INTERNATIONAL JOURNAL OF INTELLIGENT CONTROL AND SYSTEMS
VOL. 13, NO. 3, SEPTEMBER 2008,152-161

Underwater Acoustic Networks – Issues and Solutions

Zaihan Jiang

Abstract- **Underwater Acoustic Networks (UANs) are very unique and can be deployed for commercial and military applications. The research of UANs attracts increasing attention in recent years. This survey paper first introduces the concept of UANs, and then reviews some recent developments within this research area. It also lists some practical and potential research issues of UANs, ranging from energy saving and deployment to different layers. Finally, some suggestions and promising solutions are given for these issues.**

***Index Terms*—Underwater Acoustic Networks, Underwater Acoustic Communications, Energy Efficiency, Medium Access Control, Cross Layer Design**

1. INTRODUCTION

Two thirds of the earth surface is composed of water. Compared with our human being's familiarity with land, there are still many un-explored areas underwater. This needs significant research efforts.

The research of Underwater Acoustic Networks (UANs) is attracting attention due to their important underwater applications for military and commercial purposes. More and more research interest and efforts are shifting to this area in recent years. The broad applications of UANs include but not limited to:

- Information exchange among nodes that are within the range of the network, or outside the network with the help of, e.g., a gateway, or a switch center. The primary design goal of communication networks is for exchanging information. In an UAN, exchanging information among nodes is one of its essential applications. An example is that underwater Internet, in which users can share information without tether, will become realistic instead of just a dream, if UANs are deployed. Another important application is real-time communication with submarines and autonomous underwater vehicles in network configurations [33].
- Information collection for oceans, lakes, and rivers. For example, synoptic and cooperative adaptive sampling of 3D coastal ocean environment [24] was performed by Odyssey-class AUVs [25]. Such kind of activities could improve human ability to observe and predict the characteristics of ocean/lake/river environment.
- Surveillance. It includes surveillance, reconnaissance, targeting, and intrusion detection. By using different types of sensors, an UAN can achieve more accurate and classification of low signature targets compared with traditional surveillance systems.
- Environmental monitoring. Pollution in near-shore oceans is an urgent issue and needs close watch. UANS can perform different kinds of pollution monitoring, e.g., chemical, biological, nuclear, and oil-leakage pollutions in bays, lakes, or rivers [26]. UANs can also be used to monitor ocean currents and temperature change, e.g., the global warming effect to ocean.
- Underwater explorations. Underwater explorations are difficult for human beings due to the high water pressure, unpredictable underwater activities and vast size of unknown area. UANs can help us explore the underwater world that we are not familiar with. Such kinds of activities include exploring minerals and oilfields, determining routines for laying undersea cables, etc.
- Disaster prevention. By deploying Acoustic Sensor Networks in remote locations to monitor undersea activities, ocean-related disaster like tsunami and sea-quake can be warned to coastal areas in real time when it happens [27].
- Mine detection. An UAN can detect mine efficiently by using acoustic sensors and optical sensors together. An AUV network infrastructure is introduced for mine countermeasure operations in [28].

From a communication system aspect, underwater environment is much different from its ground-based counterpart. Correspondently, the research of UANs becomes different and exhibits certain unique features. It is because:

1) Acoustic signal is the only physical feasible tool that works in underwater environment. Compared with it, electromagnetic wave can only travel in water with short distance due to the high attenuation and absorption effect in underwater environment. It is found that the absorption of electromagnetic energy in sea water is about $45\times\sqrt{f}$ dB per kilometer, where f is frequency in Hertz; In contrast, the absorption of acoustic signal over most frequencies of interest is about three orders of magnitude lower [31].

   Optical signal is strongly scattered and absorbed underwater [29]. There are some investigations about utilizing optical signal for underwater applications. However, they find out that optical signal can only pass through limited range in very clean water environment (deep water, for example) [23]. Thus, it is not a proper tool for long-distance transmission underwater, or in a not-so-clean water, e.g., shallow water, environment.

Manuscript received March 18, 2008; revised July 16, 2008.

Zaihan Jiang is with Naval Research Laboratory (NRL), Washington DC, USA (email: zaihanjiang@yahoo.com). The work work conducted before he joined NRL and does not represent any view from NRL.

2) Traditional underwater communication systems are point-to-point based in most cases. In other words, a network is not formed in such kind of systems. Resource sharing is not a concern and most of the research is performed for the physical layer. In contrast, the research of UANs should always investigate how to optimize the whole system performance across different layers. Upper layer protocols, like resource allocation and collision avoidance, could become the new research focus since there are many nodes, instead of just two, to use the resource in a network.
3) UANs can give real-time communication between the underwater instruments and a control center within a network configuration. As a comparison, traditional ocean monitoring system is usually implemented with three steps: "deploy sensors, record the data and recover the instruments". It can cause long delays in receiving the recorded data. Additionally, all data could be lost if any serious failures happen before the recovery.
4) Compared with ground-based wireless networks, UANs differ in many aspects, ranging from network topologies to protocols of all the layers, thanks to the completely different underwater environment compared with the ground one.
5) There are no internationally accepted standards for UANs yet. The activity pursuing for standardization is not very active.

In the rest of this article, we first define some concepts related with UANs in Section 2, and then compare the differences between UANs and ground-based wireless networks in Section 3. In Section 4, we discuss some essential issues with UANs. Finally, we conclude that cross-layer design could be a proper solution to optimize the resource utilization in UANs.

2. Concepts and Definitions

Underwater Acoustic Networks, including but not limited to, Underwater Acoustic Sensor Networks (UASNs) [58] and Autonomous Underwater Vehicle Networks (AUVNs) [59], are defined as networks composed of more than two nodes, using acoustic signals to communicate, for the purpose of underwater applications.

UASNs and AUVNs are two important kinds of UANs. The former is composed of many sensor nodes, mostly for a monitoring purpose. The nodes are usually without or with limited capacity to move. The latter is composed of autonomous or unmanned vehicles with high mobility, deployed for applications that need mobility, e.g., exploration. An UAN can be an UASN, or an AUVN, or a combination of both.

Acoustic communications, on the other hands, is defined as communication methods from one point to another by using acoustic signals. Network structure is not formed in acoustic point-to-point communications.

Sound travels through the water the best in comparison with electromagnetic waves and optical signals. Acoustic signal is sound signal waveform, usually produced by a sonar for underwater applications. Acoustic signal processing extracts information from acoustic signals in the presence of noise and uncertainty.

3. Comparison between UANs and Ground-based Wireless Networks

UAN is a new research topic and there are many unsolved issues. As mentioned in the previous section, the unique underwater environment is the root cause of these issues.

An underwater acoustic channel is different from a ground-based radio channel from many aspects, including:

1) Bandwidth is extremely limited. The attenuation of acoustic signal increases with frequency and range [30] [31] [34]. Consequently, the feasible band is extremely small. For example, a short range system operating over several tens of meters may have available bandwidth of a hundred kHz; a medium-range system operating over several kilometers has a bandwidth on the order of ten kHz; and a long-range system operating over several tens of kilometers is limited to only a few kHz of bandwidth [1] [37].
2) Propagation delay is long. The transmission speed of acoustic signals in salty water is around 1500 meter/s [32], which is a difference of five orders of magnitude lower than the speed of electromagnetic wave in free space. Correspondently, propagation delay in an underwater channel becomes significant. This is one of the essential characteristics of underwater channels and has profound implications on localization and time synchronization.
3) The channel impulse response is not only spatially varied but also temporarily varied. The channel characteristics vary with time and highly depend on the location of the transmitter and receiver. The fluctuation nature of the channel causes the received signals easily distorted. There are two types of propagation paths: macro-multipaths, which are the deterministic propagation paths; and micro-multipath, which is a random signal fluctuation. The macro-multipaths are caused by both reflection at the boundaries (bottom, surface and any object in the water) and bending. Inter-Symbol Interference (ISI) thus occurs. Compared with the spread of its ground-based counterpart, which is on the order of several symbol intervals, ISI spreading in an underwater acoustic channel is several tens or hundred of symbol intervals for moderate to high data rate in the horizontal channel. Micro-multipath fluctuations are mainly caused by surface wave, which contributes the

most to the time variability of shallow water channel. In deep water, internal waves impact the single-path random fluctuations [35] [36].

4) Probability of bit error is much higher and temporary loss of connectivity (shadow zone) sometimes occurs, due to the extreme characteristics of the channel.

The practical deployment and design of UANs face some special challenges:

First, the cost of manufacturing, deployment, maintenance and recovery of underwater equipments is much higher than that of the ground-based counterpart. For example, an acoustic modem with a rugged pressure housing costs roughly $3000, and an underwater sensor can be even more expensive. Supporting hardware, e.g., an underwater cable connector is often more than $100 [29]. The deployment cost is very high as well. An oceanographic research vessel typically costs $5000-$25,000/day depending on its size [38] and the operation is weather dependent, which makes the situation even worse. Recovery can also be expensive.

Second, energy saving/efficiency is a critical issue for UAN. Because of the high cost of re-deploying underwater equipment, UANs are usually designed in such a way that they can work properly underwater as long as possible. Saving energy to make equipments run longer is a necessary consideration when we design protocols. For example, a coordinated sleeping MAC protocol is proposed in [39] to save energy in UANs.

Third, UANs deployment can be much sparser compared with ground-based radio networks. It is very obvious since underwater equipment is expensive and the ocean area that needs to be surveyed/monitored is usually huge [29]. It brings changes and new challenges for the network topology design and maintenance.

Fourth, nodes in an UAN should have mobility in some application scenarios. As mentioned before, the manufacturing and deployment cost of underwater equipment is high, and in many cases, the area of interest in underwater environment is vast. Nodes with mobility are often required due to that reason.

Fifth, underwater equipments are easily to be damaged due to fouling and corrosion from the hostile underwater environment. It impacts the operation life of an UAN and should be taken into consideration.

4. Issues of UAN research

We discuss the issues facing UAN researchers in the following aspects: network topology, physical layer, MAC layer, Network layer, and Application layer.

4.1 Network topology

Due to the uniqueness of underwater channels and characteristics of acoustic signal, UAN network topology is different from that of its ground-based counterparts. However, the fundamental design goals are the same, i.e., providing reliable connectivity among nodes in the network; increasing network capacity; and minimize the energy consumption.

Basically, two types of network topologies can be used: ad hoc mode and hierarchy mode. In the former one, nodes are self-organized as a peer-to-peer network, as shown in Figure 1. Peer-to-peer topology can be further divided into point-to-point connection topology, and multi-hop connection one. There is just one hop from a node to any other node in the first type of connection, i.e., routing is not necessary. In the latter one, other nodes are involved to relay a data message from a source node to its destination. In other words, routing is needed with this second type of network topology. It is found that multi-hop topology is more energy efficiency [50] [49] in ground-based wireless networks. This conclusion needs to be investigated and extended to UANs.

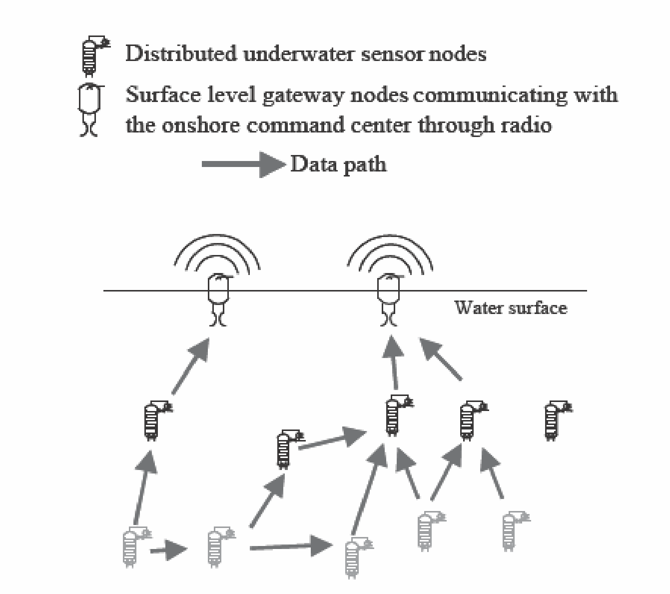


Fig 1. An example of peer-to-peer topology.

Figure 2 shows an example of hierarchy network topology in which several levels of the structure are deployed. Depending on the ways to place nodes (e.g., permanent or on-demand deployment), the time constraints imposed by the applications, and the volume of data being retrieved, different kinds of topologies can be applied to an UAN.

4.2 Physical layer

It is the physical channel that makes UAN unique. The characteristics of underwater channels are described in [1] [37]. As discussed in Section 1, the majority of the electromagnetic wave band has high attenuation in an underwater channel. Only a small part of long-wave band could go through it with relative less attenuation. For example, 1-8 kbits/sec at 122 kHz ranges up to 6-10 m [2]. However, both large antennae and high transmitter powers are required.

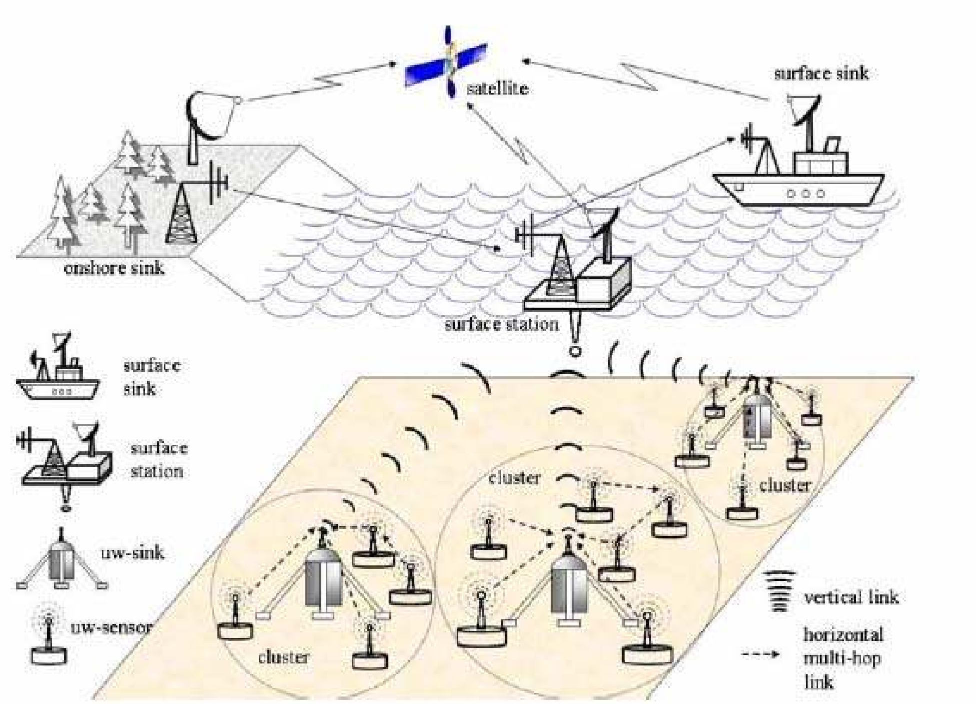


Fig. 2. An example of Hierarchy topology.

Optical signal gets scattered badly underwater, and the absorption is also high. Beside of these, optical wave transmission requires high precision in pointing the narrow laser beams. In very clean water, e.g., deep sea, blue-green wavelengths may be used for short-range connection. The advantage of optical signal lies in its high data rate up to several Mbits/sec at rang up to 100 m [23]. For very short range connections of order 1-2 m at standard IrDA, the rate can be achieved as high as 57.6kbps [2] [3].

Up to today, the only practical solution for underwater communication with acceptable range is utilizing acoustic signal, which travels underwater with longer distance, less attenuation, and higher reliability.

However, available bandwidth is extremely limited for acoustic signal. Similar to other kinds of signal waveforms do, acoustic signal encounters attenuation that increases with frequency in underwater environment, as shown in Fig. 3 [40]. Absorption is also increased with the range, which causes the increasing drop of SNR when the range increases [37], as shown in Fig. 4. According to [5], nearly no research and commercial acoustic system can exceed 40km-kbps as the maximum attainable rang and rate product, and it is mostly applicable to vertical channels in deep water. In [1], bandwidths are given for long, medium and short ranges, respectively. For a very long distance at the order of 1000 km, the available bandwidth falls below a kHz; while only at very short ranges below about 100 m, more than a hundred kHz of bandwidth may be available [37]. Lack of available bandwidth is the biggest issue for underwater acoustic communication /network.

Compared with the speed of electromagnetic wave, acoustic signal travels much slower in salty water (approximately 1500 m/s, which is $2x10^5$ lower than the electromagnetic wave counterpart [32]). This causes another big issue: very long propagation delay. Additionally, Doppler shift has more significant impacts subjects to the low velocity of acoustic propagation in water [44].

High bit error rate is common in underwater channels, due to the multi path interference and time-varying nature of underwater acoustic channels. Multi-path delay causes ISI. Compared with the one of the ground-based radio wave counterparts, multipath spread increases significantly. For example, in a shallow water channel, 10 ms spread is common, which means more than 100 symbol duration if the system is operating at a rate of 10 kbps. Frequency-selectivity is caused by multi-path interference. The mechanisms of multipath formation are different in deep and shallow water, and also depend on frequency and range of transmission.

Even if nodes are not moving, surface wave, internal wave, current, turbulence, etc., can cause the channel's rapid change with time. In addition to the time fluctuation nature of underwater acoustic channels, the Doppler shift is relatively high and hard to track due to the low carrier frequency of acoustic signal. The ratio of Doppler shift to carrier frequency in an underwater acoustic channel is in the order of 10^{-3} - 10^{-4}. To make a comparison, its ground-based counterpart is in the range of 10^{-7} - 10^{-9}. Consequently, rapid fluctuation in channel response and compression of signal waveforms happen.

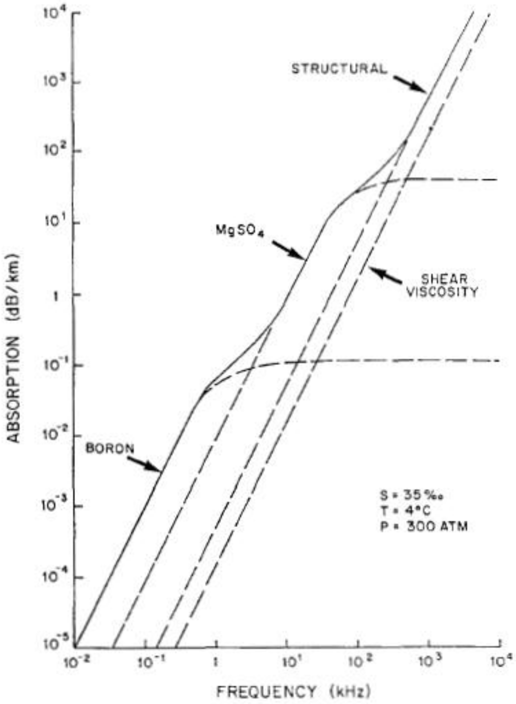


Fig. 3. Absorption rate of acoustic signal undersea [40].

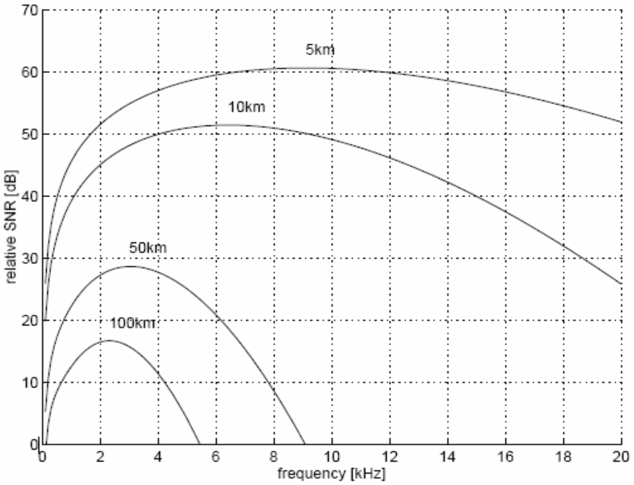


Fig. 4. SNR vs. frequency and range undersea [37].

Research direction: In the last two decades, only two fundamental changes were made in underwater acoustic physical layers. The first one is the introduction of digital communication techniques in early 1980's (FSK) and the second one is the implantation of coherent modulation in early 1990's (PSK and QAM) [5]. Equalization technology has also been introduced to compensate ISI [33]; however, different numbers and different placement of the equalizer tap coefficients are needed for different ocean environments. Another way to remove ISI is to use passive-phase conjugation (PPC) [41]. A Decision Feedback Equalizer (DFE) using a fixed set of parameters with minimal user supervision has been introduced in [42].

Many research efforts are taken to solidify system performance in different circumstance and increase data rate for underwater communication network applications. Such efforts include the research of multi-carrier orthogonal modulation like OFDM (orthogonal frequency division modulation), and multi-input multi-output (MIMO), which takes advantage of the independent channels created by different multiple paths to increase throughput [6]. Channel capacity bound analysis also attracts plenty of research interest [60].

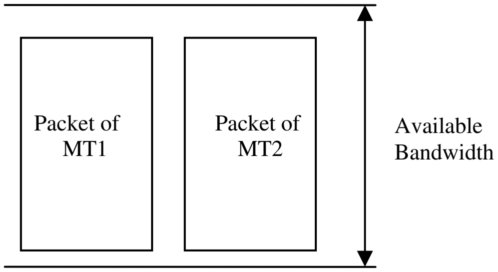
4.3 MAC Layer

Due to the extremely-limited-bandwidth, relatively long propagation delay and high-bit-error-ratio nature of underwater acoustic channels, underwater nodes in an UAN have to share the available resources. Medium Access Control layer controls the nodes in an UAN to access the underwater acoustic channel. It schedules each node to access the physical medium and allocates resources accordingly.

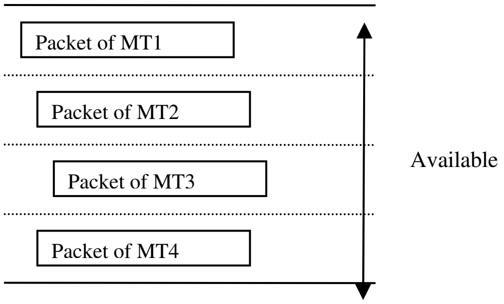
From the network's aspect, MAC layer plays a critical role in resource allocation, and ensuring the Qualify of Service (QoS) and the whole system's operation. Physical layer tries to optimize the performance with current channel condition and available resource, e.g., bandwidth. However, it should be MAC layer's responsibility to determine the resource that physical layer could have and set up some of physical layer's parameters accordingly.

The existing MAC protocols for wireless networks are classified into two categories: Serial Transmission MAC Protocols (STMP) and Parallel Transmission MAC Protocols (PTMP) [4]. STMP statistically multiplexes traffic over a single channel and at any time point the channel can transmit a packet of only one node. It is also called a Single Channel MAC protocol. PTMP divides available bandwidth into several parts and data can be transmitted on each one in parallel. It is also termed as Multi-Channel MAC protocol. Figure 5 illustrates the difference between PTMP and STMP.

MAC protocols can also be divided into two categories: centralized and distributed. The central controller in a centralized MAC plays a key role in determining which mobile terminal to access physical resource. Mobile terminals can either be polled or compete for resources, and the central controller makes the final decision. For example, in a cellular network, a Base Station (BS) decides which mobile terminal to use a channel. It avoids signaling overhead like RTS (Request-To-Send)-CTS (Clear-To-Send) dialog in IEEE 802.11 DCF. A mobile terminal does not play critical role in resource allocation. It can ask for more bandwidth. However, it is the central controller who makes the decision based on a few factors. Comparing with a centralized MAC, there is no central controller in a distributed one. Usually, each mobile terminal competes for physical medium access. It is flexible to re-allocate the resource according to the status of each mobile terminal. On the other hand, signal overhead like RTS-CTS sometimes takes a considerable percentage of available bandwidth. One typical example of distributed MAC protocol is IEEE 802.11 DCF [43] for both WLAN and ad hoc wireless network.



PTMP transmit a packet through the whole available bandwidth; it can only transmit one packet of a terminal at any time point



STMP divides available bandwidth into several parts and transmits packets in parallel

Fig. 5. STMP vs. PTMP.

MAC can also be divided as contention-based MAC and non-contention-based one. In contention-based MAC, mobile stations compete for medium access. This kind of method is often deployed in a distributed system. For example, the IEEE 802.11 DCF is used in WLAN or ad hoc wireless systems. A system with a central controller can use contention-based MAC as well. For example, the contention mechanism is used for Non-real-time Polling Services (nrtPS) in IEEE 802.16e standards. However, these kinds of MAC usually do not give QoS support for real-time applications. In a non-contention-based MAC, a mobile terminal accesses medium either by being polled or using reserved time slot/bandwidth such that there is no competition among terminals. It is usually deployed in a centrally-controlled system. One typical example is IEEE 802.11 PCF. Compared with contention-based MAC, real-time applications are easier to be supported in non-contention-based one.

Discussing the details of MAC protocols is out of the scope of this article. Instead, we will introduce several basic access techniques and analyze their pros and cons if they are applied for UANs.

Frequency Division Multiple Access (FDMA) divides the available bandwidth into several sub-bands and assigns one of them to a particular user. The band is used by this user only till it is released. FDMA has been deployed successfully in ground-based radio networks.

However, FDMA may not be a good fit in underwater environment. The available bandwidth is extremely limited for acoustic signal underwater. If we divide the band into several even smaller parts, the coherence bandwidth of the transmission channel can be bigger than an FDMA sub-channel. Correspondently, fading is caused among users with different sub-bands [7]. Another issue is that the mechanism could be inefficient in busty traffic [8] [9] [10] because the bandwidth is fixed for each sub-band and can not be adjusted.

Time Division Multiple Access (TDMA) is another basic access technology. In this technology, a time frame is divided into multiple time slots and a slot is assigned to one individual user. Each user transmits in the assigned slot. TDMA has been widely deployed for ground-based radio networks and several 2G cellular network standards, i.e., GSM (Global System of Mobility) [45], IS 136 [46], based on the idea of TDMA. It is also used extensively in satellite communication systems.

One advantage of TDMA is energy saving, which is extremely important in underwater environment. Since each user only transmits on its assigned slot and keeps idle in other time slots, the transmitter could be turned off during aforementioned idle period, such that energy can be saved. Another advantage is its flexibility. The same hardware can be used to transmit and no extra hardware is needed for other operations, e.g., to add another time slot for a user.

One of the disadvantages is its overhead. To avoid collision from neighboring slots, guard times that are proportional to the propagation time delay is included. The overhead is found larger than that of FDMA [8]. Another drawback is that it is hard to achieve time synchronization, which is a necessity for TDMA technology, in an underwater environment, due to the more significant difference in propagation delays. Consequently, collisions happen and the system throughput decreases.

Code Division Multiple Access (CDMA), which is based on spread spectrum, is another widely deployed access method. In contrast with FDMA and TDMA, CDMA does not divide time or frequency. It allows users to transmit all the time with all the available bandwidth. Users are distinguished by allocating each user a spreading code. This code is orthogonal with any other spreading codes that other users take.

Basically there are two CDMA technologies: Direct Sequence Spread Spectrum (DSSS) and Frequency

Hopping Spread Spectrum (FHSS). In the former one, original bits are spread by multiplying the spread code directly (linear modulation); in the latter case, the carrier frequency of a user is changed according to the pattern of the spread code.

The advantages of CDMA are:

a) It has higher channel efficiency, thus, higher throughput. CDMA has been shown to provide up to 1.5 times the capacity compared with TDMA and 4.6 times compared with FDMA in ground-based cellular systems [11].
b) CDMA is very effective against jamming, multi-path interference, and any interference that appears deterministic [12].
c) Concurrent transmissions in one channel without either accurate time scheduling such as in TDMA or individual allocation to specified frequency bands as in FDMA can also be achieved in CDMA.
d) It is flexible to switch from signal to signal for a transmitter or receiver by changing spread codes.
e) In a DSSS system, fine time resolution of the spreading codes provides the possibility of coherently combining the multipath arrivals using Rake receiver. If the resolvable multipath components fade independently, it is possible to extract a time diversity gain present in the channel [8] [13].
f) CDMA technology provides security protection for transmitting information.

Due to the aforementioned reasons, CDMA technology has been used widely for ground-based wireless networks, especially for cellular networks and military networks. It is one of the popular standards of 2G cellular networks: IS-95 [14], and recently deployed 3G systems, e.g., CDMA 2000 [15] and University Mobile Telecommunication Systems (UMTS) [16], and in 4G systems when combined with OFDM technology [51] [52].

However, a multi-user CDMA system needs good power control strategy to work properly. Otherwise, the near-far problem could deteriorate its performance [8] [47]. Power control is easily implemented in ground-based radio networks, but it is hard to do so in underwater environment. How to implement power control to reduce interference level is a difficult but must-solve issue to deploy CDMA technology in UANs.

Orthogonal Frequency Division Multiple Access (OFDMA) is one of the recently proposed multiple access methods. It is the main choice for future broadband communication networks, e.g., WiMAX, LTE (Long Term Evolution), and IEEE 802.11n. There are some research activities to apply OFDMA to underwater acoustic applications [53] [54] [55] [56]. Most of the research focuses on its "modulation" aspect instead of its "multiple-access" aspect. In other words, OFDMA is regarded as a modulation technology there.

Spatial Division Multiple Access (SDMA) can be a promising candidate, too, if multiple antenna elements can be deployed on the nodes of an UAN. Similar to CDMA, with different spatial signature sequences, users can transmit simultaneously over the entire frequency band and still could be distinguished at the receivers [48]. SDMA and CDMA can be combined to optimize the multiple access performance.

4.4 Network Layer

If the network range is not large and one hop is sufficient to deliver information, then there is no need for relaying message. Otherwise, when it increases such that single-hop transmission is insufficient, multi-hop is needed to relay information from source to destination. It is also shown that multi-hop delivery is more energy-efficiency in underwater network than single-hop delivery does [57].

The network layer determines the path from a source node to the destination one when multi-hop is needed. Basically, there are two methods of routing. The first one is virtual circuit routing and the second one is packet-switch routing.

In virtual circuit routing, the networks use virtual circuits to decide on the path at the beginning of the network operation. In packet-switch routing, every node that is part of the transmission makes its own routing decision, i.e., decides its next hop to relay the packet. Packet-switch routing can be further classified into proactive routing and reactive routing protocols. Most routing protocols for ground-based wireless networks are packet-switch based.

Proactive routing protocols attempt to minimize the message latency by maintaining up-to-date routing information at all times from each node to any other node. It broadcasts control packets that contain routing table information. Typical protocols include Destination Sequence Distance Vector (DSDV) [17] and Temporally Ordered Routing Algorithm (TORA) [18].

However, proactive routing protocols provoke a large signaling overhead to establish routes for the first time and each time the network topology changes. It may not be a good fit in underwater environment due to the high probability of link failure and extremely limited bandwidth there.

In contrast, reactive routing protocols only initiate a route discovery process upon request. Correspondently, each node does not need to maintain a sizable "look-up" table for routing. This kind of routing protocols is more suitable for dynamic environment like ad hoc wireless networks [61, 62]. Typical protocol examples are Ad hoc On-demand Distance Vector (AODV) [20], and Dynamic Source Routing (DSR) [19].

The shortage of reactive routing protocols is its high latency to establish routing. Similar to its proactive counterpart, flooding of control packets to establish paths is needed, which brings significant signal overhead. The high latency could become much deteriorated in underwater environment because of the much slower propagation speed of acoustic signal compared with the radio wave in the air.

Virtual-circuit-switch routing protocols can be a better choice for underwater acoustic networks. The reasons are:

a) Underwater acoustic networks are typical asymmetric instead of symmetric. However, packet-switched routing protocols are proposed for symmetric network architecture;
b) Virtual-circuit-switch routing protocols work robust against link failure, which is critical in underwater environment; and
c) Virtual-circuit-switch routing protocols have less signal overhead and low latency, which are needed for underwater acoustic channel environment.

However, virtual-circuit-switch routing protocols usually lack of flexibility. How to adapt some degree of flexibility into virtual-circuit-switch routing protocols is a question that needs to be answered by UAN network layer research.

4.5 Application Layer

The research of application layer protocols for UANs is a brand new topic. The purpose of application layer is to provide a network management protocol that makes hardware and software detail of the lower layers transparent to management applications. The functionalities include:

1) Identifying communication partners;
2) Determining resource availability; and,
3) Synchronizing communications.

Some examples of application layer protocols for ground-based wireless networks are Telnet, File Transport Protocol (FTP), and Simple Mail Transfer Protocol (SMTP) [21].

Not much effort has been made to address the specific needs of the underwater acoustic environment. Instead of designing a complete new set of protocols, we can modify existing protocols of ground-based wireless networks to meet the UAN needs. Thus, it is a necessity to understand the application areas and the communication issues for UANs, and to apply its uniqueness into the existing application protocols.

5. Proposed Solutions

To improve network efficiency, cross-layer approaches are proposed for ground-based wireless networks [63]. In this kind of mechanism, a joint design of different network functionalities, e.g., from modem design to MAC protocols, from channel coding to routing methods, is enabled. Such methods can overcome the disadvantage of lack of sharing information among layers. However, it becomes more challenging since it requires insight knowledge across different layers and collaborations among different areas.

As mentioned in Section 3, compared with ground-based counterpart, UANs suffer from much smaller bandwidth, longer propagation delay and worse channel stability. To make the network in sub-optimal mode and make efficient utilization of the extremely limited resource, a cross-layer deign is a valuable solution. It is a difficult task since a through understanding among different layers is required.

There is not much research effort of cross-layer design for UANs up to date. One example is that R. Jurdak et al. propose a method to estimate the battery lifetime and power cost for shallow water underwater acoustic sensor networks for civilian application by interacting between physical and MAC layers [22].

Due to the economic concern and the complex underwater environment, an UAN should have the capacity to adjust itself to the changing environment. Correspondently, the topology and protocol design should be able to self-adaptive if environment changes.

Energy efficiency is critical to an UAN's life and normal operation. The protocol design of an UAN should always take this into consideration. Another promising research direction is energy re-generation underwater. For example, we can use the current/turbulent/internal wave undersea to re-charge batteries, or take advantage of solar energy near the sea surface.

6. Summaries

This paper reviews the recent research development of Underwater Acoustic Networks (UANs). It analyzes the uniqueness of underwater acoustic channel first. Several practical issues of UANs are then raised, ranging from network topology, power efficiency, physical layer, MAC layer, network layer to application layer. To use the scare resource more efficiently, it is shown that cross layer design can be a proper approach for UANs, due to its optimization prospect.

REFERENCES

[1] J. A. Catipovic, "Performance Limitations in underwater acoustic telemetry", *IEEE J. Oceanic Eng.*, 15(3):205-216, Jul. 1990.

[2] F. Schill, U.R. Zimmer, and J. Trumpf, "Visible Spectrum Optical Communication and Distance Sensing for Underwater Applications", In *Proc. Australasian Conf. Robotics and Automation*, Canberra, Australia, Dec., 2004.

[3] I. Vasilescu, K. Kotay, D. Rus, M.Dunbabin, and P. Corke, "Data collection, storage, and retrieval with an underwater sensor network", In *SenSys'05*, pp 154 – 165, San Diego, USA, Nov., 2005.

[4] Z. Jiang, M. Zhou, "A prioritized parallel transmission MAC protocol for all-IP wireless WAN beyond 3G," *Proc of IEEE International Conference on Systems, Man and Cybernetics*, 2003, Vol. 4, pp.: 3852-3857, Washing, DC, USA, Oct. 2003.

[5] D. B. Kilfoyle and A. B. Baggeroer, "The State of the Art in Underwater Acoustic Telemetry," *IEEE Journal of Oceanic Engineering*, vol. OE-25, no. 5, pp. 4-27, January 2000.

[6] L. Freitag, M. Stojanovic, D. Kilfoyle, and J. Preisig, “High-Rate Phase-Coherent Acoustic Communication: A Review of a Decade of Research and a Perspective on Future Challenges”, In Proc. *7th European Conf. on Underwater Acoustics*, Delft, The Netherlands, July 2004.

[7] E. M. Sozer, M. Stojanvic, and J. G. Proakis, “Underwater Acoustic Networks”, *IEEE Journal of Oceanic Engineering*, Vol. 25, No. 1, Jan. 2000

[8] T. S. Rappaport, “Wireless Communications”, Englewood Cliffs, NJ: Prentice Hall, 1996.

[9] K. Pahlavan and A. H. Levesque, “Wireless Information Networks”, New York: Wiley, 1995

[10] D. D. Falconer, F. Adachi, and B. Gudmundson, “Time division multiple access methods for wireless personal communications,” *IEEE Commun. Mag.*, pp. 50-57, Jan. 1995.

[11] B. Sklar, “Digital Communications, Fundamentals and Applications”, 2nd ed. Englewood Cliffs, NJ: Prentice-Hall, 2000.

[12] A. J. Viterbi, “CDMA, Principles of Spread Spectrum Communication”, Reading, MA: Addison-Wesley, May, 1997.

[13] R. Rohno, R. Meidan and L. B. Milstein, “Spread spectrum methods for wireless communications,” *IEEE Communication Mag.*, pp. 58-67, Jan. 1995.

[14] L. Harte, M. Hoening, D. McLaughlin, and R. K. Lta, “CDMA IS-95 for Cellular and PCS”, New York: McGraw-Hill, 1999.

[15] J. Langer and G. Larsson, “CDMA 2000 – A world view,” Ericsson Rev., No. 3, 2001

[16] 3GPPTM, 3GPP TS 25.213, v 5.4.0 (2003-09), Release 5. [Online]. Available at: http://www.3gpp.org/ftp/Specs/2003-09/Rel-5/25_series/

[17] C. E. Perkins and P. Bhagwat, “Highly dynamic destination sequence distance vector routing (DSDV) for mobile computers,” in *Proc. SIGCOMM’94*, Aug. 1994, pp. 234-244, London, UK.

[18] V. D. Park and M. S. Corson, “A highly adaptive distributed routing algorithm for mobile wireless networks,” in *Proc. INFOCOM’97*, pp. 1405–1413, Kobe, Japan, Apr. 1997.

[19] D. B. Johnson and D. A. Maltz, “Protocols for adaptive wireless and mobile networking,” *IEEE Personal Commun.*, pp. 34 – 41, April, 1996.

[20] C. E. Perkins, E. M. Belding-Royer and S. Das, “Ad Hoc On Demand Distance Vector (AODV) Routing,” *IETF Experimental RFC*, Jul. 2003.

[21] http://en.wikipedia.org/wiki/OSI_model#Layer_7:_Application_Layer, September, 2008.

[22] R. Jurdak, C.V. Lopes, P. Baldi, “Battery lifetime estimation and optimization for underwater sensor networks”, in: *Sensor Network Operations, IEEE Press*, pp 397 – 420, New York, 2006.

[23] N. Farr, A.D. Chave, L. Freitag, J. Preisig, S.N. White, D. Yoerger, and F. Sonnichsen, “Optical Modem Technology for Seafloor Observatories”, In *Proc. IEEE OCEANS’06 Conf.*, pp. 1 – 6, Boston, MA, Sept. 2006.

[24] Ocean Engineering at Florida Atlantic University, Available online at:
http://www.oe.fau.edu/research/ams.html.

[25] AUV Laboratory at MIT Sea Grant, Available online at: http://auvlab.mit.edu/.

[26] X. Yang, K.G. Ong, W.R. Dreschel, K. Zeng, C.S. Mungle, and C.A. Grimes, “Design of a wireless sensor network for long-term, in-situ monitoring of an aqueous environment”, pp. 455–472, *Sensors 2* (2002), Vol. 11.

[27] N.N. Soreide, C.E. Woody, and S.M. Holt, “Overview of ocean based buoys and drifters: Present applications and future needs”, in: *16th International Conference on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology*, Long Beach, CA, USA, January 2004.

[28] L. Freitag, M. Grund, C. V. Alt, R. Stokey and T. Austin, “A Shallow Water Acoustic Network for Mine Countermeasures Operations with Autonomous Underwater Vehicles”, In *Underwater Defense Technology (UDT)*, 2005. Also available online at: www.hydroidinc.com/pdfs/Acoustic_Network_for_MCM.pdf

[29] J. Partan, J. Kurose, and B. N. Levine, “A Survey of Practical Issues in Underwater Networks, International Conference on Mobile Computing and Networking”, *Proc. of the 1st ACM international workshop on Underwater networks*, pp. 17 – 24, Los Angeles, CA, USA, Sept., 2006.

[30] L. Berkhovskikh and Y. Lysanov, “Fundamentals of Ocean Acoustics”. New York: Springer, 1982.

[31] A. Quazi and W. Konrad, “Underwater acoustic communications,” *IEEE Commun. Mag.*, pp. 24–29, Mar. 1982.

[32] R. J. Urick, “Principles of Underwater Sound”, 3rd Edition, McGraw-Hill Publishing Company, New York, NY, 1983.

[33] M. Stojanovic, “Recent Advances in High-Speed Underwater Acoustic Communications”, *IEEE Journal of Oceanic Engineering*, Vol. 21, No. 2, April, 1996.

[34] R. Coates, “Underwater Acoustic Systems”, New York: Wiley, 1989.

[35] R. Galvin and R. F. W. Coates, “Analysis of the performance of an underwater acoustic communication system and comparison with a stochastic model,” in *Proc. OCEANS’94,* pp. 111,478-111.482., Brest, France, Sept. 1994,

[36] R. H. Owen, B. V. Smith, and R. F. W. Coates, “An experimental study of rough surface scattering and its effects on communication coherence,” in *Proc. OCEANS’94,* pp. ILI.483-III.488, Brest, France, Sept. 1994.

[37] M. Stojanovic, "Underwater Acoustic Communications," in *Encyclopedia of Electrical and Electronics Engineering*, John G. Webster, Ed., John Wiley & Sons, 1999, Vol.22, pp.688-698.

[38] UNOLS day rates, 2005. Available online at: www.unols.org/projects/Fleet Cost Estimates.xls.

[39] M. K. Park and V. Rodoplu, “UWAN-MAC: An Energy-Efficient MAC Protocol for Underwater Acoustic Wireless Sensor Networks”, *IEEE Journal of Oceanic Engineering*, Vol. 32, No. 3, July 2007

[40] I. Dyer, subject notes for 1385: “Fundamentals of Underwater Sound Applications,” Dept. Ocean Eng., Massachusetts Institute of Technology, Cambridge, MA, 1993.

[41] D. R. Dowling, “Acoustic pulse-compression using passive phase-conjugation processing,” *J. Acoust. Soc. Amer.*, pp. III.483-III.488, pp. ILI.483-III.488, Vol. 95, No. 3, pp. 1450–1458, 1994.

[42] T. C. Yang, "Correlation-based decision-feedback equalizer for underwater acoustic communications," *IEEE J Ocean Eng*., Vol. 30, pp.865-880, Oct. 2005.

[43] LAN/MAN Standards of the IEEE Computer Society, *Wireless LAN medium access control (MAC) and physical layer (PHY) specification. IEEE standard 802.11*, 1999, Edition, 1999.

[44] Y. R. Zheng, **“**Channel Estimation and Phase-Correction for Robust Underwater Acoustic Communications,” *IEEE Milcom 2007*, pp. 1-6, Orlando, Fl., USA, Oct., 2007.

[45] Available online at: http://www.mobilein.com/gsm_standards.htm, Sept., 2008

[46] Available online at: http://www.privateline.com/Cellbasics/hart-ch3IS-136.pdf, Sept., 2008.

[47] M. Stojanovic and Z. Zvonar, “Multichannel Processing of Broad-Band Multiuser Communication Signals in Shallow Water Acoustic Channels”, *IEEE J. Oceanic Eng.,* 21(2):156–166, Apr. 1996.

[48] J. H. Cui, J. Kong, M. Gerla2, and S. Zhou, “Challenges: Building Scalable Mobile Underwater Wireless Sensor Networks for Aquatic Applications”, *IEEE Network*, Vol. 20, Issue 3, pp: 12-18, May-June, 2006

[49] M. Neugebauer, J. Ploennigs, and K. Kabitzsch, “Evaluation of Energy Costs for Single Hop vs. Multi Hop with Respect to Topology Parameters”, *Factory Communication Systems, 2006 IEEE International Workshop on***,** pp: 175-182, Torino, Italy, June, 2006.

[50] J. Haapola, Z. Shelby, C. Pomalaza-Raez, and P. Mahonen, “Cross-layer energy analysis of multihop wireless sensor networks”, *Wireless Sensor Networks, 2005. Proc. of the Second European Workshop on,* pp. 33- 44, Istanbul, Turkey, Jan., 2005.

[51] Z. Wang and G. B. Giannakis, “Wireless multicarrier communications: Where Fourier meets Shannon,” *IEEE Signal Processing Magazine*, vol. 17, no. 3, pp. 29–48, May 2000.

[52] S. Hara and R. Prasad, “Overview of Multicarrier CDMA”, *IEEE Communications Magazine*, Vol. 35, Iss. 12, pp. 126 – 133, Dec., 1997.

[53] R. F. Ormondroyd, “A Robust Underwater Acoustic Communication System using OFDM-MIMO”, *OCEANS 2007 –* Europe, pp. 1 – 6, Aberdeen, Scotland, June 2007.

[54] B. C. Kim and I. T. Lu, “Parameter Study of OFDM Underwater Communications System”, *OCEANS 2000, MTS/IEEE Conference and Exhibition*, Vol. 2, pp.: 1251 – 1255, Providence, Rhode Island, USA, Sept. 2000.

[55] A. K. Morozov, D. C. Webb, J. C. Preisig, and L. E. Freitag, “Underwater Acoustic Communications”, Available online at: http://www.onr.navy.mil/sci_tech/32/reports/docs/05/oamorozo.pdf.

[56] S. Sason, R. Anstett, N. Anicette, and S. Zhou, “A Broadband Underwater Acoustic Modem Implementation Using Coherent OFDM”, in Proc. Of *National Conference on Undergraduate Research*, San Rafael, CA, USA, April, 2007.

[57] M. Stojanavic, “On the Relationship Between Capacity and Distance in an Underwater Acoustic Communication Channel”, *ACM WUWNet '06*, pp. 41 – 47, Los Angeles, CA, USA, Sept., 2006.

[58] I. F. Akyildiz, D. Pompili, and T. Melodia, “Underwater acoustic sensor networks: research challenges”, Ad Hoc Networks (Elsevier), vol. 3, no. 3, pp. 257-279, March 2005.

[59] H. Schmidt, “Autonomous underwater vehicle networks as integrated acoustic observation systems”, Acoustical Society of America Journal, Vol. 117, Iss. 4, pp. 2409 – 2410, April, 2005.

[60] T. J. Hayward and T. C. Yang, “Single and multi-channel underwater acoustic communication channel capacity: A computational study”, J. Acoust. Soc. Am. Vol. 122, pp. 1652 – 1661, Sept., 2006.

[61] C. Zhang, M. C. Zhou, and M. Yu, “*Ad hoc* Network Routing and Security: A Review,” *International Journal of Communication Systems*, Vol. 20, pp. 909-925, Aug. 2007.

[62] Z. Wang, L. Liu and M. C. Zhou, “An Epidemic Routing Strategy for Vehicular Ad Hoc Wireless Networks in Intelligent Transportation Systems,” *International Journal of Intelligent Control and Systems*, Vol. 10, No. 1, 86-93, March 2005.

[63] Z. Wang, L. Liu and M. C. Zhou, “Cross-layer design and analysis of ad hoc wireless network,” *IEEE Transactions on Wireless Communication*, Vol. 6, No. 2, 478-485, Feb. 2007.

Zaihan Jiang received his B.E from Xi’an Jiaotong University, Xi’an, China, M.S. from New Jersey Institute of Technology, Newark, NJ, US in 1999, and Ph.D. from New Jersey Institute of Technology in 2006, all in electrical engineering. He has spent nine years with telecommunication industry in the United States, before he joined Naval Research Laboratory, Washington DC, in 2008. His research interests includes cross layer design, system security and multimedia applications for wireless networks, underwater acoustic networks/communications, wireless LAN, ad hoc, wireless sensor, and mesh networks.

He serves as a program committee member for IEEE International Conference on Networking, Sensing and Control, Sanya, China, 2008 and IEEE International Conference on Service Operations, Logistics and Informatics, Chicago, IL, 2009. He has over ten publications in referred conferences and journals. He has been an IEEE member since 2000.