UComms: A Conference and Workshop on Underwater Communications, Channel Modeling, and Validation

UNDERWATER (UW) communication technologies have progressed rapidly in recent years, with the development of advanced coherent acoustic modulation, demodulation, coding, and decoding techniques that have extended the performance limits of point-to-point systems. Examples include phase-coherent decision feedback equalizers (DFEs), time reversal and multiple-input–multiple-output (MIMO) techniques, turbo coding, and equalization. At higher communication stack layers, there have been significant advances in developing delay and disruption tolerant networking (DTN), medium access control (MAC), routing and other protocols to establish efficient and reliable communications through underwater networks. While historically the demand has been for point-to-point communications, underwater robotics has now matured to the point where distributed sensing and actuating networks are becoming a real opportunity—we are now at the brink of requiring an underwater Internet for these robots. Added to this, optical communications promises much higher data rates over short ranges, likely a crucial component in achieving robust practical networks through a diversity of technologies.

In stark contrast to the model successfully adopted in the radio-frequency (RF) world for WiFi and cellular telephone networks, the underwater communication community has no digital standards specifying modulation, coding parameters, or medium access and routing protocols. As a result, each modem manufacturer has developed proprietary schemes, and modems are generally unable to communicate with systems from a different manufacturer. Modems are now being advanced to include much more sophisticated protocols, including MAC and routing, thus compounding the problem already present in the physical layer. If we are to achieve interoperability so that we can build UW sensing networks, we must have at least some *de facto* standards for modulation, coding, and other protocols that more than one modem can recognize.

To intelligently select standards, it must be possible to rank the performance of candidates for realistic applications and environments. The cost and logistic complexity of conducting extensive trials at sea over a wide range of environmental conditions and applications inevitably steers interest toward modeling and numerical performance estimation. Therefore, we need to first establish what are the essential physics of the channel that must be captured in a realistic simulation and what fidelity is needed to adequately represent the channel for the purposes of characterizing performance. It would also be valuable to agree on channel property and performance metrics and how these can best be presented so that they are most readily comprehended.

This special issue presents some of the work brought to a conference on underwater communications held in 2012 with the aim to present a snapshot of the state of the art in UW communication technologies, both acoustic and optical, and to set the stage for agreeing on some benchmark problems and models that can be used to equitably evaluate different coding schemes and protocols. The conference was followed by a workshop that attempted to create a roadmap for future channel modeling and standardization. This guest editorial presents an introduction to the conference papers you find in this issue, together with the consensus distilled out of the workshop discussions.

I. INTRODUCTION

The Internet is now much more than it was ever envisaged to be. Rather than simply a communication system, it has become the backbone of modern society, whose growth is intertwined with socioeconomic, environmental, and cultural developments. Its penetration, strategic value, and services have grown exponentially. The Internet paradigm has been applied to connect people and things on Earth, vehicles in space, even enable interplanetary communications, but it has yet to extend into the sea, where wireless, *ad hoc* networking is not yet possible. Internet technologies have the potential to take a key role in the growth and development of the marine economy through exploration and understanding of marine environments. The development of the Internet beyond serving people, via web browsers and similar applications, to connecting smart devices (cars, navigation systems, security cameras, house appliances, etc.) is known to communication engineers as "The Internet of Things." An underwater "Internet of Things," implemented through UW sensing and actuating networks with underwater robotics and novel underwater communication technologies, could provide the missing effective, pervasive means to sense, monitor, and control ocean processes to sustainably manage our planet's resources.

The world's oceans and lakes cover 71% of the Earth's surface and play a key role in the equilibrium of many of Earth's systems including climate and weather. The marine environment is, or is fast becoming, the critical frontier of exploration for transport, oxygen and food production, hydrocarbon exploitation, aquaculture, biofuel production, mineral exploitation, climate, and global water circulation. The future of mankind is, therefore, dependent on careful monitoring, control, and sustainable exploitation of marine environments. As of today, however, our ocean basins are less well mapped, explored, and understood than not only our Moon, but even Mars. This extraordinary gap in the knowledge of our life-support

Digital Object Identifier 10.1109/JOE.2013.2283094

system called Earth is because the body of the ocean is significantly more hostile to man than the air or land surface, lacking the essential oxygen to breathe and posing the challenges of crushing pressures in a corrosive fluid. With the maturing of intelligent autonomous underwater robotics, we are now on the cusp of capability to accomplish our work at sea by means of unmanned collaborative networks. But to form a functional network, and to enable collaboration, requires communication. While the marine environment is in many ways more challenging to work in and explore than deep space, this is nowhere more true than for the challenges of communication.

When astronauts sent back messages from the Moon, there was a 1.2-s delay before they were heard on Earth due to the long distance and finite speed of light. When aquanauts transmitted acoustic signals from the bottom of Challenger Deep, it took 7 s before they were heard by ships on the surface. It is as if they were five times farther away than the Moon. We have put 12 astronauts on the Moon during six landings. The third aquanaut, James Cameron, has just returned from Challenger Deep in only the second landing ever made to that depth.

The study and development of underwater communications can be traced back to Leonardo da Vinci, but the first practical underwater telephone was not invented until 1945, with explosive growth occurring in the last two decades as high computing and signal processing power has become available. The underwater communication challenge is primarily due to seawater's opacity to electromagnetic (EM) radiation, making it both dark and radio silent at depths more than a few tens of meters. The only viable alternative to radio waves are acoustic waves, but these suffer from very limited bandwidth, long propagation delays, significant Doppler spread, temporal spreading, long interference ranges, and time-varying fading multipath.

The speed of sound in water is five orders of magnitude slower than for EM waves in air. Frequencies are similarly reduced, and bandwidths are frequently 50% of the carrier frequency, bringing in wideband frequency-dependent issues. There are typically many distinct multipath echoes in a received signal, requiring equalizers with many taps. At the same time, the channel may fade rapidly as vehicles move over an irregular ocean bottom, receiving echoes off different facets. The effect of the ocean surface on acoustic propagation is also complex and not fully understood. The surface is, to first order, an acoustic mirror but is rarely flat on the scale of the wavelengths used for communications, and so introduces random focusing effects, in addition to significant Doppler spread. Furthermore, breaking waves inject bubbles that can have an enormous effect on the sound, sometimes shielding the ocean surface entirely from the incident sound wave.

Still, lacking alternatives, acoustics has historically become the mechanism of choice for underwater communications. With the advent of low-cost lasers and bright, efficient light-emitting diodes (LEDs), this is now changing, at least over $\sim$O(100) m ranges, where optical communications can provide greater stealth and bandwidth. It is likely that we will see increasing interest in hybrid systems, combining the advantages of optical communication at short ranges with acoustic communication over longer ranges. There is also the potential for low-frequency RF systems to operate at moderate bandwidths over short ranges underwater, but with the additional capability to cross the air–water interface without a gateway. Intelligent, software-defined modems will be able to switch fluidly under the guidance of a protocol policy manager between the various schemes. For example, an adaptive multimode modem onboard a mobile platform could use an acoustic system for localization of a contact node from distances of several kilometers at low data rate and then switch over to an optical mode for high-speed data transfer at closer ranges. In another scenario, optical-to-RF gateway systems could be used to transmit data through the air–water interface to allow communication between undersea platforms and those on land or in the air, at comparable data rates.

This background provided the motivation for the Conference and Workshop on Underwater Communications (UComms), held September 12–19, 2012, in Italy. The location in the town of Sestri Levante was the site of Marconi's early experiments (the 1930s) on very-high-frequency (VHF) and ultrahigh-frequency (UHF) propagation, providing a suggestive backdrop. A central theme of the conference was the connection of the propagation physics with modem and network performance with a view to coming to a consensus about the essential physics that needs to be captured in channel models and reported in experiments to enable competing protocols to be realistically compared. Only then can standards be chosen intelligently; and standards are the foundation of interoperability, an essential, yet entirely lacking, capability that supports distributed sensing networks. The volume before you presents selected papers from that meeting.

II. SIMULATION, EMULATION, REPLAY, AND TESTBEDS

At-sea experimentation is expensive and difficult. Even when possible, there is normally only a limited time in which to perform the experiments, perhaps only one physical environment and a limited number of configurations that can be tested. There is often little or no control over what the natural environment provides. There may be no opportunity for repeating tests. If one wishes to explore how a particular coding scheme or protocol performs in comparison to another, it may not even be possible to test both under the same conditions, since the environment may change too rapidly to enable sequential testing and the channel may prohibit parallel testing. Bad weather or a broken system component can cancel an entire test. There are, therefore, many reasons why it is attractive to simulate, emulate, or replay to learn about the performance of our nascent technologies. In addition, we are now also beginning to see at-sea testbeds contributing to this mix of methods.

By simulation, we mean a process that is designed to mimic the behavior of an at-sea deployment, even though it may be implemented in an entirely different way. A good simulator outputs a realistic basic behavior of a system under inputs that lie within a closed set of considered possibilities. The simulator may not behave like the modeled system if parameters are set out of the design bounds or if the environment does not satisfy the intrinsic simplifying assumptions, because it will not generally embody the physical constraints of the system being simulated. For communication networks, the Network Simulator 2 (NS2) is often used. Designed for simulating Internet protocols, NS2 requires extensive modification to be useful for underwater wireless network simulations.

Emulation is in a sense one step closer to the "real thing" in that an emulator is built to satisfy the same physical constraints as the modeled system and may even include "hardware in the loop" so that some parts of the system are exactly those to be used in real life. An emulator is effectively a replica, usually running on the same hardware platforms and using the same software, but operating in a different environment, i.e., in air rather than in water, replacing the communication channel by a propagation model. An emulator is likely to be more accurate in that unforeseen and undocumented "features" of the hardware and software to be used are automatically included, even if the experimenter is unaware of them or their importance.

Replay is another step toward reality, exercising the system on a replayed sequence of actual at-sea recorded physical channel realizations, instead of using a propagation model to generate a simulated channel. For testing the physical-layer performance, the captured realizations should include a wide range of low-level physical attributes, as discussed in Section VI. The degree of sophistication must be matched to the modulation scheme. Phase-sensitive coding, for example, will require more environmental information than phase-insensitive methods. Similar issues arise for wideband versus narrowband signals. For higher level protocols, it may be sufficient to capture link status and packet error rates.

By testbeds we refer specifically to semipermanent installations that offer an open suite of software (and possibly also hardware) reconfigurable nodes, cabled to shore and connected to the Internet. A testbed may or may not include mobile nodes, but should have at least some platforms with sufficient flexibility in the hardware and software that they can be used to test a wide range of technologies, from the physical layer to applications. Testbeds go hand in hand with open-architecture software-defined modem stacks, necessary to allow generic hardware to support a sufficiently wide range of protocol implementations to be useful for performance comparison.

The most powerful contribution of a testbed is that it offers genuine at-sea testing, without any simulated, emulated, or captured reality, at a fraction of the cost of mounting a regular sea trial with supporting ships, because the testbed can be configured and operated over the Internet, possibly by collaborators half a world away, at their desks. The limitations are obvious; a testbed offers only one physical environment, which may not be repeatable, still requires substantial investment and maintenance, and limits the kinds of hardware that can be tested, just as for full-on at-sea testing. But if we are able to establish standard interfaces for such testbeds and federate the idea so that many such testbeds are constructed in many different physical environments, with the same interface, it will be possible for users to test their protocols in many locations and environments with only one set of tools. It will also be possible to test the long-term performance of a range of protocols, important for future applications of remote autonomous systems. This has been impossible to date because of the limited endurance of logistics support involved in regular at-sea trials.

III. CHANNEL STATISTICAL MODELS FROM REPLAY TRACES

Replay methods rely on taking sufficiently comprehensive measurements of an at-sea example channel that can be used to generate channel impulse responses for simulators and emulators. The difficulty is in taking the appropriate samples at the right resolution in space and time. Modeling the communication performance of moving assets such as autonomous underwater vehicles (AUVs), for example, can be very difficult using replay.

Fortunately, it is considered reasonable to inject noise separately at the required level(s) and to assume that the effect of changing transmit power is linear.

At higher levels of the communication stack, above the physical coding layer, it is possible to apply the replay method at the link quality level, rather than capturing the channel impulse response. This means capturing packet loss data, with the caveat that one needs to know how packet loss would be affected by interfering packets from other nodes, causing collisions. One can also model or generate (from the traces of link measurements) statistical measures of link quality. Then, assuming that links are independent, one can generate an arbitrary replay sequence that should be statistically valid. In some cases, the replay trace can be used to identify if there are multiple time scales in the statistics, the form of the probability distributions (Ricean, Rayleigh, etc.), and whether such sequences are consistent with a particular kind of Markov model. The problem here is that unless the underlying physical process can be identified and their impact on the packet error shown to be consistent with observations, one can never be sure that a sequence is representative or know how it correlates in space or over longer time scales than the sampled data support. Ultimately, it has proven extremely difficult to relate acoustic variability to communication performance variations. Sometimes the sensitivity to acoustic propagation conditions appears very low; at other times it becomes critical, since the relationship of environmental change to communication performance is highly nonlinear. It should always be borne in mind that an average sound-speed profile is one that is never observed.

In the end, as is always the case, the challenge is to find the "sweet spot" between simplifying as much as possible (to reduce computational load) while not oversimplifying (so losing the connection with reality).

IV. THE PROMISE OF OPTICS

UW optical communications is a rapidly growing area of research. Compared to acoustics, optics can provide orders of magnitude more bandwidth (megabits per second to gigabits per second) for high-speed data transfer over short ranges. However, the performance of optical links is strongly constrained by the optical properties of the channel, specifically absorption and scattering. To realize the performance promise of optical systems, we urgently need a better understanding of how to build systems that maximize performance over the wide variety of optical conditions found in ocean environments.

In clear water, such as in the deep open ocean, absorption is the dominant source of loss. Links operating in these environments are typically characterized as "photon limited." Open ocean waters have an absorption minimum at blue wavelengths. In these benign scenarios, longer ranges [or better signal-to-noise ratio (SNR)] can be achieved by using optical sources with more power, larger receiver apertures, higher receiver conversion efficiencies, etc. (all within the limits of hardware technology).

In turbid waters, such as in the littoral, coastal, and near-shore regions, scattering is the dominant source of attenuation and the absorption minimum shifts to the green. Links operating in these environments are classified as "dispersion limited." Two types of dispersion exist. The first type is spatial dispersion, which spreads and attenuates the transmitted laser beam in space. Depending on the extent of spatial dispersion, as well as receiver position relative to the transmit axis, path-length differences between scattered photons may arise. These path-length differences between scattered photons, or between scattered and nonscattered photons, result in a temporal dispersion. Temporal dispersion can be thought of as a form of micromultipath, with both spatial and temporal dispersion limiting link range and bandwidth. On the plus side, optical networks will not be plagued by the same multipath dispersion and latency issues as in acoustic networks. As such, optical networks are likely to operate with a significantly different set of constraints than acoustic networks. This issue is further complicated if acoustics and optics are used simultaneously or adaptively in some complimentary manner, since the physical layers of each are quite different.

A. Optical Modeling and Simulation

Modeling the propagation of light in the sea is generally based in the radiative transfer equation (RTE), which is a complicated integro–differential equation of time and space that characterizes a light field traversing a scattering medium. Finding tractable solutions is no trivial task. Solutions to the RTE generally fall into two categories: numerical (Monte Carlo) or analytical. Numerical techniques, while highly accurate, tend to be computationally complex. Analytical techniques are fast and far less computationally complex, but may have limits in terms of applicability depending on their simplifying assumptions.

There has been no shortage of propagation models developed over the previous 50 years since the introduction of the RTE, and it is expected that more efficient numerical codes or more accurate and simple analytical expressions that describe spatial and temporal dispersion will continue to be developed. However, to date, only a few RTE models have been built to provide an end-to-end simulation tool that could be used by communication designers. Furthermore, unlike some efforts for acoustic modems, there are virtually no "emulators" for optical systems. As the concept of operations for optical links becomes clearer and link designers are able to better articulate their needs and better describe their hardware, it is hoped that the wall between channel modelers and hardware designers will begin to erode.

B. Optical Technologies

The resurgence in interest for UW optical links has been largely driven in the past decade by a rapidly maturing technology base at blue/green wavelengths. LEDs and laser diodes (LDs) are a popular choice among hardware designers due to their size, cost, and ease of use. The output powers, beam quality, divergence, and spectral purity of LEDs and LDs can vary depending on both the type of source and the exact wavelength desired. Emerging trends in this area include the commercialization of direct-to-green LDs (as opposed to frequency doubled from the IR) and efficiency improvements of high-power LEDs capable of high-speed modulation (>1 Mb/s).

Neither LEDs nor LDs can currently provide the power densities of solid-state lasers, but solid-state lasers are typically more difficult to modulate at high frequencies. Fiber lasers (or fiber amplified lasers) stand poised to fill this gap. Fiber-based technologies have the potential to provide high output powers over a range of blue/green wavelengths in addition to exhibiting flexibility and agility with regard to a modulation scheme.

On the receiver end, large-aperture, high-efficiency, high-gain, and high-speed photodetectors are desirable. Obviously, achieving all of these in a single device is difficult. Recently, however, high-speed (>1 GHz) photomultiplier tubes (PMTs), avalanche photodiodes (APDs), or hybrid designs with high gain ($>10^3$) and large apertures (>25 mm) have become commercially available from companies such as Hamamatsu Photonics and Photonis. Additionally, improvements in optical filter technology (optical bandwidth, field of view, transmission, etc.) are expected to have significant impact on link performance, particularly in shallow environments with large contributions from solar ambient light.

Finally, there has been little work to date regarding active acquisition, pointing, and tracking for underwater optical platforms. Many of the successful commercially developed optical modems use arrays of LEDs or LDs to create a broad beam, and hence forgo any active pointing and tracking. The downside to these systems is that they typically perform best in clear waters due to the lower power density of the diffuse beam. While it is expected that there is much to be learned from free-space optics, the requirements and constraints for underwater optical links remain ill-posed. As optical technologies make their way into more applications, it is expected that there will be more research in this area.

V. CONFERENCE PAPERS IN THIS SPECIAL ISSUE

The conference aimed to explore current issues around characterizing and understanding the physical communication channel, both acoustically and optically, as well as what it will take to move from point-to-point communications to *ad hoc* networks, with good choices of protocols for MAC, link layer management, routing, etc. While the former domain of interest is more mature and encapsulates the most complex and diverse physics compared to in-air networked communications, the latter is only at the very beginning stages of development. It is interesting to explore the extent to which UW networks may inherit useful technologies from its vastly more developed older brother, in-air WiFi and similar standards.

A. Physical Acoustic Channel Properties

An excellent and comprehensive overview of the physics of the ocean channel is provided by van Walree [1]. This paper also includes a wide variety of measurements of the channel impulse response characterized in terms of time-delay and Doppler spread. Those results clearly show the complexity of the ocean channel; in some cases, there is no resolvable multipath; the overall multipath spread can vary from a few milliseconds to seconds (in deep-water, long-range propagation); and a given channel may present a mixture of stable and unstable paths depending on boundary interactions and other effects.

Bubbles, injected by wave breaking events at the sea surface, can play a critical role in the ocean waveguide. Deane *et al.* [2] provide an excellent introduction to current knowledge about the bubble physics and their effect on the surface reflected energy. The bubbles scatter the sound and can fully shield the surface. However, very small concentrations of bubbles also lower the sound speed of the ocean enormously. The resulting low-speed zone is refractively "attractive" to sound rays and can enhance the scattering due to the ocean surface waves as discussed in [3]. Dol *et al.* discuss the importance of bubbles and how to incorporate these effects into a full channel simulator for acoustic modems.

Many of the papers in this issue either develop or rely on sophisticated channel models that incorporate different propagation physics. Peterson and Porter [4] develop an approach to incorporating the stretching and compression of waves (Doppler effects) due to platform motion and ocean surface waves. Typically, such models consider propagation in a range–depth plane, ignoring scattering out of the plane. Karasalo *et al.* [5] introduce a new simulation tool that includes 3-D effects due to a rough bottom and study the effects on a representative high-speed modem. The limited frequency range that is practical for acoustic communications in water drives system designers to use very wideband signals to maximize the information transfer rate, but this incurs complications as the propagation physics can vary significantly over the band, as discussed by van Walree and Otnes [6].

Many of the important features of the acoustic channel can be expressed by a single plot showing spread in the time domain (capturing the multipath structure) and frequency domain (capturing Doppler spread) of a received signal. This 2-D plot, known as the channel scattering function, captures a snapshot of the channel that is useful for performance prediction at the physical layer. An interesting alternative to using acoustic models to predict physical communication performance is to directly measure such scattering functions at sea, together with their temporal evolution in many different ocean environments. Otnes *et al.* [7] show how such sampled scattering functions can then be used in a "replay" mode in a channel simulator called "Mime" to simulate how the channel generates "Dopplerized" echoes at the receiver. In this fashion, one can simulate modem performance at the physical layer based directly on channel measurements for a library of ocean environments. This technique in some way bridges the gap between purely model-based simulation (which may not include all the important physics or may make assumptions that are not well observed in the real-life application under consideration) and at-sea testing (which is both expensive and limited in the number of environments that can be tested). At the link and higher layers, protocols can be tested using replays of actual link traces over the network, either directly measured or generated by replaying the physical-layer realizations.

Rather than rely directly on measurements of the channel scattering function, one may also construct statistical models that provide parametric characterizations of the statistics that are observed in typical channels. This approach is developed extensively in [8], where Qarabaqi and Stojanovic offer the potential for vastly more rapid simulations. This is particularly important in network level modeling where one may wish to understand effects involving millions of packets.

Ultimately, while simulations are much less expensive than at-sea experiments and can be more easily manipulated, the results are only as valuable as their validation against real-world performance gives confidence in them. Thus, one sees throughout this issue many examples of estimates of the at-sea channel impulse response or scattering function for comparison with model predictions. In principle, this is just a matter of deconvolving the received signal with the (known) probe signal, typically by some form of matched-filter processing. However, the ocean acoustic channel is often close to being overspread, meaning that while the multipath spread requires long probe signals to capture and resolve the impulse response, the channel coherence time may be of the same order, so that propagation conditions change significantly during the duration of the probe signal. Ultimately, the accurate estimation of the scattering function is an interesting problem in itself. This topic was discussed in the workshop and is also addressed in [9], where a modified version of orthogonal matching pursuit is explored as a means to track the (typically) sparse pattern of echoes.

B. Physical Optic Channel Properties

As discussed above, optical communications are emerging as an important alternative to UW acoustic communications at short ranges, offering higher bandwidths, increased stealth, and lower power consumption. The blue/green band emerges as a favorite based on the optical absorption properties of sea water, with both LEDs and lasers now showing considerable promise, especially with recent advances bringing down the production cost and size, while increasing power and efficiency of these devices. Cochenour *et al.* [10] place these technologies in context with acoustic systems.

Doniec *et al.* [11] present a generic model of optical signal strength in a UW communication link that combines the characterization of source, detector, amplifier, and detector circuitry with a simple extinction model of the water channel. The end-to-end model is intended to provide insights into optimization approaches for underwater optical modems.

As the optical UW communication technologies mature, it can be expected that they will be increasingly integrated with acoustic modems as physical-layer alternatives within a software-defined modem architecture that is able to adaptively switch between physical layers, depending on which best suits the application needs and environmental constraints.

C. Higher Layer Considerations Supporting Ad Hoc Networking

From consideration of the physical channel properties, most relevant to early communication systems with just two modems talking to each other, we now find that we must move to considering higher level protocols to manage *ad hoc* networks if we are to support the needs of UW-distributed autonomous networks. This opens up a new area of UW network simulation and the role of the associated protocols in the overall system performance. Network simulators built for radio wireless networks may be useful as a starting point. However, they require, at the very least, extensive upgrading to integrate the complex physical-layer properties to be realistic. It is correspondingly difficult to successfully field a full network for at-sea validation. Caiti *et al.* [12] report one of the first examples of successful deployment of a mobile underwater sensor network integrated within a wide area network, including above water and UW sensors, under the European Union (EU) Undersea Acoustic Network (UAN) project. In this case, a simple characterization based on the SNR at the receiver was adequate to characterize the overall system. Tomasi *et al.* [13] study a proposed network protocol called source routing for underwater networks (SUN) and compares its performance to the simple baseline routing protocol of flooding. While their simulations suggest that SUN generally outperforms flooding, limited and preliminary results from at-sea testing suggest the opposite may be true. It seems likely that each has performance advantages in different situations, reinforcing the emerging picture that there is no "one-size-fits-all" solution to any of these problems, and that simulations rarely tell the complete story.

Chitre *et al.* [14] point out that network performance estimates require accurate packet error inputs. They propose a statistical scheme based on measured data from at-sea tests as an effective simulation framework, capturing a multitimescale bit error statistical environment to give link properties in close agreement with observation. This ties in to the idea, mentioned earlier, that snapshots of channel properties, as a statistical sample, can be useful for performance simulation, provided they are statistically representative.

At the other end of maximizing bandwidth is to optimize the use of the available information bandwidth. This is a problem familiar from the Internet, where compression has long been used to reduce the number of required bits to transfer a message. In UW networks, assets are often mobile and navigation is nontrivial, a Global Positioning System (GPS) being unavailable below the sea surface. It is natural, then, to integrate communications with ranging and position fixing to provide important updates to the network, enabling efficient control and routing of assets. Schneider and Schmidt [15] look at smart ways of compressing regular navigational reports using an entropy encoder to track the innovations of a state model of vehicle position, and they show how considerable savings ($\sim$90%) can be made with such adaptive compression techniques.

VI. WORKSHOP OUTCOMES

The UComms Conference set the stage on the state of the art in UW communications and prepared the way for the workshop that followed, addressing questions of what and how channels should be characterized, measured, and reported. The workshop provided a forum within which structured yet open discussions about these issues were conducted, with the view to moving toward a consensus on how to standardize channels and models for the purposes of performance estimation and characterization. The collected notes from this workshop form the body of the following sections.

A. Optical Channel Measurements and Link Performance Reporting

Improvements in component hardware have made physical-layer characterization and commercial development a reality in recent years. However, there remains a great deal of uncertainty regarding the limits of optical links in certain ocean environments, as well as the actual performance of commercial transceivers. As such, the following recommendations are suggested to improve the reporting of results in journals, conference papers, and marketing materials.

- As a minimum, the attenuation coefficient and measurement range should be reported. Commercial transmissometers which measure the total attenuation coefficient (absorption plus scattering) are readily available and reasonably priced (cf., WetLabs at www.wetlabs.com).
- At a slightly higher cost, similar instruments are available that measure the relative amounts of absorption and scattering for a given total attenuation. This is important as the amount of spatial and temporal dispersion observed in the physical layer is a direct result of the relative amounts of absorption and scattering, both of which can vary significantly depending on the environment.
- Beyond this, the scattering phase function (which describes the probability of single scattering events over all angles) is also highly desirable, especially in coastal and harbor scenarios, as it has direct impact on both spatial and temporal dispersion. It is also a key piece of information required by theoretical models. Direct measurements of the scattering phase function are often difficult, as there are few commercially available instruments (cf., Sequoia Scientific at www.sequoiasci.com). These sensitive instruments also tend to be more expensive than beam transmissometers.
- For laboratory studies, artificial scattering agents such as ISO standard Arizona test dusts, magnesium hydroxide, aluminum hydroxide, or commercial antacids such as Maalox, are all excellent choices for simulating particulate scattering in the sea. Furthermore, the scattering phase functions of these agents can often be found in the literature if a direct measurement is not feasible. Note that while industrial agents have similar scattering phase functions as real ocean particulates, they tend to have nearly zero absorption (i.e., a different complex index of refraction). In this case, absorbing Nigrosin dye may also be used to recreate the correct relative amounts of absorption and scattering as found in the ocean.
- Even though first introduced some 50 years ago, Petzold's 1972 work [16] that characterized the optical properties of the channel in terms of absorption, scattering, and scattering phase function remains one of the most widely cited works in this area to date. When deciding what locations to test modem performance in, recreate in the laboratory, or model via simulation, the Petzold water types remain an excellent resource.

- In addition to the environmental parameters, system variables such as Tx/Rx alignment, receiver field of view, transmitter divergence, etc., are all essential factors in understanding the relative characteristics of the system under consideration. These should be clearly reported.

While all of the above suggestions are essential for channel characterization, designers and manufacturers are encouraged to provide similar information regarding their systems such that comparisons across water types or between different systems can more readily be made or simulations more accurately performed. A more useful metric of performance is the expected performance in relevant water types (clear, coastal, turbid, etc.) rather than the ability of the hardware components "in air." While hardware technologies now exist that could provide gigahertz data rates, the performance of such a system, were it to be developed, would vary significantly with water type.

B. *Optical Coding and Modulation Schemes*

As better physical-layer measurements and propagation models become available, it should be possible to determine an upper limit on the capacity of underwater optical links from information theory. A better understanding of the physical layer should also result in the emergence of optimized modulation and coding schemes for a given environment. For example, in photon-limited scenarios that exhibit little temporal dispersion, ON–OFF keying (OOK) or some other flavor of intensity modulation [phase-shift keying (PSK), frequency-shift keying (FSK), etc.] may be best. In turbid environments, it may be necessary to maximize the peak power of the transmit signal to combat high attenuation, or to compete with a large solar ambient component. In this case, pulse-position modulation (PPM) or a similar technique may be better. Each scenario is likely to have different sources of error, and hence, a different optimized choice of error-control coding.

As the issues of spatial and temporal dispersion become better understood, the expertise of researchers in communication theory and signal processing should be brought to bear on issues that will be unique to the optical channel.

C. *Acoustic Channel Physics*

The physical processes and environmental characteristics that influence acoustic communication system performance are many and varied. For a given frequency range and environment, some play greater roles than others, as we attempt to describe in Section VI-F. For each case, we need to integrate the various physical processes that most affect acoustic communication and respect the spatial and temporal scales on which they work. Prime physical mechanism candidates include:

- surface waves (multipath + random focusing + Doppler dilations);
- near-surface bubbles (creating a rich diversity of slow and fast fluctuation effects);
- precipitation (changes sound-speed profile near the surface, flattens waves, and generates noise);
- bottom interaction (multipath + multiple sub-bottom refractions + shear conversion);
- internal waves, bores, tides, plumes, intrusions (scattering);
- biologics (scattering from fish bladders and zooplankton + added "noise");
- anthropogenic activities (shipping, fishing, drilling, surveying, etc., adds noise);
- absorption (strongly frequency-dependent, differential wideband impact).

Added to which we may add the impact of self-noise from supporting platform(s), both hydrodynamic and electronic. These physical mechanisms all have different temporal and spatial scales, resulting in nonlinear temporal and frequency variations in phase, amplitude, temporal, and Doppler spreading.

To choose which physical mechanisms to attempt to include, and the level of complexity required to capture the impact, one approach is to segment these mechanisms based on the nature of their impact and their spatial and temporal coherence scales. If the type of impact and their inherent scales map into the domain of interest (given the ranges, frequency, etc., of the acoustic communication system under consideration), then we next need to establish bounds on the degree to which that mechanism can impact the channel impulse response. Note that this, too, depends on the coding scheme. An impact on phase may not be of interest to an energy-based signaling system, but would certainly affect a phase-coherent coding scheme.

We begin with a baseline assumption of a fixed channel, then progressively add variability due to the various processes on the appropriate temporal and spatial scales in ranked order, until we reach a characterization deemed sufficiently realistic for our purposes.

D. *Acoustic Channel Measurements and Best Practices*

Measurements that give information and insight into the spatial and temporal structure of the impulse response of the underwater acoustic communication channel and their relationship to relevant physical processes are important for continued advances in the field. Such information supports a wide range of research and development in both creating new generations of underwater acoustic communication systems and understanding their performance characteristics. In addition, the availability of time series of "measured" channel impulse responses is potentially very useful to the academic, government, and commercial development communities, allowing replay to be used to exercise multiple candidate protocols and modulation schemes on a fair comparison basis. The limitation of replay is that, to be useful, a large amount of at-sea data is required (which incurs a considerable cost). They must be well documented with metadata and accessed via a standard interface. Furthermore, the power of replay can only be realized if suitable data sets exist for a variety of environments and network topologies.

The gathering of channel measurements should lead to quantitative descriptions of the channel (e.g., "realizations" of the time-varying impulse response) that are simple to use, although the descriptive channel statistics may not themselves be simple. Users should be able to make use of the data without expertise in the physics of underwater acoustic propagation or the environments in which the data were collected. Although transmit and receive hardware is inevitably part of the data collection process, care should be taken to minimize the adverse impact of hardware characteristics on the channel descriptions.

A number of different types of channel descriptions are useful for different applications. The time-varying channel impulse response sampled at greater than the Nyquist rate of the channel fluctuations (e.g., for a channel with a Doppler spread of 1 Hz, the channel impulse response should be measured at least twice a second) and the input delay-Doppler spread function (cf., [17]) are both good descriptors of the channel realizations. Useful statistical characteristics include the channel scattering function [18] and the spatial and temporal correlation of "channel quality" on relevant scales (packet length, node-to-node distances and travel time, network topology). The correlation between ambient noise and the channel impulse response is useful at both the physical and higher network layers. Both realizations and spatial/temporal statistics (on spatial scales of receive array sizes and temporal scales of the data symbol duration) of the ambient noise field are also useful. Finally, statistics of "collisions" at a receiver as a function of the environment, network topology, and transmission schedule would be useful at the network level.

Parametric representations of the channel can also be useful for some applications. For example, a set of parameters could start with the number of significant paths. Then, for each path, the nominal delay and amplitude, the angle of arrival at the receiver (if using an array and assuming that there is no refraction across the aperture of the array), delay profile of the micropath structure, the Rice factor [17], the Doppler power spectrum, the intrapath correlation of the micropath structure, and the time-varying delay due to platform or surface motion would provide a fairly complete representation and would allow channel simulations to be generated or an analysis of the expected performance in the environment.

As far as practical, the influence of the data transmission and acquisition hardware on the realizations and statistics should be minimized. The transmit and receive hardware should be time invariant and linear and the hydrophones and transducers should be omnidirectional. The combined hardware transfer functions, including that of the transducers and hydrophones and analog front ends, should be reported in addition to the transmitted signal spectrum. Specifically, the receive hardware and processing chain should be calibrated and reported in a manner that allows the user to map the units of the data to absolute referenced signal levels in the water. The source level in the water (e.g., re 1 Pascal @ 1 meter) and its uncertainty should be reported. Channel impulse responses and related realizations of the channel conditions should be calibrated and reported, for example, with path-specific signal attenuation.

The nature of the transmit signal used to probe the channel is also very important. Short windowed sinusoids, chirped (e.g., linear frequency modulated), and phase-coded signals such as continuous repetitions of m-sequences or single (pulse like) transmissions of Barker coded signals are all useful in different scenarios. In general, the pulse length (for pulsed systems) should be as short as possible consistent with achieving adequate postprocessing SNR at the receiver and adequate Doppler resolution. Longer pulses run the risk of exceeding the channel temporal coherence scale. The pulse repetition rate for such systems should ideally be at least the Nyquist rate of the channel fluctuations, although this may result in some aliasing of the measured channel impulse response in delay with overspread channels.

When the channel is overspread, there are several methods of addressing the challenge. For pulsed systems, the aliasing in delay may be mitigated to a certain extent by alternating between different pulse repetition intervals to differentiate between aliased and unaliased arrivals. The transmission schedule may also alternate between different signals with low cross-correlation properties. Finally, in overspread channels, the use of long sequences of phase-shift-keyed signals such as pseudorandom binary sequences or repetitions of m-sequences, processing using least squares channel estimators with differing averaging intervals, can give the user postmeasurement flexibility to adjust to varying rates of channel fluctuations. Finally, when dealing with environments where path-length fluctuations from either platform motion or from scattering off of the sea surface are present, care must be taken to ensure that the processing does not adversely affect the results. If we let v be the rate of the path length fluctuation, c the speed of sound, T the pulse length or averaging time of the estimator, and B the signal bandwidth, then a good rule of thumb is that adverse effects due to signal bandwidth can be avoided if $T^{*}B \ll c/v$. The "$\ll$" is often taken to be a factor of 8, giving the constraint $T^{*}B < (1/8)\ c/v$.

When reporting estimates of channel realizations, some figure of merit of the estimates should be reported. For channel estimators based upon least squares or similar techniques, a signal estimation residual (i.e., the variance of the difference between the received signal and the prediction of the received signal given the transmitted signal and the channel estimate) and its comparison to the level of the received signal and ambient noise is useful. It is not immediately clear what similar measure would be a useful figure of merit for correlation-based estimators. However, in principle, it should also be possible to compute a signal-estimation residual for such estimators.

A few topics regarding experimental design are useful to note. While there is often pressure to get as much data as possible, including allowing simultaneous transmission of different signals that are in some sense orthogonal (e.g., in different frequency bands or are based upon codes with low cross-correlation properties), in practice, this often results in interference between the different signals, and this contaminates the resulting channel descriptors. For work at the higher network layers, the correlation between performance (channel quality) along different links is useful. Experiments should be constructed to allow for the measurement of the results of small-scale fluctuations that are independent from link to link and large-scale effects that introduce spatial dependency between link performance. Time synchronization should be maintained throughout the experiment to allow for meaningful correlation measurements between measurements on different links. Measurements of received signals resulting from the transmission of channel probes and measurements of ambient noise should be made separately but in close temporal proximity to one another. Care should be taken that other sources of interference such as a ship's depth sounder or mechanical noise generated by mooring hardware do not contaminate either channel probe or ambient noise measurements.

In addition to the acoustic data, the reporting of sufficient environmental data is needed to maximize the potential of experimental results. While different measurements are important in different environments, a few measurements are useful in almost all environments. These should capture the primary physical mechanisms in the volume of propagation and the surfaces with which the significant acoustic eigenpaths interact. The volume properties are described by the sound-speed profile on temporal and spatial scales corresponding to environmental fluctuation coherence scales. Having said this, measurements at intervals O(100) m along a transmission path are desirable but often impractical, while a vertical resolution O(1) m in sound-speed measurements is more achievable. Regarding the upper surface, for open-water environments (e.g., not ice covered), the directional surface wave spectrum with wind speed and direction are also very useful. The sea-surface scattering characteristics can be vastly different (mainly as a result of injected bubbles) depending on whether wave breaking is common, in turn largely determined by wind speed and fetch. For this reason, video footage of the sea-surface conditions can also be very useful. With regard to the seabed, large-scale acoustic impedance, bottom type, and roughness are important, relating to absorption and scattering losses and refraction in the bottom.

Finally, the experimental topology (at least the source and receiver ranges and depths) as well as platform motion should be recorded and reported, together with directionality of sources and receivers, descriptions of arrays, if used, and any other factors that appear to have had an impact on the acoustic performance of the equipment.

E. Acoustic Channel Modeling and Simulation

In simulation and emulation, the propagation channel must be modeled in some way to mimic the actual at-sea propagation environment. There are many acoustic propagation models, developed over decades of effort, and each brings its strengths and weaknesses to the enterprise. For acoustic communications, we are usually interested in higher frequencies and shorter ranges than those for the sonars and geoacoustic sensing systems that many acoustic models were developed for. It is, therefore, of value to consider which of the available acoustic models best fit our needs for acoustic communication, at the physical level.

Largely because of the high-frequency and broadband nature of typical acoustic communication applications, ray-tracing methods have usually been the method of choice. Full 3-D models are reaching a state of maturity allowing effects such as surface scatter. The early ray models typically had problems near focal zones (caustics) and shadow zones. However, in recent years, beam-tracing methods have become standard in which a beam is constructed around each central ray. The resulting fields smooth out the caustics and shadow zones and typically yield more accurate results. However, ray- and beam-tracing methods are intrinsically based on a high-frequency approximation. In the end, one may say that such methods are usually sufficiently accurate; however, in some applications or scenarios, more exact methods are preferable.

Unfortunately, there are few alternatives again because of the high-frequency and broadband nature of waveforms that are typically used in acoustic communications. Besides ray/beam methods, the usual three other modeling methods considered are: 1) normal modes; 2) wave number integration; and 3) parabolic equation models. These are so-called “full wave” methods that do not invoke a high-frequency approximation and treat diffractive effects essentially exactly. (The word “diffractive” here means essentially anything not represented by simple ray theory.) The runtime of all of these methods is generally orders of magnitude higher. However, they certainly should not be ruled out and with today’s computers can be used to do high-frequency, broadband calculations. Among these full-wave approaches, the parabolic equation models are usually the best choice for range-dependent waveguides; normal mode and wave number integration methods are based on a range-independent assumption but are extendable with some awkwardness to range-dependent problems as a sequence of locally range-independent problems.

There is an emerging literature on boundary integral methods (which are essentially the same as virtual source methods) as well as full finite-element solutions. However, because of the runtimes, these are more useful for benchmark testing than production runs.

F. Acoustic Canonical Channels

It is often very helpful if a small number of canonical problems can be defined that span a significant diversity in application environments while presenting some “standard” problems that can be used for intercomparison of candidate protocols. To this end, we would like to identify some different classes of channels that are distinct from each other in terms of the driving physical processes, while each is important for some class of applications. We here propose an outline for a set of channels, along with the most relevant channel physics or environmental characteristics that should be measured in each.

1) Inshore: Local geography and tidal cycles are important. Often limited they fetch over the water, reducing wave building and breaking. Strong temperature and salinity fronts can significantly alter propagation. Vertical and horizontal sampling of the sound-speed profile, bottom bathymetry, and acoustic properties, together with currents, should be measured on scales appropriate for the spatial and temporal coherence of the inshore physical oceanographic processes.

2) Coastal: Coastal areas are characterized by surface and bottom properties dominating the propagation properties with possibly strong horizontal dependence. Wind and wave conditions, bottom bathymetric and acoustic properties, in addition to the sound-speed profile (often vertically mixed but sometimes with significant horizontal variation) are of primary importance.

3) Continental Shelf/Littoral: These areas are distinguished from the coastal channel case by an increased influence of volume processes and vertical structure, usually deeper, with internal wave propagation and other volume effects that can be an important influence in addition to sea surface and bottom conditions. Wind and wave conditions, bottom bathymetric and acoustic properties, and the sound-speed profile on a vertical and horizontal grid are required to capture internal waves and fronts.

For both coastal and continental shelf/littoral waters, the sampling density of the sound-speed profile and bottom conditions depends on the scales of local variability.

4) Deep Ocean: Such areas are deep enough for a midwater sound channel, so that surface and bottom conditions are less important. The sound-speed profile is of primary importance, with internal waves playing a critical role over longer ranges. Very long-range propagation is possible at lower frequencies. The sound-speed profile and absorption must be acquired on a vertical and horizontal grid (to capture internal waves and fronts) with, to a lesser extent, wind and wave conditions and bottom properties. Sampling density in time and space should be commensurate with internal wave activity.

5) Polar Regions: The possibility of ice cover as well as a surface duct and deeper midwater duct give the polar regions unique acoustic characteristics. The sound-speed profile as well as surface conditions (either ice covered or open) are important. If ice covered, the age and thickness of the ice are very relevant and should be measured if possible.

VII. Conclusion

The UComms Conference and Workshop brought together a select representation of many leading researchers in UW communications, with (for the first time) an inclusive approach to integrating optical and RF communications. While no RF papers were presented, there was significant input from the optical contingent, ably supported by an excellent summary that was provided to the participants by Brandon Cochenour that has allowed us to greatly enrich the optics component of this work. Good progress was made in identifying the essential physics governing the UW communication channel, both for acoustics and optics, while the tight integration of the environment and application, leading to very different solutions for different scenarios, became very clear. It is very clear that UW modems of the future will need to be adaptive and hybrid, much more intelligent, and with a much higher level of cross-layer linkages than at present. The beginnings of a structured experimental and reporting approach were defined, together with the exciting potential of intermediate (between simulation and at-sea testing) replay emulations. We look forward to seeing the community continue to knit together to align interests and methods of performance estimation so that we may see an intelligent consensus emerge that will enable standards to be established for UW network communications. It was the overwhelming opinion of the participants that this process would be valuable to repeat at regular intervals, approximately every two years, and so we look forward, provisionally, to the next meeting in 2014.

Acknowledgment

The editors would like to thank B. Cochenour who provided an excellent summary of the optical communication work for this editorial. This work was supported in part by the U.S. Office of Naval Research (ONR) under Grants N62909-12-1-1077 and N62909-12-1-1104. The conference and workshop was supported by the U.S. ONR (Ocean Acoustics, Optical Communications, and ONR Global), NATO STO CMRE, EvoLogics, Kongsberg, and Teledyne Benthos/Webb Research.

John R. Potter, *Associate Editor*
NATO STO Centre for Maritime Research and Experimentation
La Spezia, 19126 Italy
potter@cmre.nato.int

Michael B. Porter, *Associate Editor*
Heat, Light, and Sound Research, Inc.
La Jolla, CA 92037 USA
mikeporter@hlsresearch.com

James C. Preisig, *Associate Editor*
Woods Hole Oceanographic Institution
Woods Hole, MA 02543 USA
jpreisig@whoi.edu

References

[1] P. A. van Walree, "Propagation and scattering effects in underwater acoustic communication channels," *IEEE J. Ocean. Eng.*, vol. 38, no. 4, Oct. 2013, DOI: 10.1109/JOE.2013.2278913.

[2] G. B. Deane, J. C. Preisig, and A. C. Lavery, "The suspension of large bubbles near the sea surface by turbulence and their role in absorbing forward-scattered sound," *IEEE J. Ocean. Eng.*, vol. 38, no. 4, Oct. 2013, DOI: 10.1109/JOE.2013.2257573.

[3] H. S. Dol, M. E. G. D. Colin, M. A. Ainslie, P. A. van Walree, and J. Janmaat, "Simulation of an underwater acoustic communication channel characterized by wind-generated surface waves and bubbles," *IEEE J. Ocean. Eng.*, vol. 38, no. 4, Oct. 2013, DOI: 10.1109/JOE.2013.2278931.

[4] J. C. Peterson and M. B. Porter, "Ray/beam tracing for modeling the effects of ocean and platform dynamics," *IEEE J. Ocean. Eng.*, vol. 38, no. 4, Oct. 2013, DOI: 10.1109/JOE.2013.2278914.

[5] I. Karasalo, T. Öberg, B. Nilsson, and S. Ivansson, "A single-carrier turbo-coded system for underwater communications," *IEEE J. Ocean. Eng.*, vol. 38, no. 4, Oct. 2013, DOI: 10.1109/JOE.2013.2278892.

[6] P. A. van Walree and R. Otnes, "Ultrawideband underwater acoustic communication channels," *IEEE J. Ocean. Eng.*, vol. 38, no. 4, Oct. 2013, DOI: 10.1109/JOE.2013.2253391.

[7] R. Otnes, P. A. van Walree, and T. Jenserud, "Validation of replay-based underwater acoustic communication channel simulation," *IEEE J. Ocean. Eng.*, vol. 38, no. 4, Oct. 2013, DOI: 10.1109/JOE.2013.2262743.

[8] P. Qarabaqi and M. Stojanovic, "Statistical characterization and computationally efficient modeling of a class of underwater acoustic communication channels," *IEEE J. Ocean. Eng.*, vol. 38, no. 4, Oct. 2013, DOI: 10.1109/JOE.2013.2278787.

[9] S.-H. Byun, W. Seong, and S.-M. Kim, "Sparse underwater acoustic channel parameter estimation using a wideband receiver array," *IEEE J. Ocean. Eng.*, vol. 38, no. 4, Oct. 2013, DOI: 10.1109/JOE.2013.2258222.

[10] B. Cochenour, L. Mullen, and J. Muth, "Temporal response of the underwater optical channel for high-bandwidth wireless laser communications," *IEEE J. Ocean. Eng.*, vol. 38, no. 4, Oct. 2013, DOI: 10.1109/JOE.2013.2255811.

[11] M. Doniec, M. Angermann, and D. Rus, "An end-to-end signal strength model for underwater optical communications," *IEEE J. Ocean. Eng.*, vol. 38, no. 4, Oct. 2013, DOI: 10.1109/JOE.2013.2278932.

[12] A. Caiti, K. Grythe, J. M. Hovem, S. M. Jesus, A. Lie, A. Munafó, T. A. Reinen, A. Silva, and F. Zabel, "Linking acoustic communications and network performance: Integration and experimentation of an underwater acoustic network," *IEEE J. Ocean. Eng.*, vol. 38, no. 4, Oct. 2013, DOI: 10.1109/JOE.2013.2279472.

[13] B. Tomasi, G. Toso, P. Casari, and M. Zorzi, "Impact of time-varying underwater acoustic channels on the performance of routing protocols," *IEEE J. Ocean. Eng.*, vol. 38, no. 4, Oct. 2013, DOI: 10.1109/JOE.2013.2279735.

[14] M. Chitre, K. Pelekanakis, and M. Legg, "Statistical bit error trace modeling of acoustic communication links using decision feedback equalization," *IEEE J. Ocean. Eng.*, vol. 38, no. 4, Oct. 2013, DOI: 10.1109/JOE.2013.2257571.

[15] T. Schneider and H. Schmidt, "A state observation technique for highly compressed source coding of autonomous underwater vehicle position," *IEEE J. Ocean. Eng.*, vol. 38, no. 4, Oct. 2013, DOI: 10.1109/JOE.2013.2268292.

[16] T. J. Petzold, "Volume scattering functions for selected ocean waters," Visibility Laboratory, Scripps Institution of Oceanography, San Diego, CA, USA, 1972.

[17] P. A. Bello, "Characterization of randomly time-variant linear channels," *IEEE Trans. Commun. Syst.*, vol. CS-11, no. 4, pp. 360–393, Dec. 1963.

[18] S. O. Rice, "Mathematical analysis of random noise," *Bell Syst. Tech. J.*, vol. 24, pp. 46–156, 1945.

John R. Potter (M'95–SM'02) received a joint honors degree in mathematics and physics from Bristol University, Bristol, U.K., in 1979 and the Ph.D. degree in glaciology and oceanography from the Council of National Academic Awards in association with the University of Cambridge, Cambridge, U.K., in 1985.

He worked for the British Antarctic Survey from 1980 to 1985, spending four research summers in the Antarctic. From 1986 to 1991, he was a Senior Scientist for NATO SACLANT Undersea Research Centre (SACLANTCEN), La Spezia, Italy, working on high-frequency acoustics, followed by a term as a Research Project Scientist at Scripps Institution of Oceanography, San Diego, CA, USA, from 1991 to 1995. In 1996, he founded and then was Head of the Acoustic Research Laboratory (ARL) and an Associate Director of the Tropical Marine Science Institute, National University of Singapore (NUS), Singapore. He is currently the Project Leader for Communications and Networking at the NATO STO Centre for Maritime Research and Engineering, La Spezia, Italy.

Dr. Potter is a member of the Acoustical Society of America, an International Fellow of the Explorer's Club, a Master Scuba Diver Trainer with the Professional Association of Dive Instructors, and also an Associate Editor of the IEEE JOURNAL OF OCEANIC ENGINEERING. He was awarded the Polar Medal by Queen Elizabeth II, received the "Best Paper" Award in 1996 for an article in the *Scientific American*, and was the Principal Investigator for the team that won the Defence Technology Prize in Singapore in 2004.

Michael B. Porter (M'05–SM'13) received the B.S. degree in applied mathematics from the California Institute of Technology (Caltech), Pasadena, CA, USA, in 1979 and the Ph.D. degree in applied mathematics and engineering sciences from Northwestern University, Evanston, IL, USA, in 1984.

In 1983, he began working at the Naval Ocean Systems Center, San Diego, CA, USA, and, in 1985, as a Research Physicist at the Naval Research Laboratory, Washington, DC, USA. In 1987, he became a Senior Scientist for NATO/SACLANT, La Spezia, Italy. He was also a Professor of Mathematics at the New Jersey Institute of Technology, Newark, NJ, USA, and an Assistant Vice President and Chief Scientist at Science Applications International Corporation, San Diego, CA, USA. He is currently the President and CEO of Heat, Light, and Sound Research, Inc., La Jolla, CA, USA.

James C. Preisig (S'79–M'80–SM'07) received the B.S. degree in electrical engineering from the United States Coast Guard Academy, New London, CT, USA, in 1980, the S.M. and E.E. degrees in electrical engineering from the Massachusetts Institute of Technology (MIT), Cambridge, MA, USA, in 1988, and the Ph.D. degree in electrical and ocean engineering from the Massachusetts Institute of Technology/Woods Hole Oceanographic Institution (WHOI) Joint Program in Oceanography and Oceanographic Engineering, Cambridge, MA, USA, in 1992. He was a Postdoctoral Investigator at WHOI from 1992 to 1994 and a Visiting Assistant Professor at Northeastern University, Boston, MA, USA, from 1994 to 1997. Since July 1997, he has been on the scientific staff of the Department of Applied Ocean Physics and Engineering, WHOI, and is currently an Associate Scientist with tenure. His research interests are in the areas of adaptive signal processing, system identification, underwater acoustic propagation modeling, underwater acoustic communications, and numerical optimization.

Dr. Preisig is the recipient of the 1999 U.S. Office of Naval Research Ocean Acoustics Young Faculty Award and is a member of the Acoustical Society of America's Underwater Acoustics and Signal Processing Technical Committees. He served as a member of the IEEE Sensor Array and Multichannel Signal Processing Technical Committee from 1998 to 2004.