BUILDING UNDERWATER AD-HOC NETWORKS AND SENSOR NETWORKS FOR LARGE SCALE REAL-TIME AQUATIC APPLICATIONS

*Jiejun Kong, †Jun-hong Cui, ‡Dapeng Wu, *Mario Gerla
*Dept. of Computer Science †Dept. of Computer Science & Engineering ‡Dept. of Electrical & Computer Engineering
University of California, Los Angeles University of Connecticut, Storrs University of Florida, Gainesville
Los Angeles, CA 90095 Storrs, CT 06269 Gainesville, FL 32611

Abstract— *Large-scale Underwater Ad-hoc Networks (UANET) and Underwater Sensor Networks (UWSN) are novel networking paradigms to explore the uninhabited oceans. However, the characteristics of these new networks, such as huge propagation delay, floating node mobility, and limited acoustic link capacity, are significantly different from ground-based mobile ad-hoc networks (MANET) and wireless sensor networks (WSN). In this paper we adopt a top-down approach to explore the new research subject. We at first show a new practical application scenario that cannot be addressed by existing technology and hence demands the advent of the UANET and UWSN. Then along the layered protocol stack, we go down from the top application layer to the bottom physical layer. At each layer we show a set of new design challenges. We conclude that UANET and UWSN are challenges that must be answered by inter-disciplinary efforts of acoustic communication, signal processing and mobile acoustic network protocol design.*

I. INTRODUCTION

The still largely unexplored vastness of the ocean, covering about two-third of the surface of earth, has fascinated humans for as long as we have records for. First, the Earth is a water planet and its viability as a base for life is dependent on waters ability to dissolve substances and its ability to significantly transport those substances by both diffusion and advection. To assess the aqueous environment and its role and function, it is therefore necessary to identify the multiple inputs and reservoirs that interact. This calls for the need of *large-scale long-term* and *distributed* data acquisition network for *periodic oceanographic monitoring*. Second, for the past several centuries, the ocean has played an increasingly important role in transportation and military campaign. In emergent event investigations, e.g., for marine incidents (especially involved with chemical pollution and oil spill) and military demands (for example submarine attacks and submarine hunting), the state-of-the-art in communication technology has significantly surpassed the state-of-the-art of physical investigation in regard to effectiveness and efficiency. This calls for the need of building a *large-scale short-term* and *distributed* data acquisition network for *time-critical aquatic applications*.

A. Motivation

The large-scale aquatic applications demand us to build large-scale Underwater Ad-hoc Networks (UANET) and Underwater Sensor Networks (UWSN) to explore the uninhabited oceans. The difference between UANET and UWSN is due to *controlled mobility* and associated implementation cost. In a UANET, mobile nodes can be implemented by Autonomous Underwater Vehicles (AUV) [2] or Remotely Operated Vehicles (ROV), which are high-cost robots that can move under the water by following pre-programmed or autonomous motion patterns. However, the implementation cost of such self-propelling nodes are much higher than the one of any non-powered node. In the near future, we envision that these high-cost unmanned mobile robots will play important roles in underwater explorations, for example in aquatic military campaigns.

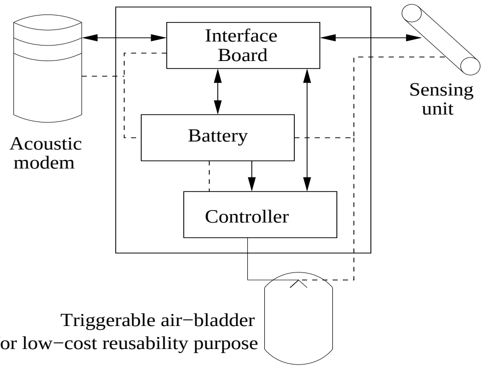

Fig. 1. **A low-cost underwater sensor node with sensing, acoustic communication and re-usability capabilities**

On the other hand, UWSN only incurs a fraction of implementation cost of UANET at the same network scale. All sensor nodes in a UWSN are of low-cost (without self-propelling power). Figure 1 shows a node configuration that is feasible given nowadays manufacturing capability. A large number of such non-powered low-cost sensor nodes can be thrown into the ocean to float at various depths for short-term monitoring, and can also be mounted on the seabed or chained to a number of buoys for long-term monitoring.

Per MILCOM's course, here we use a military application to demonstrate the need and usefulness of UANET and UWSN. (1) Nowadays satellite technology is capable of scanning the entire Earth surface in hours. Hence the data processing center can identify any surfaced submarine at the granularity of hours on the timeline. However, given the typical mobility speed of a submarine (e.g., 10-15 knots) and the delay in dispatching anti-submarine task forces, the submarine hunting task force has to locate the target in an area of hundreds of square nautical miles[1] due to the coarse granularity. (2) Modern submarines (e.g., Russian KILO class) are protected by the newly developed low-probability detection (LPD) technology. To reduce a submarine's acoustic signature, the hull of the submarine is covered with rubber anti-sonar protection tiles to reduce acoustic detection. The LPD technology hides the submarine's acoustic signature to thwart active SONAR probing and also reduces the intra-submarine noise to foil passive SONAR listening. The submarine's noise level is comparable to ocean's background noise, thus legible acoustic signature may only be collected within a very short distance from the submarine. (3) In addition, modern submarines (e.g., the same KILO class) are capable of launching anti-aircraft missiles under the water surface. This poses severe threats to nearby manned platforms.

Using unmanned large scale UANET and UWSN is free of any of the trouble described above. A number of underwater robots and a large amount of underwater sensor nodes can be air-dropped to the venue. An area of hundreds of square nautical miles may need thousands of sensor units. At real time, each sensor node monitors local underwater activities and reports sensed data via multi-hop acoustic routes to a distant command center or to nearby unmanned robots. The probability that the target submarine can escape the coordinated detection is negligible. Afterward, the networks can also be used as part of an underwater positioning and guide system to direct the anti-submarine weapons (e.g., torpedos) to find and destroy the detected target. Clearly, the advantages of the new UANET and UWSN paradigm are: (1) *Localized and coordinated* sensing and attacking is far more precise than the existing remote telemetry technology, e.g., those relying on directional frequency and ranging (DIFAR) sonobuoys or magnetic anomaly detection (MAD) equipment. (2) *Scalability* of UWSN ensures that a large area can be covered for time-critical applications. (3) Casualty ratio is expected to be zero if *unmanned* UANET and UWSN platforms are used. (4) Implementing reusable underwater nodes reduces the deployment and maintenance cost. Each underwater sensor unit can be bundled with an electronically controlled air bladder device. Once the network mission is accomplished, the command center issues commands to trigger all air-bladder devices and all sensor units float to surface to be recollected for next mission.

B. Our contributions

In this paper we adopt a top-down approach to explore the new research subject. We go down from the top application layer to the bottom physical layer according to the well-known network protocol stack. At each layer we show the new design challenges.

In underwater applications, it is critical to let every underwater node know its current position and the synchronized time with respect to other coordinating nodes. Unfortunately, as Global Positioning System (GPS) is unavailable under the water surface, scalable underwater networks must rely on *distributed GPS-free localization and time synchronization schemes* to let the underwater nodes know their positions and the synchronized time value.

Security threat is a cross layer issue that affects the entire protocol stack. A self-organizing ad hoc network needs more protections than cryptography. We have extensively studied *low-cost underwater denial-of-service attacks* [14]. The result is disastrous for multi-hop packet delivery, distributed localization, and time-synchronization.

At the transport layer, the huge acoustic signal propagation delay and low link capacity result in the well known large $bandwidth \times delay$ product problem. A reliable TCP-equivalent scheme has to address problems like *unusually large re-transmission window* and *unpredictable acoustic link loss*.

At the network layer, multi-hop packet delivery is aggravated by node mobility and heavy channel contention. *Proactive neighbor detection* and (network-wise or limited-scope) *flooding* are widely used in mobile ad hoc routing or diffusion schemes. Unfortunately, due to heavy channel contention caused by huge propagation delay in acoustic channels, flooding cannot be both robust (i.e., delivered to nearly all network members in the intended flooding area) and efficient (i.e., with low latency and transmission cost). In addition, the cost of proactive neighbor detection could be more expensive than flooding. With no proactive neighbor detection and with less flooding, it is an unanswered challenge to furnish multi-hop ad hoc packet delivery service in UANET and UWSN with node mobility requirement.

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[1] It is well-known that ocean's depth, at most 11km in Mariana Trench and averagely 4km, is not comparable to its length and width in size. Thus we will mostly discuss 2-D scenarios in regard to scalability issues.

At the link layer and physical layer, Aloha or slotted Aloha can be used for best-effort flows in a mobile network with random neighborhoods. For QoS assured flows, CDMA and other recently developed effective capacity techniques may be utilized. We elaborate on the effective capacity techniques in this paper.

At the end we conclude that building scalable UANET and UWSN is a challenge that must be answered by interdisciplinary efforts of acoustic communication, signal processing and mobile network design.

The paper is organized as follows. Section II presents the background and related work. In Section III we identify design challenges at each protocol stack layer in a top-down manner. Finally Section IV concludes the paper.

II. BACKGROUND

A. *Distinction from existing network paradigms*

First, the new UANET and UWSN paradigms are significantly different from any existing ground-based mobile ad hoc networks (MANET) and wireless sensor networks (WSN). (1) UANET and UWSN rely on low-frequency acoustic communications because RF radio does not propagate well due to underwater energy absorption. Unlike wireless links amongst land-based ad hoc nodes, each underwater acoustic link features large-latency and low-bandwidth. (2) Most ground sensor nodes in a WSN are typically stationary. But a large portion of UWSN sensor nodes, except some fixed nodes mounted on the sea floor, are with low or medium mobility (3-5 knots) due to environmental water current.

Second, UANET and UWSN are different from any existing small-scale Underwater Acoustic Network (UAN) [25] [23] [29]. UANET and UWSN are scalable networks, which rely on localized monitoring and coordinated networking amongst large amount of underwater nodes. In contrast, an existing UAN is a small-scale network relying on data acquisition strategies like remote telemetry or sequential local sensing. Therefore, neither ground-based networks nor UAN can meet a wide variety of underwater application demands to implement a localized, precise, and large-scale networking technology in a time-critical aquatic environment.

B. *Underwater acoustic (UW-A) channel assumption*

The communication characteristics of the UnderWater Acoustic (UW-A) channel are with following innate characteristics.

Narrow and low bandwidth The available bandwidth of the UW-A channel is limited and strongly depends on both range and frequency. UW-A channel's acoustic band is limited due to absorption with most acoustic systems operating below 30kHz. This fact has two significant impacts on underwater communication. First, the entire width of underwater acoustic frequency band is very narrow, so far the highest value reported is around 1MHz at the range of 60m radius [12]. The entire width of useful acoustic bands is only a small fraction of useful RF bandwidth. Therefore, underwater communications are to a large degree incompatible with spread spectrum technology and hence vulnerable to narrow-band jamming (partial-band jamming). Second, as surveyed in [13], research system or commercial system have highly variable link capacity and the attainable $range \times rate$ product can hardly exceed 40km-kbps. Long-range acoustic signal that operates over several tens of kilometers may have a capacity of only several tens of bits per second, while a short-range system operating over several tens of meters may have several tens of kilobits per second. Compared to radio or wired links, in both cases bit rates are significantly lower.

Very large propagation latency The signal propagation speed in the UW-A channel is only 1.5×10^3m/sec, which is five orders of magnitude lower than radio propagation speed 3×10^8m/sec in the air. Compared to acoustic propagation delay, electromagnetic propagation delay is negligible.

III. CHALLENGES IN COMMUNICATION, SIGNAL PROCESSING AND MOBILE NETWORK DESIGN

In this section we identify design challenges along the network protocol stack in a top-down manner . At each layer there are critical problems awaiting solutions.

A. *Distributed GPS-free localization and time synchronization services*

In underwater applications, it is critical to let every underwater node know its current position and the synchronized time with respect to other coordinating nodes. Nevertheless, the high-frequency radio wave used by Global Positioning System (GPS) is quickly absorbed by water, hence cannot propagate deeply under the water surface. So far to our best knowledge, a scalable and low-cost positioning and time-synchronization system like GPS is not yet available to underwater nodes. It is expected that underwater networks must rely on *distributed GPS-free localization and time synchronization schemes* to let the sensor nodes know their positions and the network clock value. In other words, before the network can use georouting schemes, it needs a multi-hop packet delivery service, which must be GPS-free. In a nutshell, in UANET and UWSN, network-wise localization and time-sync services strongly rely on multi-hop ad hoc packet delivery service. This is significantly different from ground-based MANET and WSN where GPS services are typically available, for example, directly from GPS interfaces in outdoor cases and at most 2 or 3 hops away in indoor cases.

The key problem in a network with node mobility is the range and direction measurement process itself. Unfortunately, we are left with only a few choices. The common GPS-free approach used in many ground sensor networks of measuring the Time-Difference-of-Arrival (TDoA) between an RF and an acoustic/ultrasound signal (e.g., the AhLoS project [24] and the Cricket project [22]) is no longer feasible as the commonly available RF signal fails under water. Receiver-signal-strength-index (RSSI) [3] is vulnerable to acoustic interferences like near-shore tide noise, near-surface ship noise, multi-path, and Doppler frequency spread. Angle-of-Arrival (AoA) systems [16] require directional transmission/reception devices, which would incur non-trivial extra cost.

Possible approaches may include acoustic-only Time-of-Arrival (ToA) approaches (e.g. measuring roundtrip time by actively bouncing the acoustic signal only) as well as deploying many surface-level radio anchor points (via GPS for instant position and time-sync info). Moreover, the underwater environment with motion of water, and variation in temperature and pressure also affects the speed of acoustic signal. Sophisticated signal processing will be needed to compensate for these sources of errors due to the water medium itself.

B. *Security, resilience and robustness*

One area which will definitely require revisiting (with respect to prior work in ad hoc and ground sensor networks) is vulnerability to security threats. This is a cross layer issue that affects the entire protocol stack. To realize a scalable ad hoc network, nodes must be low-cost and economically viable. They are limited in energy, computation, and communication capabilities. This makes many existing security mechanisms inadequate, and hence inspires new security research, such as efficient key management [8][7], authentication [21], data privacy and anonymity [18][6], that avoid expensive crypto-operations. Nevertheless, a self-organizing ad hoc network needs more protections than cryptography. Many security attacks continue to threaten ad hoc networks even when an ideal cryptosystem is efficiently protecting the network. A critical security issue is to defend against denial-of-service attack, which could be in the form of (1) depleting node's on-device resource (especially draining battery by incurring extra computation and communication) and (2) disrupting network collaboration (e.g., routing, data aggregation, localization, clock synchronization). Such attacks can disrupt or even disable ad hoc networks and sensor networks independent of cryptographic protections.

In [14], we study security attacks threatening collaborative underwater network services. We show that, no matter what kind of protocol stack we are building, UANET and UWSN can be disabled by low-cost underwater denial-of-service attacks due to the unique characteristics of underwater acoustic channel. In particular, wormhole attack [10] and its variants impose great threat to underwater acoustic communication. Figure 2 shows an low-cost implementation that connects two spatial points (i.e., network interfaces) together by a wire or equivalent high-speed connection. The adversary uses the wormhole to tunnel messages received in one location in the network and replays them in a different location. Compared to active denial-of-service attacks like brute-force jamming, wormhole attack is more "covert" in nature and harder to detect. But as shown in Figure 3, the result is disastrous for distributed localization, synchronization and routing. The topological space is effectively deformed by even a single wormhole. More wormholes will result in more aggravated deformation and lower network performance.

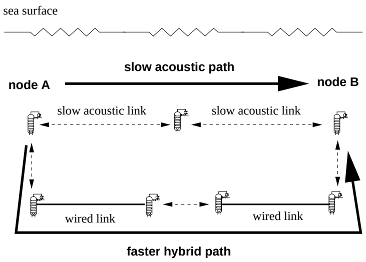

Fig. 2. **Underwater wormhole** (Low-cost underwater devices are connected by wire)

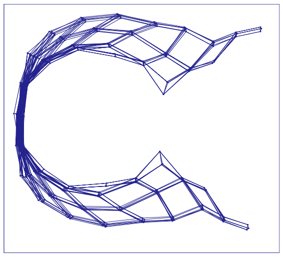

Fig. 3. **Distributed localization view** (with a wormhole)

Many countermeasures that have been proposed to stop wormhole attack in radio networks are ineffectual in UANET and UWSN. In [14], we show that low-cost wormhole links of *any* length effectively disrupt communication services in UWSN. The adversary can implement wormholes longer than or shorter than the one-hop transmission range. Because many existing wormhole countermeasures proposed for radio networks [9][26] only ensure that a transmitter and its receiver are physically one-hop neighbors, they *cannot* be used to counter underwater wormholes shorter than one-hop distance.

Moreover, no signal, including those from the adversary, can propagate faster than the radio signals in ground ad hoc networks. Many existing wormhole countermeasures proposed for radio networks [10][26][27] exploit this fact to bound the distance between a sender and its receiver. Nevertheless, in the underwater acoustic channel such distance-bounding schemes [4] are ineffective against wormholes.

C. Reliable transport of data

Reliable transport is of critical importance. The most common solution at the transport layer is TCP. We expect TCP performance to be problematic because of the high error rates incurred on the links, which was already encountered in wireless radio networks. Under the water, however, we have an additional problem: propagation time is much larger than transmission time, setting the stage for the well known large $bandwidth \times delay$ product problem. Consider a path with 20 nodes spaced by 50m with rate of 500Kbps and packet size = 1000 bits. The optimal TCP window is therefore 2000 packets. Managing such unusually large windows with severe link error rates is a major challenge since TCP would time out and would never be able to maintain the maximum rate. There are a number of techniques that can be used to render TCP performance more efficient, for instance, the strengthening of the link layer (at the expense of throughput and extra delay) and the use of TCP variants (like TCP Westwood [15]) that are robust to errors.

D. GPS-free multi-hop acoustic routing

In previous discussions of underwater localization and time-sync services, we have seen that GPS-free multi-hop acoustic routing is a critical building block of distributed GPS-free localization and time-sync schemes. Most GPS-free multi-hop routing protocols in a mobile ad hoc network fall into two categories: proactive routing and reactive routing (aka., on demand routing) [5]. In proactive ad hoc routing protocols like OLSR [1], TBRPF [17] and DSDV [19], mobile nodes constantly exchange routing messages which typically include connection status to other nodes (e.g., link state or distance vector), so that every node maintains sufficient and fresh network topological information to allow them to find any intended recipients at any time. On the other hand, on demand routing has become a major trend in mobile networks. AODV [20] and DSR [11] are common examples. Unlike their proactive counterparts, on-demand routing operation is triggered by the communication demand at sources. Typically, an on-demand routing protocol has two components: *route discovery* and *route maintenance*. In route discovery phase, the source seeks to establish a route towards the destination by *flooding* a route request (RREQ) message, then waits for the route reply (RREP) which establishes the on-demand route. In the route maintenance phase, nodes on the route monitor the status of the forwarding path, and report to the source about route errors. Optimizations could lead to local repairs of broken links.

Nevertheless, flooding is no longer a robust-and-efficient tool in underwater networking. Deployment redundancy is an innate characteristic of ad hoc networking to avoid network partitioning. Thus at every neighborhood in a radio network, the forwarding events can be received by every local node with nearly perfect probability. Therefore, flooding a message in a redundant ad hoc network is normally considered as a robust operation. Unfortunately, by analytic analysis and simulation study we know that this is no longer true in underwater networks. In contrast, each network flood cannot be both robust (i.e., delivered to nearly all active sensor nodes) and efficient (i.e., with low latency and transmission cost). Since flooding is needed in GPS-free ad hoc routing, this dilemma poses great challenge to multi-hop packet delivery service in underwater networks.

Moreover, the cost of proactive neighbor detection could be more expensive than flooding. Suppose average one-hop forwarding delay of a flood is T_f, and T_d is the proactive interval between two neighbor detection rounds. Given the network diameter d (which is the maximal hop count value of all minimal hop-count paths in the network), a flood eventually incurs network-wise transmissions in about $d{\cdot}T_f$ time. As a comparison, a proactive neighbor detection protocol incurs network-wise transmissions every T_d. In a mobile underwater network, a large T_d means stale neighbor detection, while a small T_d means an even worse channel contention status than flooding. In radio networks, channel contention can be ameoliorated by using small-size packets (to reduce packet transmission delay). Unfortunately, reducing transmission delay is useless under the water because propagation latency, rather than transmission delay, is now the dominant factor that affects the channel condition. With no proactive neighbor detection and with less flooding, it is an unanswered challenge to furnish multi-hop ad hoc packet delivery service in UANET and UWSN with node mobility requirement.

E. Acoustic link layer and physical layer

Underwater acoustic communications are mainly affected by path loss, noise, multi-path, Doppler spread, and large and variable propagation delay. All these factors determine the temporal and spatial variability of the acoustic channel, and limit the data rate of communication over the Under-Water Acoustic channel. The path loss depends on both transmitter-receiver (TR) separation distance and the acoustic frequency, which is different from that for microwave channels. Long-range systems that operate over several tens of kilometers may have a bandwidth of only a few kHz (since high frequencies experience high attenuation over long distance), while a short-range system operating over several tens of meters may have more than a hundred kHz of bandwidth. In both cases these factors lead to low bit rate, in the order of tens of kbit/s for existing devices. The multi-path effect of the acoustic channel can be mitigated by equalization or orthogonal frequency division multiplexing (OFDM). The Doppler effect due to motion of the transmitter and/or the receiver can be utilized in the design of channel codes and interleavers. For example, suppose the Doppler rate is f_D; then the coherence time T_c is roughly $1/f_D$. Then the length of the interleaver or the codeword length should be at least $2 \times T_c = 2/f_D$.

The link layer needs to be carefully designed to address the special features of acoustic channels. For best effort flows, random access such as Aloha or slotted Aloha can be employed. CSMA may not be viable due to long propagation delay. On the other hand, for quality-of-service (QoS) assured flows, which have requirements on data rate, delay bound, and delay bound violation probability, deterministic multiple access schemes such as CDMA may be used. CDMA is resistant to jamming and is robust against multi-path; hence, CDMA is a viable technique for QoS assured flows. To support QoS, recently developed effective capacity technique [28] may be utilized. We elaborate on the effective capacity technique as below.

Figure 4 shows a wireless communication system. The data source generates packets and the packets are first put into a buffer to accommodate the mismatch between the source rate and the time-varying acoustic channel capacity. Then the packets traverse a channel encoder, a modulator, a wireless channel, a demodulator, a channel decoder, a network access device, and finally reach the data sink.

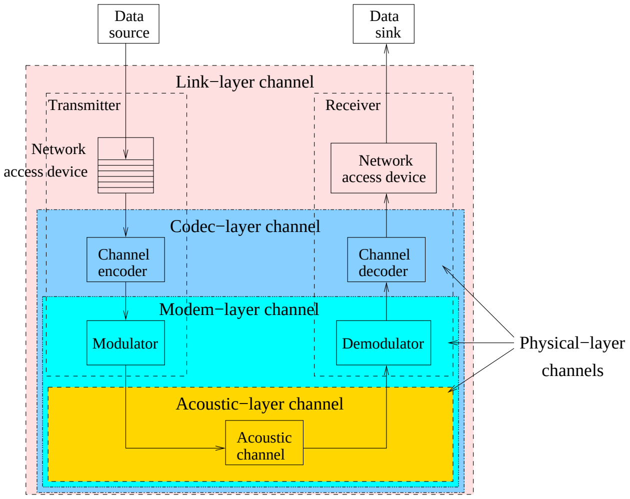

Fig. 4. **A wireless acoustic communication system and associated channel models**

As shown in Figure 4, one can model the communication channel at different layers, e.g., physical layer and link layer. Physical layer channel can be further classified into acoustic-layer channel, modem-layer channel, and codec-layer channel.

Acoustic-layer channel models can be classified into two categories: large-scale path loss and small-scale fading. Large-scale path loss models, also called propagation models, characterize the underlying physical mechanisms (*i.e.*, reflection, diffraction, scattering) for specific paths. These models specify signal attenuation as a function of distance between the transmitter and the receiver. Small-scale fading models describe the characteristics of generic radio paths in a statistical fashion. Small-scale fading refers to the dramatic changes in signal amplitude and phase that can be experienced as a result of small changes (as small as a half-wavelength) in the spatial separation between the receiver and the transmitter. Small-scale fading can be slow or fast, depending on the Doppler rate. Small-scale fading can also be flat or frequency-selective, depending on the delay spread of the channel. Uncorrelated scattering is often assumed, to extend these distributions to the frequency-selective case. The large-scale path loss and small-scale fading together characterize the received signal power over a wide range of distances.

A modem-layer channel can be modeled by a finite-state Markov chain, whose states are characterized by different bit error rates (BER). A codec-layer channel can also be modeled by a finite-state Markov chain, whose states can be characterized by different data-rates, or symbol being error-free/in-error, or channel being good/bad. The two state Markov chain model with good/bad states [31] is widely used in analyzing the performance of upper layer protocols such as TCP [30].

Acoustic-layer channel models provide a quick estimate of the performance of acoustic communications systems (*e.g.*, symbol error rate vs. signal-to-noise ratio (SNR)). However, acoustic-layer channel models cannot be easily translated into complex QoS guarantees for a connection, such as bounds on delay violation probability and packet loss ratio. The reason is that, these complex QoS requirements need an analysis of the queueing behavior of the connection, which is hard to extract from acoustic-layer models [28]. Thus it is hard to use acoustic-layer models in QoS support mechanisms.

Recognizing that the limitation of the physical-layer channel models in QoS support, is the difficulty in analyzing queues, we proposed moving the channel model up the protocol stack, from the physical-layer to the link-layer. In [28], an effective capacity channel model was proposed. Effective capacity captures the effect of channel fading (including Doppler effect) on the queueing behavior of the link, using a computationally simple yet accurate model, and thus, is the critical device we need to design an efficient resource allocation mechanism.

IV. SUMMARY

In this paper we call for the attention to build large-scale UANET and UWSN for real-time aquatic applications. We present an application scenario to demonstrate the usefulness of the new networking paradigms. Although the application scenario is presented per MILCOM's course, it can be easily extended to civilian scenarios like marine incident investigation or periodic oceanographic monitoring. We further analyze design challenges of implementing the needed underwater networks. Following a top-down approach, we analyze design challenges of each layer in the network protocol stack. Our study shows that UANET and UWSN are inter-disciplinary challenges requiring integration of acoustic communication, signal processing and mobile network design.

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