Realizing Underwater Communication through Magnetic Induction

Ian F. Akyildiz, Pu Wang, and Zhi Sun

ABSTRACT

The majority of the work on underwater communication has mainly been based on acoustic communication. Acoustic communication faces many known problems, such as high propagation delays, very low data rates, and highly environment-dependent channel behavior. In this article, to address these shortcomings, magnetic induction is introduced as a possible communication paradigm for underwater applications. Accordingly, all research challenges in this regard are explained. Fundamentally different from the conventional underwater communication paradigm, which relies on EM, acoustic, or optical waves, the underwater MI communications rely on the time varying magnetic field to covey information between the transmitting and receiving parties. MI-based underwater communications exhibit several unique and promising features such as negligible signal propagation delay, predictable and constant channel behavior, sufficiently long communication range with high bandwidth, as well as silent and stealth underwater operations. To fully utilize the promising features of underwater MI-based communications, this article introduces the fundamentals of underwater MI communications, including the MI channel models, MI networking protocols design, and MI-based underwater localization.

INTRODUCTION

Underwater communication networks have drawn the attention of the research community in the last decade and a half, driven by a wealth of theoretical and practical challenges. This growing interest can largely be attributed to new applications enabled by large-scale networks of underwater devices (e.g., underwater static sensors, unmanned autonomous vehicles, and autonomous robots), which are capable of harvesting information from the aquatic and marine environment, performing simple processing on the extracted data, and transmitting it to remote locations. Significant results in this area over the last few years have ushered in a surge of civil and military applications. However, the underwater environment imposes great challenges on reliable and real-time communications primarily based on acoustic waves as well as electromagnetic (EM) and optical waves.

Ian F. Akyildiz is with the Georgia Institute of Technology.

Pu Wang is with Wichita State University.

Zhi Sun is with the State University of New York at Buffalo.

EM waves experience high attenuation under water, which severely limits the achievable communication range. To increase the communication range, large antennas are required for low-frequency EM communication, which is not practical for small underwater vehicles and robots. For example, the antenna size of an EM transmitter is a couple of meters for a 50 MHz operating frequency. Optical waves experience multiple scatterings of light, which results in intersymbol interference and short transmission range [1]. To prolong the transmission range, the transmission of optical signals requires high precision in pointing narrow laser beams at the receiver, which is difficult for highly mobile underwater vehicles and robots. The common and most used acoustic waves, while promising long communication ranges under water, exhibit high propagation delay along with unreliable and unpredictable channel behavior and low data rate, which is caused by complex multi-path fading, prevalent Doppler effects, and significant variation of these properties due to temperature, salinity, or pressure [2].

In the last decade our research on magnetic induction (MI)-based communications in challenged and harsh environments [3, 4] such as soil, oil reservoirs, and water pipelines has demonstrated many promising features of MI-based communication. Adopting similar communication principles as in [3, 4], recent research provides mathematical analysis of the MI-based communication channel in underwater applications [5–7]. Compared to commonly used acoustic, optical, and EM communication, MI-based communication has the following advantages:

Negligible signal propagation delay: Different from acoustic waves that propagate at a speed of 1500 m/s under water, MI waves propagate at a speed of 3.33×10^7 m/s under water. This extremely high propagation speed of MI waves can significantly improve the delay performance of underwater communications, while facilitating the design and implementation of the underwater networking protocols, such as medium access control (MAC) and routing, and the underwater networking services (e.g., localization). Moreover, physical layer synchronization among wireless devices becomes simple and reliable due to the negligible delay and stable channel.

Predictable and constant channel response: Since the radiation resistance of a coil is much

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Communication paradigm	Propagation speed	Data rates	Communication ranges	Channel dependency	Stealth operation
MI	3.33×10^7 m/s	~ Mb/s	10–100 m	Conductivity	Yes
EM	3.33×10^7 m/s	~ Mb/s	≤ 10 m	Conductivity, multipath	Yes
Acoustic	1500 m/s	~ kb/s	~ km	Multipath, Doppler, temperature, pressure, salinity, environmental sound noise	Audible
Optical	3.33×10^7 m/s	~ Mb/s	10–100 m	Light scattering, line of sight communication, ambient light noise	Visible

Table 1. Comparison of underwater MI, EM, acoustic, and optical communications.

smaller than that of an electric dipole, only a very small portion of energy is radiated to the far field by the coil. Hence, compared to acoustic communication, multi-path fading is not an issue for MI-based underwater communication. Moreover, because of the high propagation speed of MI waves, the frequency offsets caused by Doppler effect can be greatly mitigated. Without suffering from multi-path fading and Doppler effect, the MI channel conditions (e.g., data rate and packet loss rate over a given transmission range) are highly constant and predictable. Moreover, without suffering from light scattering as in optical communications, the transmission range and channel quality of MI communications are independent of water quality factors such as water turbidity. In addition, both acoustic and optical communications have to deal with a high level of acoustic and ambient light noises. The EM noise experienced by MI channels is limited under water because the high-frequency noise is absorbed by the water medium.

Sufficiently large communication range with high data rate: In MI-based communications, the transmission and reception are accomplished through the use of a pair of small-size wire coils, that is, coil antennas. Different from the dipole antenna used in most EM wave-based communications, there is no minimum frequency below which the antenna cannot work. On the one hand, the time varying magnetic field can be generated no matter how small the coil is at the MI transmitter. On the other hand, as long as there is magnetic flux going through the coil, the MI receiver can capture the signal even if the frequency is as low as the Megahertz band. This property means that each small coil antenna can be utilized to emit low-frequency MI signals, which allow small underwater robots and vehicles to communicate over sufficiently long distances. Moreover, the operating frequency of MI coils can reach Megahertz bands while maintaining predictable and constant channel quality, which leads to much higher data rates than in the acoustic communications.

Stealth underwater operations: While acoustic and optical communications depend on the generation, propagation, and reception of audible sounds or visible lights, respectively, underwater MI communications utilize non-audible and non-visible MI waves, suitable for a wide range of civilian and military applications that require stealth underwater operations.

The comparison of MI, EM, acoustic, and optical communications is summarized in Table 1. It is also worth noting that the cost of MI coils is very low, generally less than US$1.00 per coil for mass production. Therefore, it is very suitable for large-scale deployment of MI-based underwater nodes. The promising features of underwater MI communications can enable many new and emerging underwater applications:

Collaborative sensing and tracking with underwater swarming robots: Fish behavior shows an astonishing ability to efficiently find food sources and favorable habitat regions through schooling behavior, that is, rapid orienting and synchronized moving of a group of fish with respect to environmental gradients, such as local variations in chemical stimuli such as odorant plumes or other environmental properties such as phytoplankton density. Underwater MI communications can enable a swarm of underwater robots (e.g., agile robotic fish) to mimic this collective and synchronized intelligence of fish by exchanging control and environmental gradient information with guaranteed delay bounds. In such a way, swarming robots can collaboratively track sources of pollution, toxicity, and biohazard with high convergence speed and accuracy.

Stealth and real-time underwater surveillance and patrol: The high bandwidth along with the constant and reliable channel conditions achieved by underwater MI communications can enable real-time underwater surveillance, which demands high-speed delivery of a large volume of multimedia contents (e.g., audio, video, and scalar data). In addition, the stealth and silent features of underwater MI communications allow underwater surveillance to be carried out in stealth mode.

Disaster assessment, search, and rescue in a cluttered underwater environment: Underwater structures, such as leaking submarine cabins, sunken ships, and completely submerged buildings, can create a cluttered underwater environment, which is constituted by confined, hard-to-reach, and complex underwater spaces. Such environments prevent the deployment of bulky underwater vehicles and the application of conventional acoustic communications, which inevitably experience severe multi-path fading with significantly degraded channel quality. In this case, a small and agile underwater robot equipped with small coil antenna can maneuver in such clustered environments much more easily, while allowing reliable and real-time MI

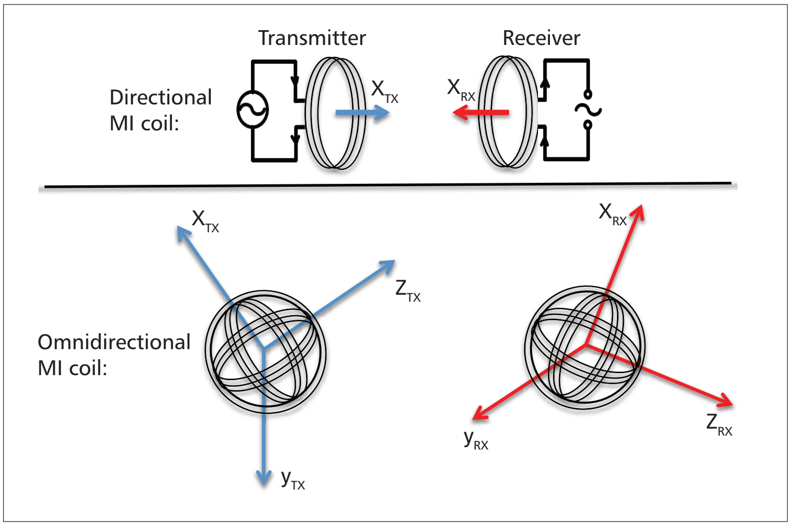

Figure 1. Illustration of MI-based communications with a tridirectional coil antenna.

underwater communications for comprehensive in situ disaster assessment as well as timely survivor search and rescue.

In the remainder of this article, we first focus on the MI channel modeling and physical layer techniques. Then we introduce the design guidelines for underwater MI networking protocols. Finally, we highlight the underlying principles of the MI-based underwater localization method.

Underwater MI Channel Modeling

MI Channel Path Loss

With MI communication, the data information is carried by a time varying magnetic field. Such a magnetic field is generated by the modulated sinusoid current along an MI coil antenna at the transmitter. The receiver retrieves the information by demodulating the induced current along the receiving coil antenna, as shown in Fig. 1. In MI communications, the transmission distance is shorter than a wavelength. As a result, the communication channel experiences less absorption due to the lossy underwater medium. Moreover, the multipath fading is negligible in underwater MI systems. As previously mentioned, the MI transceivers work at the Megahertz band that has a wavelength of tens of meters. Since the communication range in underwater MI systems is within one wavelength, even if there are multiple paths between the transceivers, the phase shifting of multiple paths is so small that the coherence bandwidth is much larger than the system bandwidth. Hence, the fading and channel distortion are negligible.

To rigorously characterize the above unique underwater MI communication channel, an analytical channel model is of great importance. In the MI channel models [3], the EM fields around the transmitter and receiver coils are first expressed using Maxwell's equations. Based on the field analysis, the coupling between the transceiver coils is modeled using the equivalent circuit method. Finally, the MI path loss can be derived as a function of the operating frequency, transmission distance, coil antenna size, number of turns, the relative angle between the two coils, and the underwater environmental conditions, especially the water conductivity.

While the MI channel models in [3, 5, 6] consider the directional coil antennas, Fig. 2 shows the numerical path loss of the underwater MI communication channel with small-size omnidirectional coil antennas [7]. We consider the MI transceivers to be equipped with coil antennas with 10 cm radius and 20 turns of AWG26 wire. The operating frequency is 10 MHz. Three types of underwater environments are considered: sea water with conductivity 4 S/m, lake water with conductivity 0.005 S/m, and drinking water with conductivity 0.0005 S/m. According to Fig. 2a, using a pocket-sized wireless device can achieve 20 m communication range in the drinking water, more than 10 m range in the lake water, but less than 1 m range in the sea water. (Note that here the maximum communication range is considered to be the distance where the path loss reaches 100 dB.) Such big differences in communication ranges are due to the orders of magnitudes differences in the medium conductivities in the sea water, lake water, and drinking water. Highly conductive sea water induces significant Eddy current that incurs very high path loss, which is the problem for both the EM waves and MI techniques in the seawater applications.

The transmission range of underwater MI communications can be increased by using the optimal operating frequency and larger coil antennas. Figures 2b and 2c show the influence of the operating frequency and coil antenna size on the MI channel path loss in the lake water. As the operating frequency increases from 100 kHz to 15 MHz, the MI path loss decreases at first and then keeps increasing after a turning point. The minimum value in Fig. 2b indicates that there is an optimal operating frequency for MI communications in the lake water. On the one hand, the higher frequency can enhance the MI coupling between the transmitter and the receiver. On the other hand, due to the non-zero connectivity in the lake water, the higher frequency also encounters higher loss due to Eddy current. Hence, there is an optimal frequency that achieves the minimum path loss and maximizes the communication range. Moreover, the coil size has a monotonically positive influence on the MI coupling, which means that less path loss and longer communication distance can be realized by increasing the coil antenna size, as shown in Fig. 2c. In addition, the path loss can be further reduced by increasing the wire turns of the coil antenna. For example, based on our channel model, the path loss can be reduced by 6 dB if the number of turns is doubled. It should be noted that the performance shown in Fig. 2 is based on the assumption that the transmitter coil and receiver coil are coaxially positioned. However, the orientation of the coil antenna can be highly random, since underwater robots and vehicles can move and rotate freely in the target underwater environment. Hence, we introduce underwater MI-based omnidirectional communication.

Omnidirectional Communication

Despite the promising properties of MI underwater communications, according to the derived channel models, if the underwater robots and vehicles use the single coil antenna, the path loss performance of the MI channel varies according to the uncontrollable coil orientations. To solve the problem, we propose utilizing a tridirectional coil antenna at the receiver and transmitter, which consists of three coils that are perpendicular to each other, as shown in Fig. 1. Here we show that underwater robots and a vehicle equipped with a tridirectional coil antenna constitute an omnidirectional receiver, and the coil direction has almost no effect on communication performance. It should be noted that, for illustrative purposes, we only let one of the three coils work at the transmitter in Fig. 1. Due to the field distribution pattern of the coil, the orthogonal coils on the same wireless device do not interfere with each other since the magnetic flux generated by one coil becomes zero at the other two orthogonal coils.

To prove the advantages of the tridirectional coil antenna, we numerically compare the performance of the systems using either a unidirectional or tridirectional coil in the MI communication channel. When the receiver is a unidirectional coil, the path losses with different antenna orientations are shown in Fig. 3a. In contrast, when the receiver is a tridirectional coil, the path losses with different antenna orientations are given in Fig. 3b. According to the results, the tridirectional coil antenna has much lower path loss and more reliable performance than the unidirectional coil when the antenna deviates from its optimal orientation. Moreover, since the path loss of the tridirectional coil antenna does not obviously vary when the orientation of the antenna changes, the tridirectional receiver can be regarded as omnidirectional.

Open Research Issues

3D MI channel modeling: Although tri-coil MI communications have demonstrated promising omnidirectional features, an analytical 3D model of the tri-coil MI channel still needs to be developed. Based on such an analytical channel model, the optimal omnidirectional performance can be achieved by properly combining the received signals at the three coil antenna elements by maximizing transmission gain through optimal power allocation, and by adopting spatial-temporal coding mechanisms.

Transmission range extension through underwater MI waveguide: The transmission range of MI communications can be extended by adopting the MI waveguide technique. The channel model of the MI waveguide was developed in [3] delicately for underground wireless communications. The MI waveguide consists of a series of relay coils between two transceivers. An MI relay is just a simple coil without any power sources or processing devices. Since the MI transceivers and relays are coupled, the relays will get the induced currents one by one up to the receiver, so the signal strength at the receiver side becomes large enough over long distance. Since the original channel model of MI-waveguide is developed for 2D directional MI-coil antennas [3], the omnidirectional MI-waveguide channel model still needs to be developed in the 3D aquatic space.

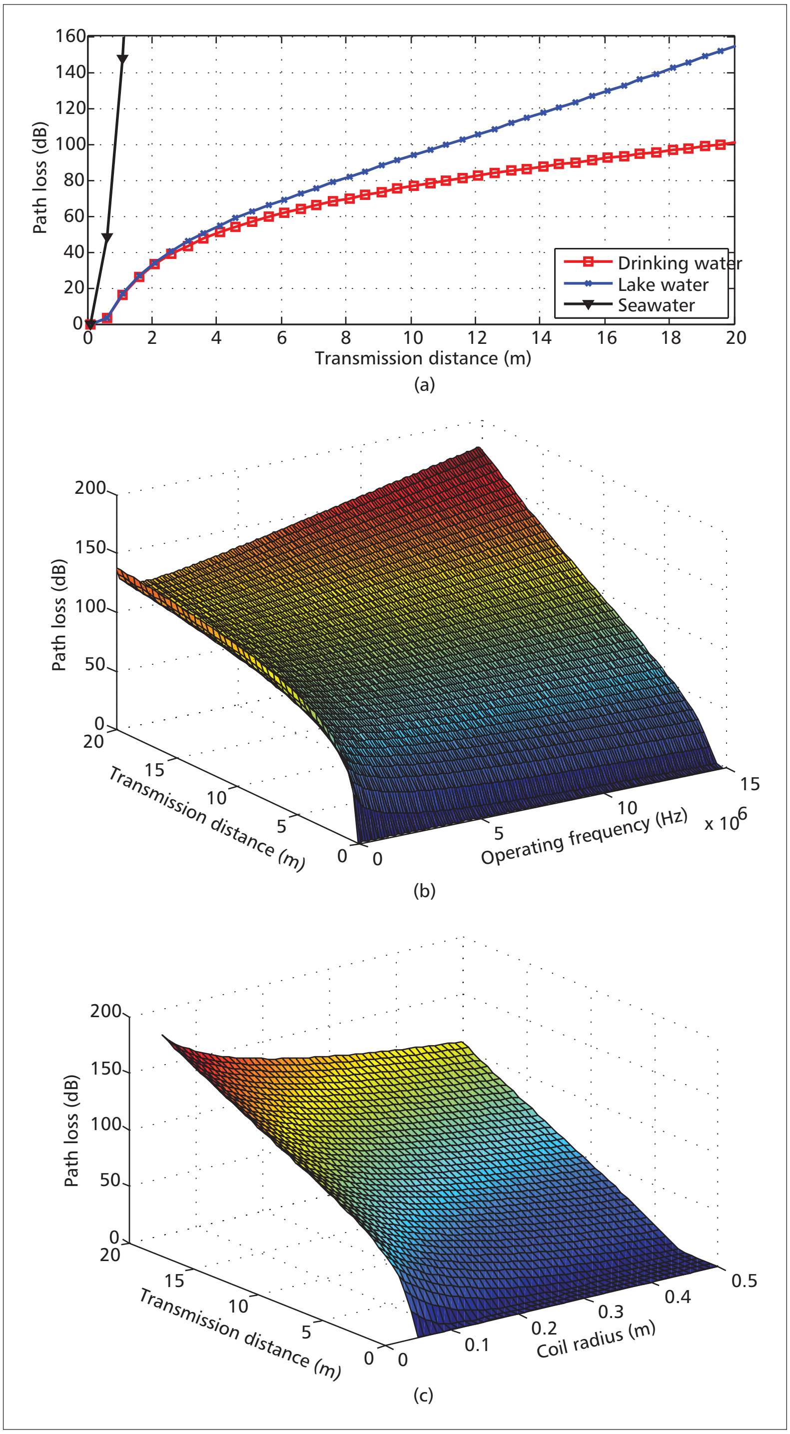

Figure 2. Path loss of the underwater MI communication channel: a) path loss of MI underwater communications; b) influence of operating frequency (lake water); c) influence of coil antenna size (lake water).

Underwater MI coil antenna design: The parameters of the coil antenna, including the size, number of turns, as well as the lumped and the distributed impedance, have significant influence on the underwater MI communications. Therefore, to maximize the underwater MI communication distance as well as the bandwidth, the optimal coil antenna parameters need to be designed by jointly considering the trade-off between the induced current and the absorption due to skin depth, the trade-off between the MI path loss and the antenna size, as well as the

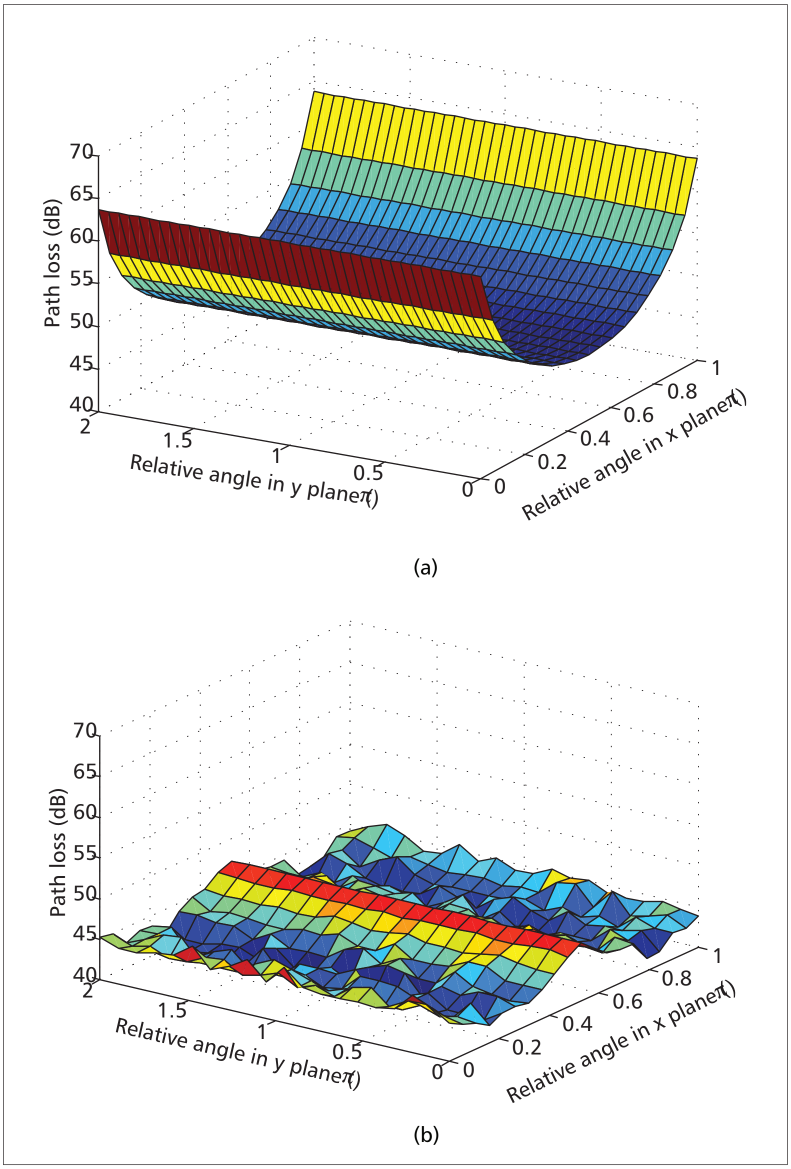

Figure 3. Comparison between the path loss in the MI system with unidirectional and tridirectional coils (as a function of antenna orientations): a) path loss of a unidirectional receiver; and b) path loss of a tridirectional receiver.

trade-off between the quality factor of the coil circuit and the system bandwidth.

Underwater MI transceiver design: To realize the underwater MI communication scheme, the MI transceiver needs to be designed and implemented, which consists of the RF front-end, analog-to-digital/digital-to-analog converter (ADC/DAC), modulator, and equalizer. In particular, since the MI channel is insensitive to multipath fading, Doppler effect, and underwater acoustic noise, an extremely high-order modulation scheme and corresponding channel equalization scheme can be jointly designed based on the underwater MI channel models, which can provide high data rate MI communication links under water.

Energy modeling: Since the underwater robots and vehicles are usually powered by batteries and are expected to operate for a long time period, energy-aware communication, and networking mechanisms are of great importance, which rely on an accurate energy consumption model of the whole system. Therefore, a precise energy model needs to be developed based on the unique underwater MI channel model as well as the optimal antenna and transceiver parameters.

Underwater MI-Based Cross-Layer Design

Overview of MI-Based Cross-Layer Protocol

The performance of underwater MI-communications can be further enhanced through the cross-layer design approach. For example, we have proposed a cross-layer communication framework for the MI-based wireless sensor networks [4]. This cross-layer module provides a unified solution for underground, soil, oil reservoir, and underwater environments because it can adaptively adjust the communication parameters according to the channel characteristics such as bandwidth and path loss under different environments.

More specifically, the proposed cross-layer communication framework is a distributed routing/MAC/PHY solution and allows each node to jointly optimize the next-hop selection, transmitted power, modulation scheme, and forward error correction (FEC) coding rate, with the objective of simultaneously minimizing energy consumption and maximizing packet transmitted rate, while satisfying the application-specific QoS requirements such as delay and packet loss rate. The proposed solution relies on a highly scalable geographical routing paradigm and adopts the direct sequence code-division multiple access (DS-CDMA) as the MAC-layer protocol, the performance of which is further enhanced through distributed game-theoretic power control to combat the near-far problem [4]. Our preliminary results show that the proposed cross-layer protocol outperforms the layered protocol solutions with 50 percent energy savings and 6 dB throughput gain.

Open Research Issues

Underwater MAC protocol design: The existing MAC design in underwater mainly aims to combat the adverse impact of acoustic channels [8, 9]. The underwater MAC protocols via MI-based communications are still unexploited. Carrier sense multiple access (CSMA) schemes are easily implemented in a distributed and low-complexity manner, and are robust to time-varying network topology caused by node mobility. However, conventional underwater acoustic communications face fundamental limitations in implementing CSMA-like schemes because of the high and variable propagation delay of underwater acoustic waves [1]. On the contrary, there are no such barriers to implement CSMA-like schemes for underwater MI communications because the propagation delay MI waves under water are negligible. In addition, the relatively high operating frequency of MI waves paves the way for the design and implementation of frequency-division multiple access (FDMA) protocols under water, which is not feasible for underwater acoustic communication because of its low operating frequency. Similar to MI-based communications, EM-based communications also exhibit low propagation delay and can operate at high frequency. However, the existing MAC protocols designed for EM-based communications in the terrestrial case cannot work effectively and efficiently for underwater MI-based communications because they fail to capture the unique features of the MI channel. For example, because MI-based communications depend on the time-varying near-field magnetic strength, the signal strength of MI-based communications will drop dramatically in the far field. This means that instead of considering the complicated physical model, that is, the signal-to-interference-plus-noise ratio (SINR) model, the MAC protocol design for underwater MI-based ad hoc networks can safely adopt the simple protocol model, where the impact of interference from a transmitting node is only determined by whether or not a receiver resides within the communication range of this transmitting node. Moreover, because of the constant and predicable MI channel, each node can accurately estimate its instantaneous transmission rate only based on its relative location to the receiving party. This can greatly enhance the performance of the celebrated maximum weight scheduling protocols, the throughput optimality of which depends on the channel estimation accuracy.

Routing protocol design: Because of the long propagation delay and high bit error rate of acoustic channels, it is very difficult to provide reliable, timely, and energy-efficient data transfer in large-scale underwater networks over multihop communications. To address the challenges of acoustic channels, sophisticated underwater routing protocols [10, 11] have been developed. However, the promising features of MI channels necessitate revisiting the underwater routing protocol design, taking into account the 3D feature of the underwater environment and the robust underwater MI channel. Moreover, different from the routing operations for EM, acoustic, or optical communications, the nodes in underwater MI-based communications can forward the packets to the next-hop node by acting as either a passive relay working in the MI waveguide mode or a conventional active relay by first receiving the packets and then transmitting them to the next-hop node. A passive relay does not consume any energy, while the forwarding distance is relatively small. An active relay can achieve longer forwarding distance by inducing the transmitting and receiving energy consumption. Therefore, by adaptively selecting different relay modes, the optimal routing protocols can be designed to yield the best trade-off between network lifetime and network latency.

Error control techniques: Since the underwater MI channel exhibits totally different characteristics from conventional acoustic channels, it is necessary to investigate the most suitable error control technique. For example, an MI channel experiences much lower variations, and such a stable channel may only require low-complexity FEC code with high coding rate to achieve high reliability. Our recent research [4] has shown that the low-complexity Bose, Ray-Chaudhuri, Hocquenghem (BCH) code, which is more energy-efficient than convolutional codes, is suitable for MI-based communications in challenging underground environments. Therefore, it is necessary to investigate the optimal FEC coding schemes that yield the best trade-off among the complexity, energy efficiency, and error correction capability of underwater MI-based communications.

This cross-layer module provides a unified solution for underground, soil, oil reservoir, and underwater environments because it can adaptively adjust the communication parameters according to the channel characteristics such as bandwidth and path loss under different environments.

Underwater MI-Based Localization

Localization is an important functionality for underwater communication networks. In particular, coordination and maneuvering of underwater robots and vehicles requires each robot to be aware of the relative 3D positions of its immediate neighbors as well as the absolute coordinates in the 3D underwater space. However, the absence of GPS underwater imposes great challenges in the realization of effective relative and absolute localization under water.

The existing underwater localization methods can be mainly categorized into acoustic-based and dead-reckoning ones, both of which have fundamental limitations. Acoustic-based methods, such as long baseline (LBL) and short baseline (SBL) systems, determine the relative or absolute positions of underwater vehicles by measuring the travel time of acoustic waves between vehicles or between the vehicle and anchor nodes, based on the measured or assumed sound speed, and/or the known locations of the anchor nodes. The acoustic-based methods require large acoustic antennas for emitting low-frequency sound, and are thus not suitable for small-scale underwater robots, and suffer unavoidable localization errors caused by the inherent multi-path propagation of acoustic waves especially in cluttered, confined, or shallow underwater environments. On the other hand, dead-reckoning methods estimate the current position of an underwater vehicle based on its last known position along with its speed and heading measured by the onboard sensors, such as gyroscopes, Doppler velocity sonar (DVS), and accelerometers. Utilizing the dead-reckoning methods, the errors in the position estimate grow without bounds as the underwater vehicle travels continuously.

To conquer the above problems, we propose the novel received magnetic field strength (RMFS)-based localization method, which uses the by-product of MI-based communication with tridirectional antenna: the RMFS between the 3 × 3 transmitting and receiving coil antennas. The novelty of the proposed solution relies on the unique multi-path fading free propagation properties of MI-based signals and the inherent orthogonality of tri-coil MI antennas, which guarantee accurate, simple, and convenient relative localization strategy. Moreover, such a method does not induce additional cost, occupy extra space, or increase the weight of the resource constrained underwater nodes. Specifically, each time underwater nodes communicate with each other, the RMFS is measured. Then the mutual distance between underwater nodes can be estimated using the MI channel model and maximum likelihood estimation (MLE) method. Because of the multi-path fading free feature, the RMFS-based localization method

To fully utilize the promising features of underwater MI-based communications, this article introduces the fundamentals of underwater MI communications, including the MI channel models, MI networking protocol design, and MI-based underwater localization.

will yield much more accurate estimation than the conventional acoustic-based solutions. Relying on real-time RMFS measurement, it does not induce accumulated estimation error as the dead-reckoning methods do. Moreover, since the MI-based technique is sensitive to direction, by using three coils in orthogonal planes, we can estimate the distance in each of the three directions separately, and calculate the distance and angular coordinates of the other underwater nodes relative to a fixed known reference [12]. The open research issues include the development of robust localization under inter-node MI interference for swarming underwater nodes.

CONCLUSIONS

In this article, we introduce a new underwater communication paradigm, namely underwater magnetic-induction (MI) communication. Fundamentally different from the conventional underwater communication paradigm, which relies on EM, acoustic, or optical waves, underwater MI communications rely on the time-varying magnetic field to covey information between the transmitting and receiving parties. MI-based underwater communications exhibit several unique and promising features such as negligible signal propagation delay, predictable and constant channel response, sufficiently large communication range with high bandwidth, and silent and covert underwater operations. To fully utilize the promising features of underwater MI-based communications, this article introduces the fundamentals of underwater MI communications, including the MI channel models, MI networking protocol design, and MI-based underwater localization.

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BIOGRAPHIES

IAN F. AKYILDIZ [F'96] (ian@ece.gatech.edu)received his B.S., M.S., and Ph.D. degrees in computer engineering from the University of Erlangen-Nuremberg, Germany, in 1978, 1981 and 1984, respectively. Currently, he is the Ken Byers Chair Professor in Telecommunications with the School of Electrical and Computer Engineering, Georgia Institute of Technology (Georgia Tech), Atlanta, director of the Broadband Wireless Networking (BWN) Laboratory, and chair of the Telecommunication Group at Georgia Tech. Since 2013, he has been a FiDiPro Professor (Finland Distinguished Professor Program supported by the Academy of Science) with the Department of Electronics and Communications Engineering, Tampere University of Technology, Finland, and the founding director of the Nano Communications Center. Since 2008, he has also been an honorary professor with the School of Electrical Engineering at Universitat Politecnica de Catalunya, Barcelona, Spain, and the founding director of the NaNoNetworking Center in Catalunya. Since 2011, he has been a consulting chair professor with the Department of Information Technology, King Abdulaziz University, Jeddah, Saudi Arabia. He is Editor-in-Chief of Elsevier's *Computer Networks Journal* and founding Editor-in-Chief of Elsevier's *Ad Hoc Networks Journal*, Elsevier's *Physical Communication Journal*, and Elsevier's . He is an ACM Fellow (1997). He has received numerous awards from IEEE and ACM. His current research interests are in wireless sensor networks in challenged environments such as underwater and underground, nanonetworks, terahertz band, 5G cellular systems, molecular communication, and software defined networking.

PU WANG [M] (pu.wang@wichita.edu) received his B.E. degree in electrical engineering from Beijing Institute of Technology, China, in 2003, and his M.E. degree in electrical and computer engineering from Memorial University of Newfoundland, Canada, in 2008. He received his Ph.D. degree in electrical and computer engineering from Georgia Tech under the guidance of Prof. Ian F. Akyildiz in August 2013. Currently, he is an assistant professor with the Department of Electrical Engineering and Computer Science at Wichita State University, Kansas. He received the BWN Lab Researcher of the Year Award from Georgia Tech in 2012. He received the TPC top ranked paper award at IEEE DySPAN 2011. He was also named Fa ellow of the School of Graduate Studies, Memorial University of Newfoundland in 2008. His current research interests are wireless sensor networks, cognitive radio networks, cloud radio access networks, software defined networking, cyber-aquatic systems, nanonetworks, and wireless communications in challenged environments.

ZHI SUN [M] (zhisun@buffalo.edu) received his B.S. degree in telecommunication engineering from Beijing University of Posts and Telecommunications and his M.S. degree in electronic engineering from Tsinghua University, Beijing, China, in 2004 and 2007, respectively. He received his Ph.D. degree in electrical and computer engineering from Georgia Tech under the guidance of Prof. Ian F. Akyildiz in 2011. Currently, he is an assistant professor in the Electrical Engineering Department at the State University of New York at Buffalo. Prior to that, he was a postdoctoral fellow at Georgia Tech. He won the Best Paper Award at IEEE GLOBECOM 2010. He was given the outstanding graduate award at Tsinghua University in 2007. He received the BWN researcher of the year award at Georgia Tech in 2009. His expertise and research interests lie in wireless communications, wireless sensor networks, and cyber physical systems in challenged environments.