization.

Despite extensive research in radio DAS and the existence of operational underwater testbeds with spatially distributed elements, there has been very limited study on underwater DAS. This article discusses the design challenges and opportunities in the underwater DAS from the perspectives of operation strategies, transceiver algorithms and underwater localization. Recent research addressing relevant challenges in similar system setups will be described. Future research directions to enhance the underwater DAS performance will be highlighted.

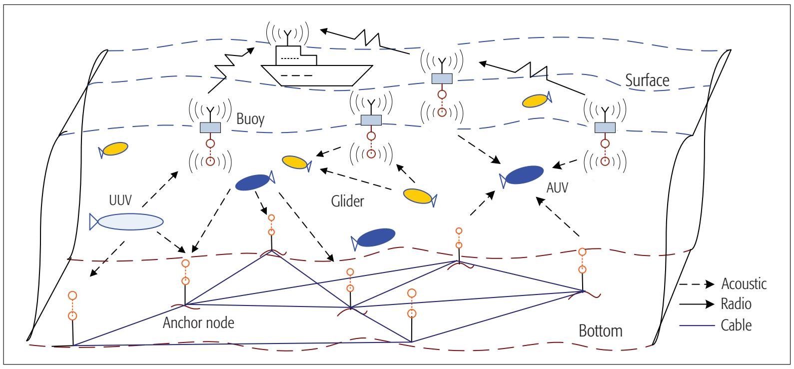

Figure 1. A general underwater distributed antenna system (DAS). The nodes anchored at the sea bottom are connected to a control center via cables. The surface buoys can communicate using radios. There are three types of traffic: AUV to DAS, AUV to AUV, and DAS to AUV.

Underwater Distributed Antenna Systems

Acoustic wave is the main type of carrier for underwater wireless communications. In this section, we will provide an overview of underwater acoustic channel characteristics and discuss several important design aspects pertaining to acoustic communications in underwater DAS.

Characteristics of Underwater Acoustic Channels

The unique features of underwater acoustic channels make an underwater DAS distinct from the commonly studied terrestrial radio DAS.

Large Sound Propagation Delay: The propagation speed of sound in water is about 1.5×10^3 m/s, five orders of magnitude lower than the radio speed in air (3×10^8 m/s). For a transmission distance of 1 km, the signal propagation delay is around 0.67 s, which is on the order of packet duration. As will be illustrated in later sections, such large signal propagation latency yields both design challenges and opportunities.

Frequency-Dependent Signal Attenuation: Different from the terrestrial radio channel where the major cause of signal attenuation is spreading loss, underwater acoustic attenuation consists of both spreading loss and absorption loss [5]. Specifically, for a transmission distance of d, the acoustic attenuation in decibels is proportional to $[\beta \times 10\log_{10}(d) + d \times 10\log10_{10}\alpha(f)]$, where the first summand is the spreading loss that increases logarithmically with distance, and the second summand is the absorption loss that increases linearly with distance. The spreading loss exponent β is practically taken as 1.5, much less than its terrestrial radio counterpart that varies from $2 \sim 6$. The absorption coefficient $\alpha(f)$ increases drastically with the frequency, leading to large attenuation of high-frequency signals; see, for example, the Thorp's formula [5] for $\alpha(f)$. Consequently, compared to terrestrial radio transmissions over the same distance, underwater sound attenuates less for near-range transmissions and more for long-range transmissions, especially at high frequencies.

Large Doppler Effect: Due to the low sound speed in water, small platform motion and media instability could lead to severe Doppler effect. For instance, for a moving speed of 1 m/s, the Doppler scaling factor is around 0.67×10^{-3} in underwater acoustic channels and is around 0.33×10^{-8} in terrestrial radio channels. A more challenging underwater scenario occurs when multiple signal propagation paths (e.g., the surface-bounced paths) experience different Doppler scaling factors. A path-specific Doppler rate varying from −0.5 m/s to 0.5 m/s is often observed in field experiments with stationary transmitters and receivers.

Limited Communication Bandwidth: In the radio DAS for cellular systems, the traffic is either uplink, from users to the base station, or downlink, from the base station to users. The uplink traffic is well separated from the downlink traffic in the frequency, time, or code domain. However, in the underwater acoustic environment, due to the frequency-dependent sound absorption, the communication bandwidth is very limited. Underwater nodes typically operate in the same frequency band for both transmitting or receiving. Hence, all types of traffic are mixed together within the same frequency band.

Design Aspects of an Underwater DAS

The underwater DAS architecture is largely application-dependent. The DAEs are deployed on stationary infrastructure units. The number, location and geometric structure of stationary units, as well as the mobility pattern of AUVs, are determined

Design aspects		Channel and system characteristics	Opportunities	Challenges	Methods
Information-theoretic considerations	Communication system architecture	• Frequency-dependent absorption loss • Less spreading loss than radio channels	• Less signal loss for low-frequency near-range transmissions • Less multiuser interference for high frequency long-range transmissions	Realistic evaluation of the underwater communication system capacity is difficult due to channel dynamics, long signal propagation latency, etc.	Outage performance and throughput analysis under ideal assumptions [6]
	Transmission strategies	• Large sound propagation latency • Spatial distribution of DAEs and AUVs	Interference alignment for throughput improvement	Arbitrary possible values of the signal propagation delay from one node to another	Nonlinear programing [7]
			Signal alignment for communication secrecy		Nonlinear programing [8]
Design aspects		**Opportunities**	**Channel and system characteristics**	**Challenges**	**Methods**
Transceiver algorithm design	AUV-to-DAS transmissions	Multi-DAE reception	• Large sound propagation latency • Large Doppler effect • Spatial distribution and DAEs and AUVs • Backbone (e.g., cable or radio frequency) connection among DAEs	For a receive DAE, asynchronism and large Doppler derivation of signals from multiple AUVs	• Interference aggregation and cancellation [9] • Multi-resampling receiver front ends [10, 11]
	DAS-to-AUV transmissions	DAE-coordinated transmissions		For an AUV, signals from different DAEs have different propagation delays and Doppler effects	Delay-and-Doppler precompensation at transmit DAEs
	AUV-to-AUV transmissions	Two or more DAEs can function as a full-duplex virtual relay		Design of effective cooperation strategies	Amplify and forward, decode and forward, and so on [12]
Design aspects		**Opportunities**	**Channel and system characteristics**	**Challenges**	**Methods**
Localization and tracking	At DAS	Use of communication signals for localization and tracking	• Spatially distributed DAEs serve as reference nodes • Sound stratification • Channel dynamics	• Multipath channel with large delay and Doppler spreads • Non-straight line propagation • Outlier range estimates	• Precise timing [13] • Sound stratification compensation • Probabilistic data association filter and particle filter [13, 14]
	At AUVs	On-demand localization supports localization of all AUVs			

Table 1. A summary of design opportunities and challenges in the underwater DAS.

by application needs, for example, in scientific studies to achieve a desired spatiotemporal resolution of water parameters of interest under the geographic and budget constraints.

The acoustic transmission strategy to achieve a large coverage and a high throughput depends on the DAS architecture and the characteristics of underwater acoustic channels. To support the three types of traffic, AUV-to-DAS transmission, DAS-to-AUV transmission, and AUV-to-AUV transmission, each DAE can act as an information source (transmitter), an information sink (receiver), or a relay to assist AUV-to-AUV communications. A number of DAEs can simultaneously send or receive multiple data streams in the multiplexing mode to increase the system throughput, or simultaneously send or receive a single data stream in the diversity mode to improve system reliability, or combine the above two modes using the space-time coding techniques. For a given transmission strategy, the challenges posed by underwater acoustic channels need to be addressed during the acoustic transceiver design; typical challenges include the multi-transmission asynchronism caused by the large sound propagation latency and the transmitter-receiver-pair-dependent Doppler scaling effect caused by AUV mobilities.

In addition, efficient and reliable communication in underwater DAS requires AUVs' location and velocity information. Given the large attenuation of electromagnetic waves in water, submerged underwater vehicles cannot access services provided by the Global Positioning System (GPS). A system equivalent to the GPS can be developed with the DAS infrastructure support, where each DAE possessing its own precise location information can play a role akin to that of satellites in space.

In the following sections, we will discuss the design challenges and unforeseen opportunities in the underwater DAS from three fundamental perspectives: information-theoretic insights, transceiver design, and underwater localization. A brief summary of the design challenges, opportunities, and potential solutions is provided in Table 1. In all discussions, the unique features of underwater acoustic channels previously mentioned will be revisited.

Information-Theoretic Considerations

This section focuses on the system architecture and transmission strategies, and discusses from an information-theoretic perspective the design challenges and opportunities raised by the atten-

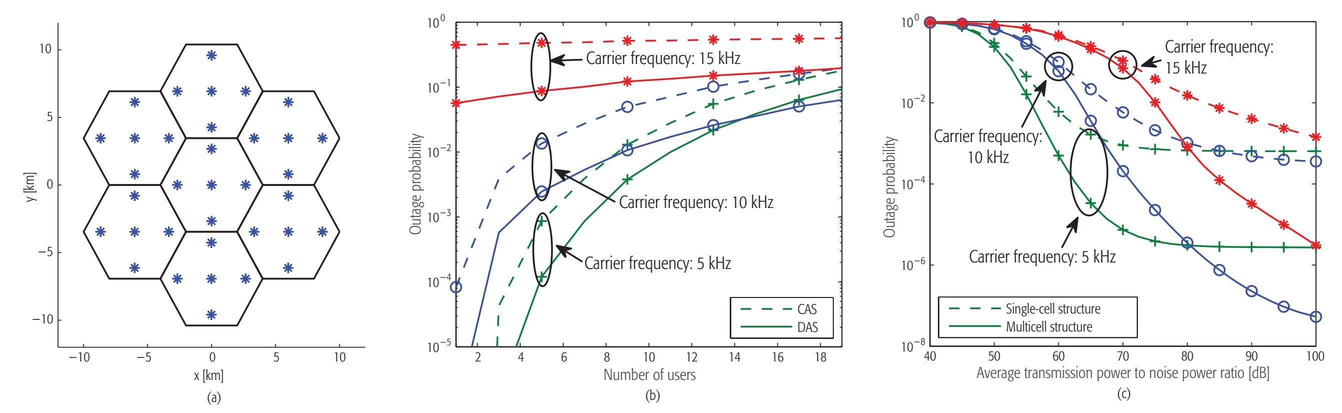

Figure 2. a) The simulated operational area. * marks the DAE locations in the DAS. The CAS has all antenna elements located at the origin of the overall operational area. b) The per-user outage probability during multiuser transmissions. The users are uniformly distributed within the overall operational area. The average transmission signal power to noise power ratio (TSNR) is 70 dB. c) The per-user outage probability of two DAS structures at different TSNR levels.

uation characteristics and the large sound propagation latency in underwater acoustic channels. We would like to note that although theoretical analysis of the system throughput can be carried out in a way similar to that in terrestrial radio communications when the channel state information (CSI) is assumed, realistic evaluation of the capacity of underwater DAS is not trivial due to the fast variation of underwater acoustic channels, the large channel temporal and frequency dispersion, and the long signal propagation delay.

System Architecture

Underwater acoustic signal propagation suffers both spreading loss and frequency-dependent absorption loss. When the frequency is low and the communication range is small, the effect of absorption loss is small and the signal attenuation is mainly caused by the spreading loss. In this case, a CAS would suffice for underwater wireless data transfer. On the other hand, for a large operational area or high carrier frequencies, the absorption loss would be dominant. In this case, using a DAS has an advantage over a CAS to cover the large operational area.

To shed light on the performance of different system architectures, we compare numerically the outage probabilities of asynchronous multiuser uplink transmissions in a centralized system and in a distributed system, based on an analytical study in [6]. We consider an operational area covered by the hexagons in Fig. 2a. The ratio of the signal bandwidth to the carrier frequency is set as 1/2. To model the channel multipath fading and the frequency-dependent transmission loss, we divide the frequency band into three subbands, and model each subchannel as a circularly symmetric complex Gaussian random variable with zero mean and a variance that is equal to the channel attenuation loss. For each user, an outage occurs when the instantaneous received signal-to-interference-and-noise ratio (SINR) after the maximum radio combining is below 3 b/s/Hz. The outage probability of each user is depicted in Fig. 2b. It can be seen that due to the frequency-dependent signal absorption loss, the outage probability increases drastically as the frequency increases. The DAS outperforms the CAS, and the advantage is pronounced at higher frequencies.

We further compare the outage probabilities of two DAS operational structures: a single-cell structure where the overall operational area is taken as one big cell with seven uniformly distributed users, and a multi-cell structure where each hexagon in Fig. 2a is taken as one cell and one user is uniformly distributed within each cell. In real systems, the cell structure suggests the survey regions of multiple AUVs. As shown in Fig. 2c, as the transmission power increases, the multiuser interference causes an error floor in the outage probability. Due to the frequency-dependent absorption loss, the level of multiuser interference decreases as the frequency increases, which leads to a lower error floor for higher frequency signals. Comparing the outage performance of the two cell structures, the multi-cell structure has a lower outage probability, benefiting from the further separation of users, hence less multiuser interferences.

Time-Domain Interference and Signal Alignment

When multiple transmissions are allowed and have different intended receivers, the overall transmission throughput could be improved through *interference alignment* [15]. However, it typically requires the accurate CSI at all transmitters and all receivers. In underwater systems, it is difficult to obtain accurate CSI due to the fast channel variation.

Thanks to the large signal propagation latency, underwater channels offer distinct possibilities for interference alignment. The idea is to appropriately schedule the packet transmission from multiple transmitters, such that the interference packets would overlap at a receiver and without contaminating the desired signal;[2] see an example in Fig. 3. In real systems, perfect alignment in channel delays is difficult to achieve due to their arbitrary values, but sizable gains have been shown possible through judicious transmission scheduling [7].

The large acoustic propagation latency and the spatial distribution of DAEs can be exploited to achieve other desired system features such as communication secrecy. As shown in Fig. 3, with an appropriate transmission schedule, AUV_2 cannot overhear the transmission to AUV_1, as the packets destined to AUV_1 collide at AUV_2. For general underwater DAS, a thorough treatment of

[2] A practical issue related to the time-domain signal or interference alignment is the clock synchronization among DAEs. Given the backbone connection among DAEs, sufficient clock synchronization accuracy can be achieved for the above purpose.

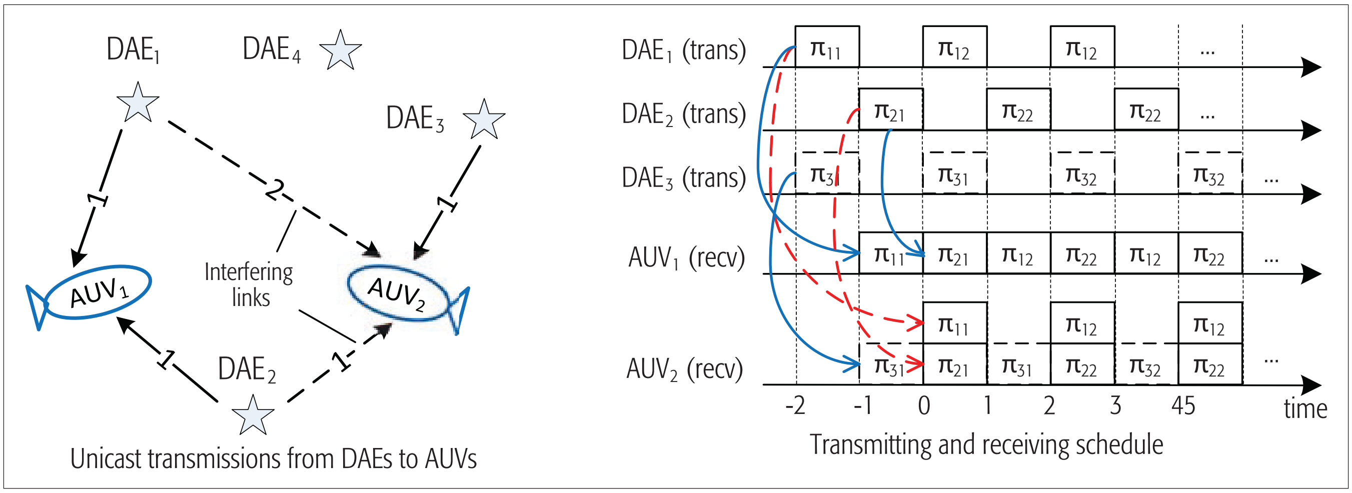

Figure 3. Illustration of the interference alignment and the signal alignment. The number on each link is the propagation delay in the unit of packet duration. Here, we assume the propagation delays being integer multiples of the packet duration. π_{ji}: the *i*th packet from the *j*th DAE.

transmission scheduling for communication secrecy can be found in [8], where a set of transmit DAEs are optimally selected to superimpose their transmissions at the eavesdropping node (e.g., the honest-but-curious AUV$_2$ in Fig. 3) to create self-interference, while keeping the transmissions well separated at the desired user (e.g., AUV$_1$ in Fig. 3).

Transceiver Design

In this section, we focus on the challenges and opportunities in the transceiver design for three types of traffic: AUV-to-DAS transmission, DAS-to-AUV transmission, and DAS-assisted AUV-to-AUV transmission. Since DAEs typically have sufficient power supply and stronger infrastructure support than AUVs, most of the communication and processing overhead can be shifted to DAEs.

AUV-to-DAS Transmission

Due to the broadcast nature of acoustic transmissions, the signal from an AUV can reach one or multiple DAEs. In the scenario with a single transmit AUV, single-DAE reception or multi-DAE reception with the the maximum radio combining can be performed. When multiple AUVs access the medium simultaneously, the low sound speed in water and the AUV mobility make the decoding task nontrivial. First, due to the spatial distribution of DAEs and the large sound propagation latency, it would be difficult to (quasi-)synchronize the multiple AUV signals at all the DAEs. Second, the transmission from an AUV could be compressed or dilated. The Doppler scaling factor depends on the projection of the AUV's velocity onto a line that connects the AUV and the receive DAE. Due to different moving velocities of AUVs and the geographic separation of DAEs, the transmissions from different AUVs may have different Doppler scaling factors at the same receive DAE, and the transmission from one AUV may have different Doppler scaling factors at different receive DAEs.

To address the asynchronism of multiuser transmissions, an *overlapped truncation approach*, as shown in Fig. 4a, was developed in [9] for transmissions modulated by the zero-padded orthogonal frequency-division multiplexing (OFDM) technique. Each truncation retains the desired OFDM block information from all the users. By taking the aggregate co-channel interference caused by the asynchronism as one interference, the asynchronous multiuser problem can be converted to a quasi-synchronous multiuser problem with interference contamination. The algorithm was evaluated in a two-user system based on data sets collected in the MACE10 experiment [9]. Figure 4b shows the decoding performance of four receiver algorithms. One can see that the conventional multiuser reception approach without interference cancellation almost fails completely, and that the receiver with successive multiuser interference cancellation via iterative forward and backward message passing achieves an impressive decoding performance [9].

To address the large Doppler deviation of signals from multiple AUVs, a receiver front end with multiple resampling branches has recently been introduced for both single-carrier and OFDM-modulated multiuser synchronous transmissions [10, 11]. Each branch resamples the received signal using the Doppler scaling factor of a single user. Joint multi-user receiver processing or the low-complexity single-user receiver processing with successive multiuser interference cancellation can then be performed. For thorough development and evaluation of the algorithms, please refer to [10, 11].

Although iterative processing algorithms can be designed, tackling both the aggregate co-channel interference and the Doppler deviation is a computationally challenging task. In the present context, the receiver processing can start from the DAEs that receive signals with small temporal misalignment levels and small Doppler deviations, and progressively incorporate the signals received by other DAEs that have large misalignment levels or large Doppler deviations. Sequential multiuser decoding and successive interference cancellation will be major components in the receiver design.

DAS-to-AUV Transmission

The DAEs can cooperate for downlink transmissions to AUVs. In the single-AUV scenario, a trivial strategy is to select the DAE with the best

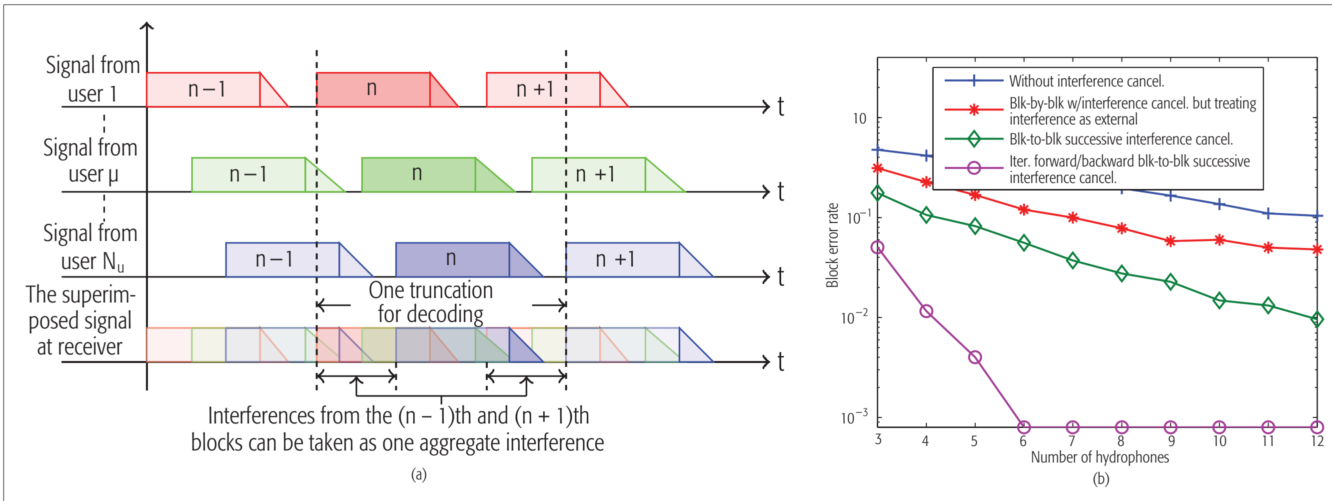

Figure 4. a) Overlapped truncation of the received signal and the interference aggregation in a zero-padded OFDM-modulated asynchronous N_u-user system. b) Receiver processing performance in an emulated experiment [10].

link quality for transmission. Several DAEs with good link qualities can perform coordinated transmission. However, due to the spatial distribution of DAEs, signals from different DAEs may have different propagation delays. In addition, due to different AUV's projected velocities, those signals are subject to different Doppler scaling effects. To facilitate the receiver decoding at the AUV, delay and Doppler pre-compensation can be performed at each transmit DAE, such that at the receive AUV, signals from the transmit DAEs are quasi-synchronous and have similar Doppler effects.

Due to the diverse locations of AUVs, the DAE coordination mechanism for joint transmission to multiple AUVs is much more involved than that in the single-AUV scenario. Applying the time-domain interference alignment concept from above, an ideal scenario is that each AUV receives a "clean" copy of the Doppler-pre-compensated signal destined to itself in one time slot, and has the signals destined to other AUVs overlapped as much as possible in a different time slot. To this end, a judicious design of the DAE-AUV association and the transmission schedule is essential. Since the AUVs and DAEs could have arbitrary geographic locations and hence arbitrary signal propagation delays, a loose time-domain alignment of interfering signals would be more practical in real systems.

DAS-Assisted AUV-to-AUV Transmission

In addition to being information sources or sinks, the DAEs can assist AUV-to-AUV communications. An example is shown in Fig. 5, where one DAE close to the source AUV is fiber-connected to another DAE that is close to the destination AUV. The two DAEs can collaborate to relay the message from the source to the destination. Specifically, the signal received at the first DAE, which tends to have a large strength, can be instantly sent to the second DAE via the fiber connection. The second DAE then relays the signal to the destination. We note that in practice more DAEs could cooperate as relays.

Compared to a typical three-node relay network where the relay mainly operates in a half-duplex mode, the fiber connection allows the DAEs to function as a *large-aperture full-duplex virtual relay* where receiving and transmitting can happen simultaneously at different locations. Take the setup in Fig. 5 as an example. If the signal from the source AUV is above the noise level at the destination AUV, the second DAE's transmission can be superimposed on the source signal at the destination AUV, using the delay-and-Doppler pre-compensation techniques. Otherwise, the second DAE can adopt a variety of relaying strategies in the literature [12], for example, amplify and forward (AF), decode and forward (DF), and compress and forward (CF), where the relayed signal is separate from the source signal.

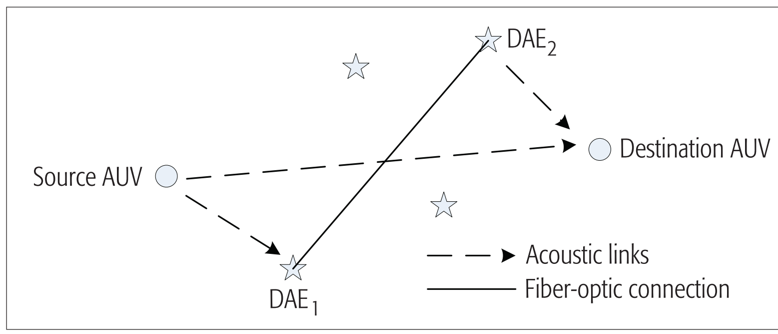

Figure 5. An example of DAE-assisted AUV-to-AUV transmissions.

Localization and Tracking

AUV localization and tracking are important for system operation in unknown environments. For the underwater CAS, the antenna array can measure the range and the direction of the AUV to be localized, and use the two types of measurements for AUV positioning. However, this method suffers reduced accuracy as a small angle measurement error could cause a large position error at far distances. When high positioning accuracy is required, geographically separated reference nodes need to be deployed. In the underwater DAS, the DAEs can serve naturally as the reference nodes without requiring extra infrastructure support.

Due to the geographical separation of DAEs, the large sound propagation delay and the large Doppler variation caused by AUV mobilities pose grand challenges for transceiver design. Additionally, the channel multipath effect, sound stratification, and channel dynamics render localization and tracking in underwater DAS nontrivial.

Localization and Tracking at DAS

Consider the first scenario where the localization is performed at the DAS. One localization beacon message can be sent from the AUV to be localized. The differences of arrivals at spatially separated DAEs can be used to localize and track the moving vehicle [14]. Consider the unknown 3-D coordinates and the clock offset between the AUV and the DAS. The time measurements from at least four DAEs are needed.

Furthermore, since the DAS monitors all the communication traffic, once a communication message is successfully decoded, the transmitted waveform can be perfectly reconstructed. It can then be treated as a known probing signal for positioning. This approach based on the "signal of opportunity" allows the DAS to integrate localization, tracking and communication, without any change to the AUV. In addition, since the communication waveform contains the identity information of each AUV, such a positioning system can work even when multiple AUVs are transmitting at the same time, a feature that is not available for positioning based on narrowband pingers. As a result, all the AUVs can be constantly monitored at the cost of an increased processing load at the DAS.

Localization and Tracking at AUVs

Consider the second scenario where the localization is done at the AUV. An AUV may rely on a non-acoustic method such as an inertial system for navigation. Once in a while, the AUV needs the help of the DAS to recalibrate the inertial system for improved localization accuracy. In an on-demand localization scheme [13], an AUV can request a localization cycle by requiring the DAS to send out several beacon messages from multiple DAEs in a certain order. By comparing the differences of arrivals of the returned messages, the AUV can localize itself [13]. In addition, all the other AUVs in the DAS that listen to the messages can locate themselves. Hence, one localization cycle can support the localization of all passive units. In a buoy-based DAS where the clocks of DAEs might not be accurately synchronized, an asynchronous on-demand localization solution [13] can be carried out, where the DAE reacts to the received signal from the previous DAE transmission and schedules its own transmission after a pre-specified reaction time.

Challenges

Based on the range difference of an AUV to multiple DAEs, the localization algorithm that considers the clock bias between the AUV and the DAS has been well developed. Pilot tests of AUV self-localization based on four surface nodes have been carried out in swimming pools and in a lake, where the root mean square error of the position estimate is about 0.5 meter in the pool and about 5 meters in the lake [13]. In a swimming pool test, a DAS consisting of four surface nodes can track a moving AUV with an error around 5 meters [14].

To reach a desirable accuracy, underwater localization faces the following challenges. First, underwater acoustic channels have multiple paths (e.g., several or tens of paths) with large delay spreads and Doppler spreads. The first path is often not the strongest path, and the correlation-based peak-finding method often identifies a strong non line-of-sight path. Second, sound waves do not necessarily travel in straight lines, as the water medium can be inhomogeneous and the sound speed varies depending on environmental parameters, for example, the temperature, pressure and salinity. Ignoring this stratification effect could lead to considerable bias in the range estimates. Third, due to channel variability and interferences, underwater acoustic links are not stable. Some of the range estimates could be so poor and should be treated as outliers. Advanced tracking algorithms that can deal with outlier estimates by treating those as false alarms or clutters, are needed.

Conclusions

Although practical underwater systems often deploy distributed transceiver elements, there is a lack of systematic study of underwater distributed antenna systems. This article provided a formal description of the underwater DAS, and discussed its design challenges and unforeseen opportunities from three fundamental perspectives: theoretical insights, transceiver design, and underwater localization. In particular, the information-theoretic analysis revealed that the optimal antenna deployment and system operation depend on the signal frequency and the size of the operational area. Due to the geographical separation of DAEs, the large sound propagation delay and the large Doppler variation caused by AUV mobilities pose grand challenges for transceiver design. Additionally, the channel multipath effect, sound stratification, and channel dynamics render localization and tracking in underwater DAS nontrivial. Nevertheless, the DAS architecture and the characteristics of underwater acoustic channels open up an array of research opportunities: time-domain interference alignment and signal alignment to improve system throughput and to achieve communication secrecy, harvesting the full-duplex feature of cooperative DAEs for relay operations, and leveraging the concept of "signal of opportunity" for localization and tracking. Innovative research exploiting the design opportunities is needed to fully realize the potential of underwater DAS.

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Biographies

Zhaohui Wang [M'13] received her B.S. from Beijing University of Chemical Technology in 2006, an M.Sc. from the Institute of Acoustics, Chinese Academy of Sciences in 2009, and a Ph.D. from the University of Connecticut in 2013. She is with the Department of Electrical and Computer Engineering at Michigan Technological University. Her research interests include signal processing, wireless communications and networking, with recent focus on signal processing and machine learning for underwater wireless communication networks.

Shengli Zhou [F'14] received his B.S. and M.Sc degrees from the University of Science and Technology of China in 1995 and 1998, respectively, and a Ph.D. from the University of Minnesota in 2002. He is with the Department of Electrical and Computer Engineering at the University of Connecticut. His research interests include wireless communications and signal processing.

Zhengdao Wang [F'16] received his B.S. from the University of Science and Technology of China in 1996, the M.Sc. degree from the University of Virginia in 1999, and a Ph.D. from the University of Minnesota in 2002. He is with the Department of Electrical and Computer Engineering at Iowa State University. His research interests include signal processing, communications, information theory and machine learning.