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TOPICAL REVIEW

A Review on Electromagnetic, Acoustic, and New Emerging Technologies for Submarine Communication

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ABSTRACT The significance of the ocean in scientific research and military applications is growing, with submarines being pivotal for exploration and naval operations. However, the challenge of wireless communication with submerged submarines due to the strong absorption and scattering of electromagnetic waves in seawater limits their utility. This paper addresses the need for submarine communication methods characterized by speed, stability, cost-effectiveness, and long-range capabilities. It provides a comprehensive overview of current and potential future submarine communication techniques, including electromagnetic, acoustic, and optical methods, analyzing their performance in various channel complexities and discussing their advantages and drawbacks. Additionally, emerging technologies such as magnetic, translational acoustic-RF (TARF), photo/thermo-acoustic (PA/TA), neutrino, and quantum communication are explored, showing promise for the future of submarine communication systems. The upcoming generation of communication technology may establish a three-dimensional communication network connecting land-based stations, buoys, drones, satellites, and submarines to enhance the efficiency and reach of underwater communication.

INDEX TERMS Submarine communication, electromagnetic, optical, acoustic, underwater network, cross-boundary communication, buoy-based communication.

I. INTRODUCTION

Seventy percent of the earth is covered by the ocean, and exploring the deep ocean is one of the most important topics of scientific research. The submarine is one of the most significant means we can use to explore the unknown deep sea. After the First World War, submarines were widely used and occupied important roles in the navies of many military affairs countries. At the same time, submarines were also used for non-military purposes, such as marine scientific research [1], property rescue [2], exploration and mining [3], scientific reconnaissance [4], maintenance of equipment, submarine cable repair [5], underwater tourism, academic investigation, etc. For all kinds of submarines, communication is quite important. Since the sixth generation (6G) of wireless networks is developing and may play an important role in future communication, the Internet of Things (IoT) can become the future trend [6], [7]. As the communication technology between objects above the ground is quite mature, the communication system connecting the sky to the deep ocean still needs to be further established, considering the communication of the IoT network requires a fast and stable connection between the nodes both above the ground and underwater [8]. For example, satellites, drones, and ships need to communicate with the underwater submarine [9], [10]. The collaboration of the plane and the submarine is also an urgent demand in military operations.

Nowadays generally used method to communicate with the submarine is a mainly low-frequency electromagnetic wave (from 30kHz to 300kHz). However, this method

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has its intrinsic drawback: to promise the communication distance, its data rate is extremely low. At the same time, underwater acoustic communication is another common submarine communication technology, but it has poor flexibility, low transmission data rate, and difficult achieving two-way communication between sky and underwater.

Compared with the fast, low latency, and long-distance communication above ground, effective communication technologies are still lacking for submarines. The data rates, stability, and communication distance are still far from satisfactory and are the limitation of the application prospect of the submarine [10], [11], [12]. The following difficulties exist for electromagnetic and acoustic submarine communication. First of all, the air-to-water channel includes two very different media. Thus, the air is suitable for electromagnetic wave transmission, while long-distance transmission in water is difficult. However, the transmission of the sound waves in the water and air is just the opposite. For most of the methods, if its performance in one media is great, its performance in another media may not be that great. Such as the electromagnetic wave performs well in the air, but meets huge absorption in the water; the sound travels a long distance in the water channel but scatters a lot in the air [12]. If the media needs to be transformed on the boundary, the energy loss (such as reflection) is a big problem that needs to be solved. The second problem is that the high-frequency electromagnetic/acoustic waves attenuated seriously in the water indicate that the frequency band used to communicate should be narrow, thus the data rate can not be very high. Furthermore, turbulence, scattering, and inhomogeneous media, all of which can make submarine communication unstable and low transmission rate [13], [14]. Thirdly, if the buoy is used in the submarine communication system, it can be costly, hard to deploy, and inflexible.

There have been several surveys on underwater communication recently. In 2021, Kaza et al. provided a review on achieving energy efficiency in underwater wireless communications, covering network architectures, physical layer technologies and power-saving techniques, upper layer energy-saving techniques, and alternative energy sources [15]. In 2022, Luo et al. provided a review of recent progress in air/water cross-boundary communications, categorizing existing works into three types: optical direct communication, relay-based communication, and non-optical direct communication [16]. Also in 2022, Aman et al. explored the security challenges and countermeasures for underwater and air-water wireless communication networks, including a review of state-of-the-art technologies and a discussion of various security breaches and potential solutions [17]. In 2023, Dao et al. explored the potential of underwater wireless communication (UWC) in complementing the sixth-generation (6G) network infrastructure [18]. Later, Junejo et al. provided an overview of the physical layer techniques and channel modeling challenges of underwater communications, including various modulation technologies, and their merits and demerits [19].

Through extensive literature research, we observed that the majority of submarine communication studies rely on well-established electromagnetic, acoustic, and optical methods (see table 1 for a brief comparison). These methods are mature and practical. Yet, there has been limited exploration of emerging methods for effectively transmitting information across the air-water boundary, which is a crucial aspect of submarine communication. While some of these methods are currently in the prototype stage, they hold significant potential as future trends.

The contributions of this review include a detailed examination of electromagnetic, acoustic, and optical communication methods and their performance under varying channel complexities. The paper also explores promising emerging technologies like magnetic, TARF, PA/TA, neutrino, and quantum communication, which hold great potential for the future of submarine communication. Furthermore, the paper discusses future directions, focusing on the increasing deployment of autonomous underwater vehicles (AUVs), the integration of different communication technologies, optimization using deep learning, and the development of active and passive buoys. These future directions aim to address current limitations, improve data rates, reduce latency, and ensure cost-efficiency, security, and reliability in underwater communication.

The rest of the paper is structured as follows: in sections II, III, and IV, electromagnetic, acoustic, and optical submarine communications are introduced respectively. In section V, some new methods of communicating with submarines are discussed, including magnetic, translational acoustic-RF (TARF), photo/thermo-acoustic (PA/TA), neutrino, and quantum communication. In section VI, the future direction of submarine communication is discussed. Finally, in section VII, the conclusion is made and the future trend is discussed. Fig. 1 shows the scenario of communication with submarines, and the communication methods that will be introduced in this paper are included.

II. ELECTROMAGNETIC COMMUNICATION

Since Oster discovered the magnetic effect of current in April 1820, the classical electromagnetic field theory was established, and modern communication technology has laid the tone for the use of electromagnetic waves for communication. Long before the invention of the modern submarine, electromagnetic waves have been used extensively for communications on land. People have summed up many classic electromagnetic wave laws in practice, and continue to iterate wireless electromagnetic communication technology. After the need for submersible communication, the use of electromagnetic waves for communication became a very natural choice.

As the nowadays most accepted communication method, the most mainstream way to enable communication between the military submarine and the onshore command center,

TABLE 1. Comparison of electromagnetic, acoustic, and optical communication.

Type of technology	Data rate/Transmission distance	Propagation speed	Frequency	Applicable scene	Benefits	Limitations
Electromagnetic communication	1-10 Mbps/1-2m [20] 50-100 bps/200m [20]	3.3×10^7m/s	30-300 Hz	Shallow water	Low propagation delay; Relatively smooth propagation in air-water channel	Limited propagation range and data rate; Huge bulky antenna
Acoustic communication	1.5-50 kbps/0.5km [21] 0.6-3.0 kbps/28-120km [22]	1500 m/s	10-1000 Hz	Deep water	Propagate over long distance	Multipath effect in shallow water
Optical communication	1 Gbps/2m [23] 1 Mbps/25m [24]	3.3×10^7 m/s	$10^{12} - 10^{15}$Hz	Clear water	Low propagation delay; High data rate	Attenuation in air-water boundary; Need alignment

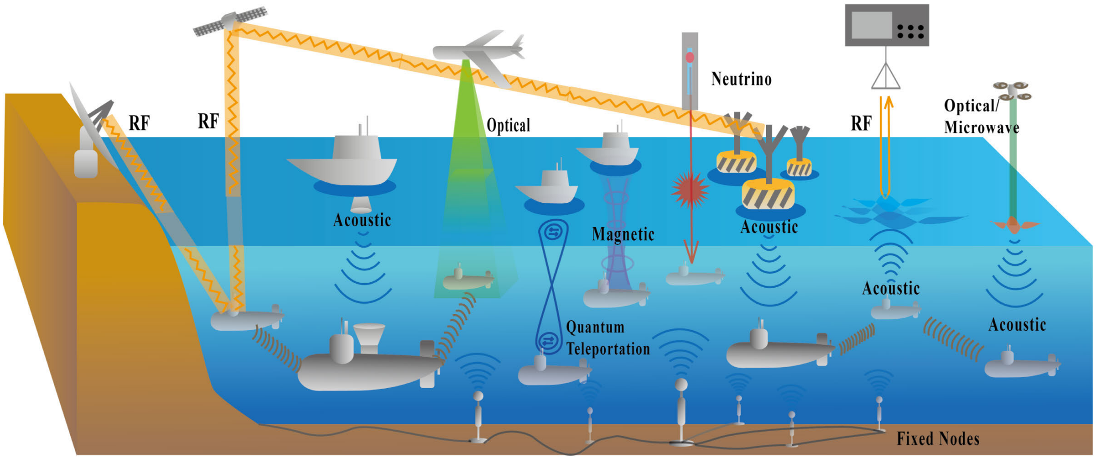


FIGURE 1. Scenario of communication with submarines.

electromagnetic communication plays an important role in military defense and country safety. The electromagnetic wave has a relatively smooth progression in both air, water, and air-water boundary channels and has a low doppler shift, which makes it the first choice to realize communication to submarine.

Electromagnetic wave, however, also has some limitations. Since seawater is highly conductive media, the 800 MHz electromagnetic wave has an attenuation of 825 dB/m in sea water [25], [26]. Compared with the 0.035dB/m acoustic wave attenuation in sea water [27], that is a huge number. As a result, the frequency of the electromagnetic should be very low to ensure enough communication distance. It is almost impossible to realize submarine communication with very-high frequency (VHF) or ultra-high frequency (UHF) range [28]. The extremely low frequency (ELF) and very low frequency (VLF) ranges are commonly used in electromagnetic submarine communication. However, the low frequency will lead to a low data rate, extremely powerful base stations, and bulky transmit antennas. For example, the 200m distance electromagnetic submarine communication can only reach 50 to 100 bps [20]. Many world military powers build huge transmit stations for electromagnetic submarine communication, they are energy-consuming but can only support some basic functions because of the data rate limitation. Fig. 2 is the schematic of electromagnetic submarine communication.

The world's first ELF station was built by the US Navy in 1968. Its transmission power was 800 megawatts and took an area of 20,000 square miles. It used a modulation method called minimum key-shifting. This kind of modulation used a smooth connection between segments of 72 and 80Hz sinusoids to indicate the "1" and the "0". While the frequency is so low, the researchers masterly used the ground as a giant plane and let the current flow through the earth. Meanwhile, Russia also built its 82Hz ELF transmitter, and India built one in 2015.

Channel attenuation is one of the most important things that need attention. It can be described as (1), where $\alpha(f)$ represents the attenuation per meter, f and σ represent the

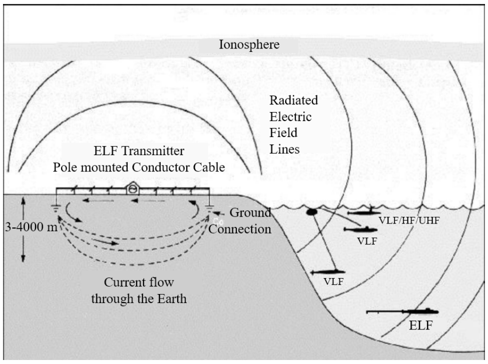


FIGURE 2. **Schematic of electromagnetic submarine communication [28].**

RF wave frequency in Hz and seawater conductivity in S/m, respectively. $\mu_0 = 4\pi \cdot 10^{-7}$ is the vacuum permeability [29].

$$\alpha(f) = \sqrt{\pi\sigma\mu_0}\sqrt{f} \tag{1}$$

Since the permeability is quite unified, the factor that decides the attenuation is the salinity of the seawater.

The multipath effect is another factor that should be taken into consideration [30]. Except for the water path, the large refraction angle of the electromagnetic wave can create a path almost parallel to the air-water boundary in the air. That means the repeater buoy on the sea surface is needless. Another path is the path on the seabed. Since the conductivity is rather low, this seabed path is low noise and covert. Therefore, the receiver can be further improved and anti-multipath signal processing and adaptive cancellation technology can possibly be used to face the multipath effect.

In the future, electromagnetic communication can still be improved in antenna design, modulation method, transmitter design, etc. It's also more likely to invite other methods to realize the communication to a submarine or fuse the traditional RF communication with new methods.

III. ACOUSTIC COMMUNICATION

As introduced above, electromagnetic submarine communication has some limitations because of the intrinsic characteristic of the electromagnetic wave. As a very effective communication method for ships on the sea surface, electromagnetic wave communication is very limited in communication with underwater targets because of electromagnetic waves' huge attenuation in water. In other words, the communication distance and the data rate can not be both promised. Since the researchers were precisely aware of this problem, in order to solve this problem and find out the direction for the communication with deep-sea submarines, they began to study underwater acoustic communication as early as 1914 and great progress has been made so far.

The low attenuation for sound in the water makes it a good candidate for communication between the above-water transmitter and the underwater submarine. Its working principle is as follows: after encoding and modulating information such as text, voice, image, or even video, the power amplifier drives the acoustic transducer to convert the electrical signal into an acoustic signal. The transducer transmits the information to the remote receiving transducer through the medium of water. Then the acoustic signal is converted into an electrical signal. After amplification, filtering, and digitization, the digital signal processor performs adaptive equalization and error correction on the signal and restores to sound, text, and pictures or video.

Compared with RF waves, underwater acoustic communication (UWAC) has a better performance in the water. It has a data rate of 50 kbps for 0.5km [21] and 0.6-3.0kbps for 28-120km [22]. Its propagation range is almost the longest of all of the existing methods, but the communication latency is relatively higher than electromagnetic communication because sound travels far slower in the water than electromagnetic waves. The sound can reflect on the air-water boundary and the ocean floor, making the UWAC system need to solve a lot of problems if wants to have a very good performance in shallow water.

The origin of the idea to use acoustics to transmit information is from the experiment made by Leonardo da Vinci. In 1750, the partial differential equation of motion based on the sound wave was introduced, forming the fundamental basis of the theory of the UWAC system [31]. In 1826, the speed of the sound in the lake water was measured by J.D.Collado [32]. In the late 19th century, the UWAC could reach the data rates of 8 kbps for the distance of 13km [33]. The first modern military UWAC system was built by the British Navy in 1914, later in 1945, the US Navy built the underwater telephone used to maintain the communication between the underwater submarines. In 2005, the researchers achieved the data rates for 125 kbps by using 32-quadrature amplitude modulation(QAM) [31].

The underwater channel is quite complicated for acoustic communication. First, the acoustic speed varies with different factors. The temperature, salinity, and depth can all influence the speed of the water. For example, with the temperature increase for 1°C, the speed of the acoustic wave can increase by 4m/s. If the salinity increases for 1 practical salinity unit, the speed of the acoustic wave can increase by 1.4m/s. If the depth increases by 1 km, the speed of the acoustic wave will increase by 17m/s. There's an acoustic model to calculate the speed as (2) shown, in which T is the temperature in degrees celsius, S is the salinity in parts per thousand(ppt), z is the depth in meters [34].

$$\begin{aligned} c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 \\ + (1.34 - 0.01T)(S - 35) + 0.016z \end{aligned} \tag{2}$$

Second, the transmission loss can be caused by several factors such as the ambient noise, multipath effect, and Doppler effect, together with the low bandwidth of acoustic communication [28]. The noise is from various sources and has different frequencies: earthquakes, wave turbulence, atmospheric storms, and underwater volcano eruptions are the main sources of the low-frequency noise; shipping and

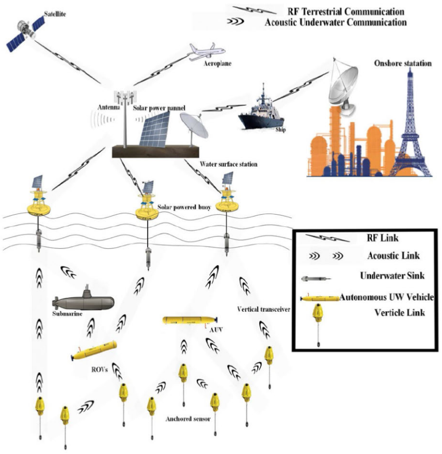


FIGURE 3. **Different carriers of the UWAC system, including buoy and underwater nodes [31].**

wind are the main sources of the noise from 100Hz to 100kHz; thermal noise is in high-frequency range [35]. Third, in the water environment, absorption is unavoidable, which is highly related to the signal frequency [36].

To deal with the problems listed above, some of the channel estimation models have developed during the past few years. These models can be divided as the Multipath channel model, SISO (Single-input single-output) and SIMO (Single-input multiple-output), Pilot assisted OFDM, Cyclic prefix (CP) OFDM, Zero-padded (ZP) OFDM, MIMO, and MIMO-OFDM system models [37]. Meanwhile, the researchers are not only focusing on channel estimation but also on detection, coding, equalization, and transmission. These whole systems of methods together form the support of the UWAC system.

The acoustic transducer plays an important role in the UWAC system. It is the device that can realize the transformation between the sound and electric signal. The acoustic transducer generally functions as a transmitter and receiver. The transmitter is generally omnidirectional or hemispherical, while the receiver can both be directional or omnidirectional [38]. Meanwhile, the system can be improved by composing an array with several omnidirectional receivers. Commonly, the transducers are piezoelectric and magnetostrictive [39].

In the future, the UWAC system still needs to be further explored. The data rate and the stability of the UWAC system can be further improved. Meanwhile, the carrier of the UWAC system can be developed as shown in fig. 3, especially for the passive relay, which can possibly be the next-generation trend of acoustic communication for its low cost and high security.

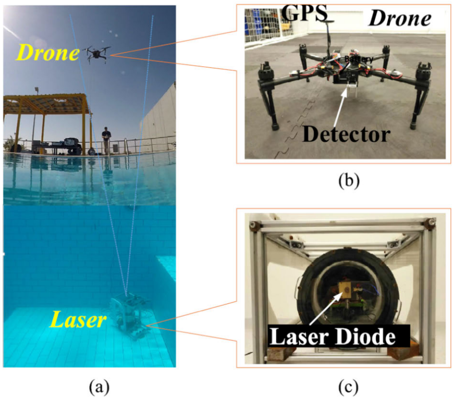
IV. OPTICAL COMMUNICATION

Compared with electromagnetic and acoustic communication, underwater optical communication (UWOC) is a kind of newborn communication method between the sky and the submarine. Only in 1980, did the US Navy begin to research the communication method with blue and green lasers, trying to realize communication with a rather high data rate and high flexibility. They assume that optical communication can possibly become the next-generation communication method.

It is widely known that optical communication has a data rate of up to Gbps due to the high modulation bandwidth and can transmit for up to 100 meters in clear water [40], [41], [42]. Its transmitting speed is very fast, almost the same as the RF wave communication, and reaches 3.3×10^7 m/s [42]. Meanwhile, the light-emitting diodes (LEDs), laser diodes (LDs), and photodiodes (PDs) UWOC used are comparatively low cost, which makes optical communication a method easy to promote [43].

In 1962, the LED and LD were invented, and later in 1963, the transparent window for light in the water was found, these two inventions together form the theoretical basis of the UWOC system [44], [45], [46]. In 2004, scientists from Australia achieved a data rate of 57.6 Kbps and a distance of more than 1m [47]. In 2018, Huang et al. conducted an experiment in which the data rate achieved 14.8Gbps for 1.7m, using 16 QAM-OFDM modulation [48].In 2019, Hong et al. reached a data rate of 18.09 Gbps and a distance of more than 5 m by using Discrete Multi-Tone (DMT) modulation and probabilistic constellation shaping technique [49]. In the same year, Wang et al. realized the communication at a distance of 100m with a data rate of 500 Mbps by using 520nm green LD and NRZ-OOK modulation [50]. In the future, according to the research by Sun et al., it is possible for the drone-based transmitter to realize real environment communication as shown in fig. 4 [12]. To be specific, the research in [12] presents a high-speed system for direct communications across a water-air interface and achieved a gross data rate of 10 Mbit/s and a high data rate of 850 Mbit/s when perfectly aligned. The system was proven to be robust in harsh underwater environments and can facilitate a 44-Mbit/s direct and mobile communication link over a transmission distance of 2.3 m underwater and 3.5 m in air. The results suggest that the system is favorable for stable communications in harsh environments.

To realize the communication between the transmitter in the air and the underwater receiver with light, the biggest challenge is the complex channel characteristic under the water surface. The light scatters, diffracts, and can be absorbed under the water, which makes the transmission challenging, especially in the turbid harbor water [31]. The optical properties of the seawater can be divided into inherent optical properties and apparent optical properties, inherent optical properties are more dominating and will be discussed as follows [51]. The attenuation coefficient of the light in the water can be described as $c(\lambda) = a(\lambda)+b(\lambda)$, $a(\lambda)$ and $b(\lambda)$ represent the absorption coefficient and scattering coefficient with the unit of m^{-1} respectively [43]. The power of received light can be described by Beer Lambert's law as (3), I_0 is the power of transmitted light, $c(\lambda)$ is related to the different water types, the biggest in turbid harbor water



(a) (b) (c)

FIGURE 4. (a) A photograph of the drone-aided pool deployment apparatus, (b) APD430A2/M receiver mounted on a drone, and (c) transmitter laser mounted in the capsule. [12].

and smallest in the pure ocean water, and z is the distance of light transmission [52].

$$I = I_0 e^{-c(\lambda)z} \tag{3}$$

This indicates that the UWOC is most suitable for the condition in the area where the water is clear, for example, an ocean away from the coast. In other words, in some coastal areas, the performance of the UWOC may not be very satisfactory.

There are two types of UWOC channel models named point-to-point line-of-sight (LOS) configuration and non-line-of-sight (NLOS) configuration [53]. LOS link needs strict alignment and the NLOS link transmits data by using the reflection of the ocean surface [54]. For the LOS link, the researchers used the Radiative Transfer Equation(RTE) model to precisely describe the behavior of light in the ocean environment [43], [55]. The RTE model is hard to find general analytical solutions and can be found in numerical solutions by using methods such as Monte-Carlo [56], Discrete Ordinate [52], Invariant Imbedding [52] and Stochastic Model [57]. For the NLOS link, several models were established [58], [59], [60], but the existing models are still not accurate enough and many factors such as fluctuations in the ocean surface had not been taken into consideration.

The nowadays commonly used UWOC transmitter is made of LDs and LEDs, while superluminescent diodes (SLD), Vertical-cavity surface-emitting laser (VCSEL), and micro-LED are also employed. Since the bandwidth of the transmitter is directly linked with the data rate, this is one of the factors that should be considered. Researchers from the National Taipei University of Technology reported the −3dB modulation bandwidth with 8 GHz using LD [61], and US researchers realized 340 MHz using Micro-LED Arrays [62]. Moreover, several technologies can be used to improve the data rate and transmission distance, such as high-performance device technology [63], equalization technology [64], and light injection locking and optoelectronic feedback techniques [65].

Since the complex feature of transmitted light, the receiver of the UWOC system should be able to receive the scattered light and have a high signal-to-noise ratio (SNR) to resist the interference of the ambient light and turbulence. As the result, Photomultiplier tubes (PMTs) [66], photodetectors [67], and multi-pixel photon counters (MPPCs) [68] are used in UWOC receiver. The main source of noise is quantum noise, photodetector dark current noise, transmitter noise, electronic noise, optical background noise, and oceanic turbulence [53]. These kinds of noise can be suppressed by filters like optical filters and band-pass filter [69], [70].

There are several modulation methods used in the UWOC system. The mainstream modulation method is intensity modulation (IM) since it's quite simple. The on-off keying modulation(OOK) is also very popular, it's simple, low-cost, and easy to employ. Pulse amplitude modulation(PAM) is also used, similar to OOK but more efficient than the OOK since it uses several different levels of amplitude to modulate information. Apart from the modulation methods listed above, there are some other modulation methods used in the UWOC such as pulse position modulation (PPM) [71], quadrature amplitude modulation (QAM), and carrierless amplitude and phase (CAP) modulation [72]. In addition, orthogonal frequency division multiplexing (OFDM) is used for its performance in resisting multipath effect [71]. It can be combined with QAM as QAM-OFDM modulation [73].

Though the UWOC technology has been a great achievement, there are still a lot of challenges and short-backs. First of all, long-distance transmission is currently unreliable, because of the intrinsic feature of underwater light as scattering and absorption [62]. Secondly, the alignment problem of the UWOC system is still hard to solve. It directly influenced the communication quality [74]. Thirdly, as the present experiments are mostly in the lab, there needs to be a more practical experiment and more precise modeling that can be aided by deep learning [75], [76], [77], [78]. It also would be better for the future UWOC system to be low-cost and energy-efficient to satisfy the need for small-scale submarines.

V. NEW METHODS OF COMMUNICATING WITH SUBMARINES

We have reviewed the three mainstream communication methods with submarines, which respectfully use three different carriers. Those methods used to communicate with the submarine are relatively mature, some of them are even widely used in practice. However, they all have some shortcomings and cannot perfectly realize the high data rate, long distance, and high stability. While in the process of communicating with the submarine, the signal has to pass through both the air and water. As a result, the researchers propose that it can possibly use two different carriers to transmit signals in the two media to decrease the attenuation in the transmit path. For example, Translational acoustic-RF communication (TARF) uses both microwave and sound, the photo/thermo-acoustic (PA/TA) uses both laser/microwave

TABLE 2. Comparison of new communication technologies.

Type of technology	Data rate	Transmission distance	Benefits	Limitation
Magnetic communication	∼Mb/s [79]	10-100m [79]	Simple antenna structure; Relatively smooth propagation in air-water channel	Need alignment
TARF communication	∼Bits/s [10]	Several meters	Low cost; Possible low attenuation in signal path	Hard to apply more efficient modulation method; Only support uplink communication
Photoacoustic / thermoacoustic communication	∼Bits/s [80]	Several meters	Low cost; Possible low attenuation in signal path	Hard to apply more efficient modulation method; Only support downlink communication
Neutrino communication	0.1 bit/s(1.035km) [81]	more than 700 km [82]	Long distance; Low attenuation	High energy consumption; Huge transmitter and detector
Quantum communication	170 kb/s (security guaranteed) [83]	100m (security guaranteed) [83]	High security	Currently high cost

and sound. Meanwhile, some other mediums such as magnetic, quantum, and neutrino are also experimented to realize submarine communication.

In this section, these five new methods will be introduced and compared(table 2). They all have different advantages and disadvantages and are suitable for different scenarios. These methods have a different theoretical basis and may be the next generation of mainstream communication methods between the air and underwater submarine.

A. MAGNETIC COMMUNICATION

Magnetic communication is a method through coupling between magnetic fields that can realize communication across the air-water boundary(shown in fig. 5). As a newborn communication technology, magnetic Communication has some advantages such as low latency and the simple structure of antenna [84], [85], [86], [87]. Compared with the huge antenna electromagnetic communication needed, magnetic communication uses small-size coupling coils to induce magnetic components to realize communication [88]. In the underwater environment, the water has almost the same magnetic permeability as the air, and the underwater channel is very stable [79].

Magnetic communication is mainly based on the principle of electromagnetic induction, which uses the change of magnetic field generated by the transmitting end to transfer information. The receiving end utilizes the principle of magnetic induction to convert the received magnetic signal into an electrical signal for decoding. Specifically, the transmitting end generates a magnetic field by placing a transmitting coil in the water and modulates the frequency, amplitude or phase of the magnetic field to transmit information. The receiving end uses a receiving coil placed in the water to receive the magnetic field signal. After amplification, filtering and demodulation, the received magnetic signal is converted into an electrical signal that can be decoded.

In 2001, Sojdehi et al. proposed the idea of magnetic communication and indicated the difference between the magnetic signal and the electromagnetic signal [90]. Later, Rajeev Bansal realized the near-field communication with magnetic [91]. In 2012, Mari C Domingo established the underwater magnetic communication model, verifying the feasibility of magnetic communication in the underwater environment [92]. In addition, there is a lot of further research on various directions such as the combination of magnetic communication and the acoustic communication [93], and the influence of the transverse wave in the shallow water [94], [95], trying to improve the SNR, bandwidth and lower the Bit Error Rate (BER) [96]

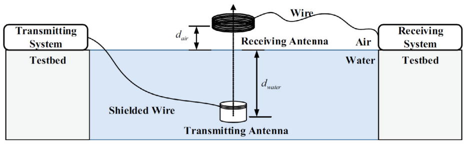


FIGURE 5. The fundamental of magnetic communication [89].

The physical property of the magnetic field may also limit the transmit distance of the signal. As (4) shown, the magnetic field strength H decreases as an exponential function, where H_0 is the original magnetic field strength, r is the distance in meters, σ is the electrical conductivity, μ is the magnetic conductivity, f is the signal frequency [97].

$$H = H_0 \times e^{r\sqrt{\pi\sigma\mu f}} \tag{4}$$

Nowadays, the research on magnetic communication mostly focuses on the scenario that the transmitter coil and the receiver coil have the same axis. As a result, it's not enough for the real ocean environment since the underwater node does not have a fixed location and orientation. In the future, research on the omnidirectional magnetic communication model may fix this problem and improve the stability of communication.

B. UPLINK: TARF COMMUNICATION

Different from all of the methods listed above, translational acoustic-RF communication(TARF) uses two media to realize the communication. It is a one-way communication method, able to communicate from the underwater submarine to the above-water receiver. Therefore, it has great application prospects in two-way communication. TARF

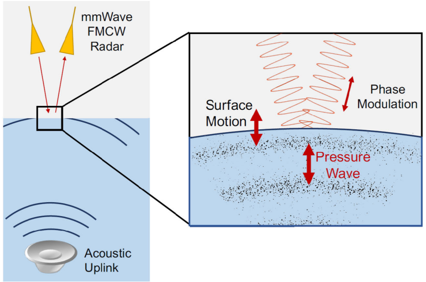


FIGURE 6. **The principle of TARF [10].**

was first introduced by the MIT media lab in 2018 [10]. Its principle(shown in fig. 6) is as follows: The acoustic signal from the underwater transmitter can cause a tiny vibration on the surface of the air-water boundary. The receiver is an airborne radar above the water surface, which can measure the displacement of the surface and decode these displacements.

As a newborn communication method, there are several challenges to TARF communication. Firstly, the displacement is very tiny which is of the order of a few tens of microns. If the submarine is deep under the water's surface, the surface displacement might be even harder to detect. Secondly, the ocean surface itself has fluctuation and it is almost random. The environmental fluctuation is much bigger than the vibration caused by the transmitter. Thirdly, since the mechanism to estimate the overall channel is lacking, it can not choose the appropriate modulation and coding schemes to match the channel quality.

To deal with the issues mentioned above, the researchers improved the transceiver architecture with the communication protocols. Firstly, the millimeter wave sensor was used to detect the small displacement on the surface. Even a few microns can lead to phase change and be detected. The frequency-modulated carrier wave(FMCW) radar is also incorporated, decreasing the environmental noise. Secondly, the filter is designed following the mechanical nature of the wave. Thirdly, the modulation scheme is designed based on some unique properties, such as the channel's frequency-selective fading being inversely proportional to the transmit acoustic frequency. Moreover, a pressure sensor is used to make a proxy for the channel. By detecting the distance between the water-air surface and the transmitter, it can estimate the dominant path loss components to compensate for the lack of receiver feedback.

For TARF, it's important to choose an appropriate modulation method since the channel is highly frequency-dependent. The researchers employ Orthogonal Frequency Division Multiplexing(OFDM) in the TARF system [98], which makes decoding be done in the frequency domain without channel equalizers.

The TARF receiver measures the variance in the distance by estimating the difference in the phase of the reflected signal. The wavelength employed can not be too long, making the phase change immersed in the noise and hard to be detected; or too small, leading to the phase rotation and unable to measure the displacement of the water surface.

The researchers do the experiment in both the water tank and the swimming pool. The results indicate that the SNR decreases from 25 dB when the transmitter is 90cm underwater and 14 dB when the transmitter is 3.6 m underwater [10]. This SNR trend follows a $1/r^2$ curve. It is also shown that the SNR decreases from 11 dB to 3 dB when the system changes from completely aligned to horizontally misaligned for 28 cm, which means that the system heavily relies on alignment. Additionally, TARF's channel can maintain minimal degradation when the vibration is up to 6 cm and is more tolerant when the moving speed of the fluctuation is slow. When the wave has more than 22cm peak-to-peak amplitude(100,000 times more than the displacement caused by the transmitter), the TARF's throughput will be zero, since the phase will wrap very quickly and the large fluctuation wave can deflect the radar wave reflection away from the receiver due to the radio wave's specular nature.

In conclusion, TARF communication is still a method that has a long way to go since it has several limitations. First, because of its theoretical basis, it only enables uplink communication, which means the submarine can only send messages to the above-water receiver but do not able to receive the message from the above-water transmitter. This can be the biggest drawback since the submarine needs to receive instructions from outside and get to know its location. Second, the ocean environment is far more complex than the water tank or the swimming pool, the wave height can even reach 20 to 30 meters. If the system wants to work stably in such an environment, the surface status should be actively monitored and the communication protocol should be improved. Thirdly, the communication of the system needs sophisticated alignment, which means the receiver needs to scan the water surface to find the location of the underwater transmitter. This can be improved if the scanning solution can be adapted.

After all, while the TARF system is still lacking research, it innovatively gives out a solution for communication from the submarine to the sky. It has great potential to be further improved and combined with the other methods.

C. DOWNLINK: PHOTO/THERMO-ACOUSTIC (PA/TA) COMMUNICATION

TARF communication provides a great idea that uses different media in air and water for uplink communication. Photo/Thermo-Acoustic Communication (PAC/TAC) also applies this idea. While the TARF communication only supports the uplink communication, PAC/TAC can realize the downlink communication and play as a supplement [99], [100].

The theoretic basis of the PAC/TAC is the photoacoustic or thermoacoustic effect. As shown in fig. 7, the water surface absorbs the pulsed electromagnetic energy and further

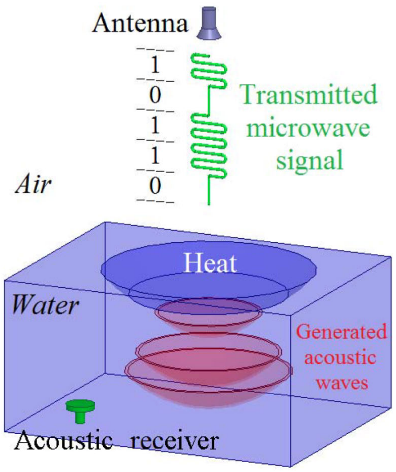


FIGURE 7. The principle of TAC [80].

induces temperature rising [101]. The temperature rising can cause the local thermal expansion thus producing sound signal [102], [103], [104], [105]. This effect is usually used as PA/TA imaging in biomedical non-invasive detection, but it can also be introduced in submarine communication [106], [107]. The intensity of the acoustic signal is proportional to the incident electromagnetic power [108].

The OOK is the most basic modulation method used in the PAC and TAC. A binary "1" corresponds to the time when an electromagnetic wave(light or microwave) works on the water surface and "0" corresponds to the rest of the wave. Since this method can only send one bit at a time, the data rate is very low. As a result, some advanced modulation methods must be further explored.

The performance of the PAC or the TAC model is related to factors such as the antenna gain, height of the antenna, depth of the receiver, frequency, and angle of the incident radiation [80]. To be specific, firstly, the acoustic signal will be improved when the antenna gain is improved since the power density on the water surface will increase. Secondly, the heat density will decrease proportional to $1/H^2$, H is the distance between the water surface and the antenna; the acoustic signal the receiver receives will decrease proportionally to $1/D^2$ too, and D is the distance between the water surface and the underwater receiver. Thirdly, from the experiment made by Wang et al., when the microwave frequency increase, the thermoacoustic signal will increase when the microwave frequency is less than 14GHz, and decrease when the microwave frequency is bigger than 14GHz since the cancellation effect will become dominant [80].

PAC may be the solution to the problems listed above. From the newest research made by Zhong Ji et al., PAC based on the passive relay may be able to minimize the energy loss and reduce the difficulty of target seeking compared with TAC [109]. By using a 660 nm laser beam and 14 ns pulse width at a repetition frequency of 1 kHz, they realize the communication with pulse energy only 27μJ [109]. Moreover, compared with TAC, some advanced methods such as Optical Focusing-based Adaptive Modulation (OFAM) can be applied [110].

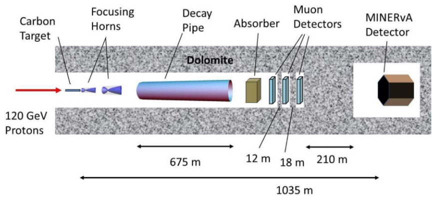


FIGURE 8. The prototype of neutrino communication. [81].

The PAC and TAC are innovative and provide us with a possible solution to deal with the communication to submarine issue, and may be compatible with the existing communication technologies. However, its energy loss on the surface of the air-water boundary is a big problem waiting to be solved. And it should also be adaptive to the complex underwater environment, same as the traditional underwater acoustic communication.

D. NEUTRINO COMMUNICATION

The main difficulties in communication with the submarine are caused by the complex ocean environment. All of the methods mentioned above struggled to build channel models and adapt to them. Because of the characteristics of neutrinos, it can probably be used for communication with less care about the channel characteristic.

Neutrino is a kind of lepton, with no charge, a very small mass(some less than one-millionth of an electron), and almost has the speed of light. Its interaction with other matter is very weak, and can freely pass through human bodies, walls, mountains, and even entire planets, making it difficult to be captured and detected. Since it has an extremely strong penetration ability, the channel characteristic becomes inconsequential for submarine communication. Submarines can receive neutrino signals anywhere in the ocean, making it of low possibility to be attacked [81], [82]. The prototype of neutrino communication is shown in fig. 8.

The neutrino was first designed to be used for interstellar communication [111], [112], [113], and some researchers have also discussed its underwater usage [114], [115]. Such as K2K [116], MINOS [117], and ANTARES [118] are all famous neutrino experiments. By using a high-energy proton accelerator, protons can be accelerated and obtain high-energy electron beams up to several hundred billion electron volts. It is then used to bombard the target, thus creating unstable particles. These particles, after constant changes, finally form neutrinos and other particles. Then they are allowed to pass through a thick steel plate, which sifts out the charged particles, and the uncharged neutrino beam is obtained.

Detecting Cherenkov light can be a method to obtain the neutrino signal in the water environment [119]. When a high-speed neutrino hits the proton in the water, the proton will get energy from the neutrino and have a very high speed. If the proton's speed is higher than the speed of light in the water c/n, the Cherenkov light will be produced and detected by the light detector.

As for the submarine, the most straightforward approach to neutrino signal detection is to convert the submarine itself into a detector: a modern submarine has a big surface area, which allows an effective detection area. Thus we can use thin detector modules to cover the majority of the outer layer of a submarine.

Neutrino communication has some favorable characteristics such as long distance, low attenuation, and very stable. However, transmitting neutrinos consumes a great amount of energy if the number of neutrinos transmitted wants to be promised. Moreover, the neutrino detector can be bulky. Its radius can be more than 100m and impossible to be carried by submarine. Plus, the Cherenkov light is weak, which is primarily attributed to the low interaction rate of neutrinos, and the high-speed, low-charge nature of the secondary particles they produce. As a result, the neutrino detector can only work in the deep ocean in case of interference from the environmental light.

E. QUANTUM COMMUNICATION

For all of the communication methods introduced above, the security of the communication has not been in detail discussed. For submarines, especially the submarines used for military purposes, communication security is of great significance. As the only communication method that proved to be unconditionally secure so far, quantum communication's application prospects in the field have been widely recognized.

Quantum communication is based on the principles of quantum mechanics, using quantum bits (qubits) to transmit information. Unlike classical bits, which can only have a value of either 0 or 1, qubits can exist in a superposition of both states simultaneously, allowing for more efficient transmission and processing of information. Quantum communication typically involves the use of entangled qubits, which are correlated in a way that any change in one qubit is immediately reflected in the other. This allows for the transmission of information in a way that is inherently secure, as any attempt to intercept or measure the entangled qubits would disturb their correlation, alerting the receiver to the potential presence of an eavesdropper.

In 2005, Pan et al. achieved quantum entanglement distribution and quantum key distribution at the 13 km level in free space [120]. The quantum entanglement distribution and quantum key distribution have been demonstrated for the first time. In 2010, a research team from Tsinghua University and the University of Science and Technology of China (USTC) successfully realized a 16 km quantum invisible transfer between Beijing and Hebei [121]. In 2012, researchers from USTC successfully realized the 100 km level quantum invisible transmission and two-way quantum entanglement distribution in free space [122] and the all-round ground-based verification of star-ground quantum communication [123]. In the same year, the Max-Planck-Institute in Germany and the Institute for Quantum Optics and Quantum Information (IQOQI) in Austria realized a free-space experimental quantum invisible transfer communication with an optical link of more than 143 km between LaPalMa and Tenerife islands [124]. Later in 2017, Jin et al. from SJTU successfully conducted the first seawater quantum communication experiment, indicating the feasibility of underwater quantum communication. Fig. 9 shows the prototype of quantum communication.

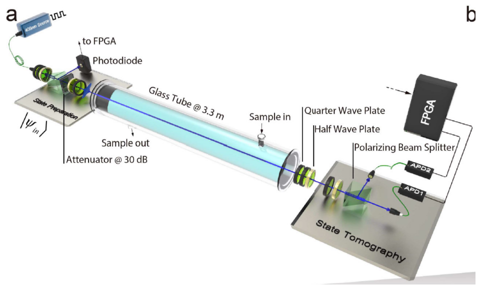


FIGURE 9. **The prototype of quantum communication [125].**

Based on the three principles including uncertainty, measurement collapse, and unclonability in quantum mechanics, quantum communication provides absolute security guarantees that cannot be hacked by eavesdropping and computing. This is the biggest advantage of quantum communication.

In the future, the improvement of the quantum relay technology and the building of the quantum communication internet can possibly help quantum communication achieve longer communication distances and a wider coverage area. Of its long communication distance and high security, quantum communication has great potential for future communication with the submarine.

VI. DISCUSSION: FUTURE DIRECTIONS FOR SUBMARINE COMMUNICATION

This section will discuss possible future directions for submarine communication. First, we will explore how the increasing deployment of AUVs and cluster AUVs will change underwater communication, bringing new opportunities for an effective communication network but also create higher demands. Second, the combination of different communication technologies such as electromagnetic, acoustic, and optical will be discussed. Then, we will analyze how deep learning can optimize communication parameters, and how the interconnection of mobile networks can be applied to overcome limitations in submarine communication. Finally, we will examine the development of active and passive buoys as possible solutions, and how the use of advanced signal processing tools can improve data rates and offset environmental unpredictability.

With the development of autonomous underwater vehicles (AUVs), cluster AUVs will gradually become an indispensable part of ocean exploration, resource development, environmental protection, and maritime rescue in the future. In cluster AUVs, a large number of AUVs will work together to achieve more efficient and accurate task execution, this will put higher demands on the communication network. In fact, due to the miniaturization, low cost, and large quantity of AUVs, the solution to communication problems of AUVs has become somewhat different. AUVs can substantially reduce data collection time and latency, which is a challenging task for traditional submarine communication due to its lack of environmental data collection methods. AUVs also have the ability to to overcome node localization challenges and predict routing voids for repairing any network [126]. Additionally, AUVs can self-optimize network topologies to reduce latency, and improve robustness and adaptability, thus achieving low energy consumption and high reliability [127].

In the future, the synergy of multiple technologies holds the potential to enhance communication performance by leveraging the complementary attributes of each. For instance, electromagnetic communication boasts a lower propagation delay and relatively smooth propagation across the air-water surface in shallow waters. Nevertheless, as submarines navigate into deeper waters, the deployment of acoustic communication becomes essential for ensuring effective long-distance communication. Furthermore, in scenarios involving clustered submarines, conventional electromagnetic communication with shore-based stations can be employed, while high-bandwidth, low-delay communication methods such as optical communication can be integrated within the cluster to ensure optimal maneuverability. In situations that require heightened security, the use of compact coils emitting non-visible and non-audible waves can fortify MI-aided underwater communication. This feature proves especially advantageous for applications in naval and military fields. The strategic combination of these diverse communication technologies offers a versatile and robust framework that can adapt to varying environmental conditions and specific operational requirements.

Based on our research, generally, there are several possible ways to improve the communication performance parameters in the future, including increasing signal power, increasing channel bandwidth, improving modulation schemes, using error-correction codes, and optimizing the transmission protocol. Deep learning can also help optimize the parameters of sonar and underwater acoustic communication systems to achieve faster and more reliable data transmission [75], [76], [77]. By analyzing sensor data and underwater environmental characteristics, deep learning can determine the optimal transmission frequency and encoding scheme to minimize channel losses and interference. Additionally, using deep learning can suppress noise and interference through adaptive signal processing techniques, thereby improving the signal-to-noise ratio and transmission rate.

Moreover, as for communication between submarines, while the existing acoustic communication technology has achieved some improvements in communication distance and speed by adopting water acoustic channel coding technology, adaptive equalization technology, and time-reversal communication technology; limitations such as multi-path effects, frequency channel selectivity fading, limited available frequency band resources, and high bit error rate constrain further improvements. Therefore, to overcome these limitations, the mindset of network interconnection can possibly be applied in submarine communication. AUVs can be used as underwater mobile network relays, buoys or unmanned ships as surface network mobile relays, and drones or satellites as air network mobile relays to establish a three-dimensional oceanic mobile communication network.

In recent years, communication buoys also shown a good development trend and are also commercially used [128]. By deploying buoys on the sea surface, long-distance communication with submarines can be realized. The buoys can receive electromagnetic information from satellites or command stations on land and convert it into sound waves to communicate with submarines.

The primary developmental objectives for communication buoys revolve around achieving higher transmission speeds and signal-to-noise ratios, all while ensuring cost-efficiency, safety, and reliability. These goals underscore the pursuit of advanced communication technologies capable of delivering faster data transfer rates, improved data quality, and reduced interference. The emphasis on cost-efficiency underscores the need for economical solutions that can be widely adopted. Safety and reliability are of paramount importance, especially in underwater and maritime environments where robust communication is critical for applications such as naval operations, scientific research, and offshore industries. Achieving these objectives demands innovative approaches that strike a balance between performance enhancements and practicality.

Current solutions commonly employ active surface buoys as relay stations. These relay stations receive modulated electromagnetic wave signals from the surface and convert them into corresponding modulated acoustic signals for underwater transmission using active excitation circuits. While leveraging the advantages of minimal attenuation of electromagnetic waves in gaseous mediums and minimal acoustic wave attenuation in liquid mediums, this method facilitates cross-medium communication. However, it is characterized by complexity, high costs, and a lack of flexibility due to the requirement for active relays in modulation, demodulation, and secondary information distribution. Additionally, it is susceptible to tracking interference and must contend with power consumption and energy supply issues. Hence, addressing the challenges posed by active relays in cross-medium communication between gas and liquid environments becomes crucial.

In the future, the passive buoy can be developed and expand the application scenarios of buoy-based underwater

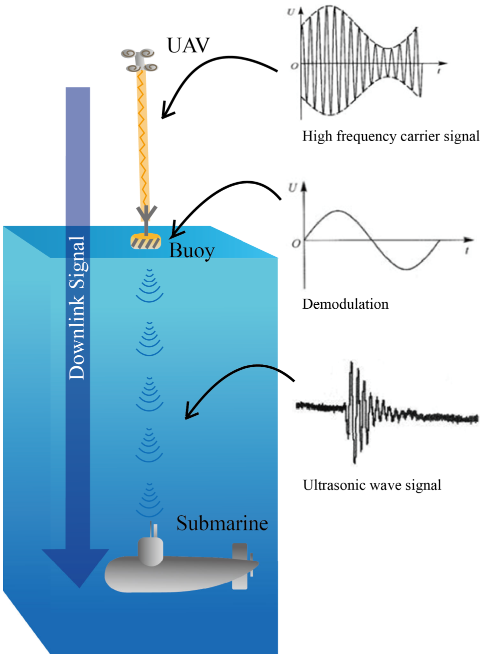


FIGURE 10. The prototype of passive buoy system.

communication. One of the solutions is shown in fig. 10. While retaining the advantages of active buoys, passive buoy has the extra advantage of its low cost, and low latency. In addition to state-of-the-art methods, passive buoys offer an additional layer of security assurance [129]. The signal transmission process can be described as follows: A passive relay station receives an RF signal from the air, where the RF signal is modulated to carry the desired information to be transmitted. The relay station receives the intended information from the air and demodulates it, obtaining an excitation signal used to generate an acoustic signal for transmission in the water. This excitation signal is generated based on electromagnetic wave-to-acoustic wave conversion effects, such as piezoelectric effects and electromagnetic-to-acoustic methods within metals. The excitation signal stimulates the passive relay station to produce an acoustic signal for transmitting the correlated signal originally sent through the air into the water. The resulting acoustic signal propagates within the water, carrying the correlated signal information originally transmitted through the air. An underwater receiver demodulates the received acoustic signal to obtain the intended information sent through the air medium, thereby achieving cross-medium communication.

Some advanced signal processing tools can also be applied to improve the data rates and offset the unpredictability of the environments and the above-listed methods can also be combined to achieve better communication performance. In the future, the new generation of communication technology based on THz may also play a great role, connecting the land-based station, buoy, drone, satellite, and submarine to form a three-dimensional communication network.

TABLE 3. Used abbreviations in the paper.

Abbreviation	Meaning
AUV	Autonomous Underwater Vehicles
BER	Bit Error Rate
CAP	Carrierless amplitude and phase modulation
CP	Cyclic prefix
DMT	Discrete Multi-Tone
ELF	Extremely-low frequency
FMCW	Frequency-modulated carrier wave
IM	Intensity modulation
IoT	Internet of Things
LD	Laser diodes
LED	Lightemitting diodes
LOS	Line-of-sight
MIMO	Multiple-input multiple-output
MPPC	Multi-pixel photon counters
NLOS	Non-line-of-sight
NRZ-OOK	Non-Return-to-Zero 0n-off keying
OFAM	Optical Focusing-based Adaptive Modulation
OFDM	Orthogonal Frequency Division Multiplexing
OOK	On-off keying modulation
PA/TA	Photo/thermo-acoustic
PD	Photodiodes
PMT	Photomultiplier tubes
PAM	Pulse amplitude modulation
PPM	Pulse position modulation
QAM	Quadrature amplitude modulation
RTE	Radiative Transfer Equation
SIMO	Single-input multiple-output
SISO	Single-input single-output
SLD	Superluminescent diodes
SNR	signal to noise ratio
TARF	Translational acoustic-RF
UHF	Ultra-high frequency
UWAC	Underwater wireless communication
UWC	Under water communication
VCSEL	Vertical-cavity surface-emitting laser
VHF	Very-high frequency
VLF	Very-low frequency
ZP OFDM	Zero-padded Orthogonal Frequency Division Multiplexing

VII. CONCLUSION

In this paper, we've analyzed current and potential future submarine communication methods. We've evaluated basic techniques like electromagnetic, acoustic, and optical communication, highlighting their pros and cons. Additionally, we've explored newer methods, including magnetic, TARF, PAC/TAC, neutrino, and quantum communication, detailing their potential to overcome existing limitations.

Our study underscores the benefits of combining multiple techniques to achieve superior communication performance. Therefore, developing integrated communication methods is crucial for reliable communication between submarines and surface vessels.

Notably, magnetic communication, TARF, PAC/TAC, neutrino, and quantum communication show significant promise for the future of submarine communication. By further developing these technologies and exploring their applications, we can greatly enhance underwater communication, enabling a three-dimensional network connecting land-based stations, buoys, drones, satellites, and submarines.

The future of submarine communication will probably be marked by several key directions. The increasing use of Autonomous Underwater Vehicles(AUVs) and their clustering presents new opportunities and challenges. Combining different communication technologies, such as electromagnetic, acoustic, and optical, offers a comprehensive and adaptable approach. Deep learning can optimize communication parameters, enhancing data transmission speed and reliability. Network interconnection, utilizing AUVs, buoys, and satellites, can establish a three-dimensional oceanic mobile communication network. Additionally, active and passive buoys show potential for long-distance communication with submarines, with passive buoys offering cost-efficiency and security advantages. Advanced signal processing tools can further improve data rates and offset environmental unpredictability. In the future, THz communication technology may play a significant role in creating a three-dimensional communication network.

In summary, this paper offers a comprehensive review of electromagnetic, acoustic, and emerging technologies for submarine communication. By addressing the limitations of current methods and highlighting the potential of emerging technologies, we aim to advance safety and efficiency in underwater operations. We hope this review provides valuable insights for researchers and engineers in this field.

APPENDIX

ABBREVIATIONS

The abbreviations used in this paper are shown in table 3.

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