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6G: Ubiquitously Extending to the Vast Underwater World of the Oceans

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1. Introduction

There is a significant gap between atmospheric space and undersea space for wireless radio transmission. The interface between air and seawater is a barrier to prevent radio wave transmission across the boundary. This is because seawater is an electrically conducting medium, and radio waves suffer significant absorptive attenuation there. As a result, there is no internet, reliable mobile communication, high-quality video, and long-distance duplex wireless communication in the underwater world of oceans. It is pitiful since the oceans share 71% of the surface of our planet and are of great importance to our economy, ecology, and living environment.

It seems very strange to mankind that we have very good signals and images transmitting to and receiving from the Moon and Mars, but it is still impossible to do the same for the nearby oceans. We cannot do the same to the underground space either. It should be recognized that the physical constraints of transmission media introduce great difficulty to us [1].

Tremendous effort has been made over the past 100 years to find favorable means for underwater data transmission. It is concluded that acoustic waves are the best in comparison to radio, electromagnetic (EM), and optic waves, although the latter three waves still have some limited or special merit in some cases. To give a clear idea, let us show you some typical examples: for ultra-low frequency (ULF, 300 Hz–3 kHz) EM wave at 1 kHz and so-called green–blue laser, the values of attenuation in seawater for 100 m distance are 110 decibels (dB) and 15.5–50.0 dB, respectively. However, the value of attenuation is only 7 dB for 1 kHz acoustic wave at a 100 km distance. Roughly speaking, the acoustic wave is 1000 times more in terms of transmission distance where a complete seawater path is concerned.

Therefore, when undersea communication and networks are discussed, acoustic technology is the greatest concern. Studies of underwater acoustics usually include the basic part of underwater acoustic physics and the technological part of undersea sensor networks and sonar. EM and optic waves and other means, such as biological and radioactive waves, act as complementary methods.

2. Demands pull for oceanic technology innovation

Economists extracted the rule for innovation, such as demand pull and supply push. The demand concerns opportunities from the needs of people and the market, while the supply concerns opportunities from scientific discoveries and technological advancements. The demands from the ocean economy are enormous (Fig. 1) [2,3]. Look at the following data [2–6]:

- World shipping transported 1.1×10^{10} t of goods in 2018, which means 1.4 t per capita on average. The shipbuilding industry, seaport management, transport safety/security, and One Belt One Road stimulate e-commerce, the Internet of Things, blockchain, and artificial intelligence.
- Exploration and exploitation of ocean oil, gas, and minerals (including manganese nodules and combustible hydrate) are huge for seaborne trade and industries. This stimulates surveillance and production automation, robotics, undersea monitoring, and water-to-air teleportation.
- Seafood production, including seaweed farming and fishing, has a large scale, which provides nutrients for people. For example, the world fish capture total is approximately 8×10^{10} kg, that is, approximately 10 kg for each person. Seaweed is one of the fastest growing plants in the world and may grow up to 3–4 m in three months. Oceanic farming also provides sea cucumbers and oysters that are important for seafood-loving people. Farming and fishing stimulate water quality monitoring, underwater fish school detection, localization, and quantity estimation.
- Renewable green energy power plants and windmills on the sea are quickly expanding emerging industries. To avoid interference with the populated coastline area, windmills are normally constructed dozens or even hundreds of miles apart from coastlines. Considering the harsh environment, it is necessary to adopt advanced mechanical and digital technologies.
- A submarine cable system across continents is a wired data transmission network system currently supporting global information services. Currently, there are 378 cables with a total length of 1.2×10^6 km, supporting over 99% percent of international data transmission. The most advanced fiber optic cable is capable of transmitting 200 terabits in seconds. They are expensive and hard to construct and continuously maintain maintenance. Very special techniques are needed to keep it working and prevent information leakage from spy eavesdropping [7].
- Research and development (R&D) for ocean research, human life environment, and defense. The ocean gas–heat exchange, atmospheric wind flow, and seawater current circulation influence weather variation, climate change (greenhouse

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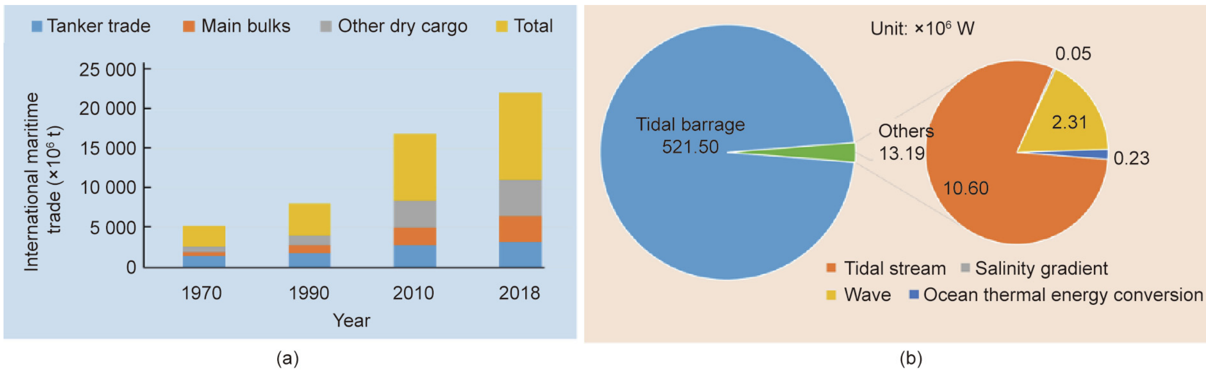

Fig. 1. Demands for oceanic technology innovation. (a) Development in international maritime trade in the last 50 years. The data of international maritime trade are from United Nations Conference on Trade and Development [2]. (b) The current ocean energy deployment and cumulative installed capacity. Current cumulative installed capacity across all ocean energy technologies is approximately 5.4×10^8 W. The data of ocean energy are from International Renewable Energy Agency [3].

effect), and disasters such as floods, storms, typhoons, hurricanes, earthquakes, and mountainous fires. These introduce many emergency issues to the Earth. Ocean pollution, seawater acidification, ocean ecosystem protection (in particular, biodiversity and sea animal protection) together with anti-piracy and anti-smuggling, to name a few, are also emerging issues for R&D. Regarding defense, various vessels, from aircraft carriers to high-speed hovercrafts, submarines and unmanned underwater vehicles (UUVs), ship-based drones, various sensors, and military C4ISR (namely, command, control, communications, computers, intelligence, surveillance, and reconnaissance) facilities, have formed a large-scale naval military industry.

Our discussion dose not attempt to be inclusive of all sea-based industries. We want to show the large scale and the varieties of the ocean economy, which possess strong demands for technology innovation. The strong demands for present the fifth generation mobile communication technology (5G) and forthcoming sixth generation mobile networks (6G) related technologies are real rather than fictitious imagination.

3. Opportunities for sea-based communication and networking

Sea-based networking can be divided into several very different categories: The first is wired networking, including submarine cable systems, ships and seaport fiber optic networks; the second is above water radio communication networks, including communication among ships, buoys, unmanned surface vehicles (USVs), airborne vehicles, coastline base stations, and satellites; the third is nonacoustic communication and networking, including laser and EM teleportation (an extremely important example is the extremely low frequency (ELF, 3–30 Hz) and ULF far distance command transmission system); and the fourth is undersea acoustic communication and networking. The preceding three categories mentioned above are similar to land-based systems, and related technologies can be found elsewhere [8–11]. Thus, our emphasis is on the fourth category: undersea acoustic (wireless and mainly mobile) communication and networking.

During the past decades from the early days of the last century, great efforts have been paid to this aspect, particularly because of the urgent demands of World War I, World War II, and the subsequent United States–Soviet Union confrontation. Breakthroughs have been made, and the remaining difficulties are still open [12]. Forthcoming innovation is advanced by the scientific discoveries and technological advancement obtained thus far together with the strong demand pull of the ocean economy.

3.1. Data-rate is closely related to range and frequency

The seawater absorptive attenuation of acoustic waves exponentially increases with increasing frequency. Lower frequency has to be used for longer-range transmission. As a result of the lower frequency, the useful bandwidth drops down, and the data rate drops down correspondingly. That is, you may have a higher data rate for short ranges and higher frequencies, while you may have a very low data rate for long ranges and very low frequencies. Daniel B. Kilfoyle and Arthur B. Baggeroer [13] summarized the status approximately 20 years ago that the performance envelope can be approximately expressed as a product of range and data rate less than or equal to 40 km·kbps (kbps: kilobit per second). The spectral efficiency was relatively low at that time, while recent modifications have been proposed up to 100–200 km·kbps [14].

3.2. Complicated properties of shallow water acoustic propagation

The propagation speed of underwater acoustic signals depends on the conductivity (salinity), temperature, and depth (pressure) (CTD) distribution along with the change in the medium depth. The distribution of sound speed along depth is called the sound velocity profile (SSP). The nonconstant value of SSP introduces refraction and bends the sound propagation path. In addition, the CTD suffers strongly from location, season, weather, and current factors. Therefore, shallow water acoustic channels show characteristics of time–space variation. Underwater acoustic signals also present multipath fading due to rough surfaces, complex reflections due to bottom topography and sediments, time and frequency spreading, and changeable transmission loss. Due to the increasing importance of shallow water and coastal areas in industrial and military fields, shallow water acoustics has been investigated intensively [15]. Three aspects are emphasized: first, modeling and propagation performance prediction; second, real-time sensing by CTD, surface data acquisition by satellite, and data assimilation together with historical samples; and the third, shallow water short-range communication, target imaging, and ad-hoc network demonstration. At present, some progress has been made, but open problems concerning commonly applicable and reliable solutions require further study [16].

3.3. Discoveries of the deep-sea acoustic channel for long-range propagation

In the early forties of 20th century, it was discovered by the United States and Soviet Union scientists almost simultaneously that there is a depth (called channel axis) in the deep ocean where sound speed shows a minimum [17]. This discovery provided an opportunity for long-range propagation in a channel around this axis. It is a so-called "deep sea acoustic channel" (or sound fixing and ranging (SOFAR) channel). Communication inside the channel can reach thousands of miles with much less propagation loss than in the outside area. The thickness is approximately 1000 m in the medium latitude region and may gradually become shallower for higher latitudes. This channel is very stable since ocean surface turbulence does not affect the SSP in deep water. However, a limited application has been shown, probably due to engineering difficulties introduced by the large depth (waterproof conditions are approximately 100 atmospheric pressure). The lack of very low frequency and high-power sound sources, and security concerns about the public access of the channel may also be restrictions. Due to the potential advantages of long-range propagation and progress made in engineering, it is hopeful that the channel is exploited for future innovative use.

3.4. Reliable acoustic paths (RAPs) worthy of intensive investigation

Another deep-sea channel has accepted serious concern in recent decades. It spans from the near-surface mixed-layer depth to its conjugate counterpart at the deeper side, which has the same sound speed as the former, but normally, the depth is near the bottom [18]. A trans-receiver working at or below the conjugate depth may experience stationary transmission, a very low oceanic noise level, and less propagation loss. More importantly, the shadow zone above it disappears. The signal produced by a source at shallow depth (less than 300–500 m) immediately curves down due to negative refraction. This phenomenon introduces severe propagation loss in shallow depth areas and often limits the operating range of shallow water receivers to a few kilometers. That is, the shadow zone in which sensors should not be placed. The merit of near sea-bottom observations at conjugate depth is obvious: It provides a direct propagation zone approximately 30 km in radius near the surface (in the medium latitude region). Many studies have investigated RAP by American and Chinese scientists, and encouraging results have been obtained.

Another deep-sea acoustic propagation phenomenon that should be mentioned is so-called convergence zones, which are formed by recurrent downwards and upwards refraction inside the water column. Convergence zones repeatedly appear in an interval of approximately 60 km at medium latitudes. The depths of the zones are approximately or around the source depth in the surface layer and the conjugate depth near the sea bottom. The convergence zone provides the signal focusing gain and further reduces the propagation loss. RAP communication may use this convergence zone effect to extend connection ranges further [19].

3.5. Emerging mobile platforms under, on, and above seawater

The oceanic world is vast, and human activities in the oceans are sparsely distributed. Unlike terrestrial networks, there is no continuous power supply, no human intervention to the link components, and no possibility of deploying densely located base stations all over the oceans. That is why mobile communication platforms are necessary. They have to be cost-effective, energy-efficient, size/weight acceptable, environmentally friendly, reliable, and easy to deploy. Following these requirements, many innovative platforms with on-board sensors have emerged in recent decades [20].

On the surface, in addition to traditional moored buoys and sea-going ships, new platforms such as wave gliders, wind/wave propelled unmanned boats, autonomous surface vehicles, and auto movable buoys appear. The wave glider and wind/wave-propelled unmanned boats harvest sea energy to run and may stay moving for several months. The voyage can reach up to 1×10^4 km continuously. It is also possible to have it hovering around a given location. This is particularly suitable to act as an access point or relay node on the surface. A ship towed sensor system called underway CTD (U-CTD) is worth mentioning. The system drops down a salinity–temperature–pressure chain of sensors while cooperating with the towing ship to move forward and release the tether line in a circular manner [21–23].

Inside the water volume, there are Argo buoys, manned/UUVs (autonomous underwater vehicles (AUVs) and tethered remote robotic underwater vehicles (RUVs)), moored buoys, and robots together with some multifunctional sea-bottom observatories [12,24]. The latter may provide RAP surveillance, payload releases (pop-up buoy or weaponry), exchange of data, and battery recharge functions. Thus, observatories are particularly important for undersea sensing, communication, and network construction, although they are fixed systems currently relying on optical cable connections. Above the surface, there are drones, helicopters, aircraft, and satellites. Some vehicles may dive down/jump up, crossing the water surface. They have much better environmental conditions for radio transmission and necessarily act as the first stop of the undersea acoustic world connecting to the global radio world. A very important factor should be pointed out: a radio signal propagates for 1600 km with an approximately 5×10^{-3} s time delay, while an underwater acoustic signal has an approximately 1000 s time delay. This fact clearly shows that the combined application of underwater paths and air paths must be considered primary for sea-based networking.

4. Building "data bridges" to break the water surface data barrier

In consideration of the low data rate and large time delay characteristics of undersea acoustic channels, it is wise to transfer the acoustic signal into the radio signal and pass it into the radio channel in the air. However, how can it be done? The answer could be to build data bridges. Another question is how many bridges have to be built. The answer could be that it depends on the applications. It is not feasible to have very close nodes, such as in urban areas where the spatial interval between base stations is as small as 1–2 km. For 5G and 6G, the interval becomes even much smaller. On the other hand, the sea-based network is likely sparse and heterogeneous. To cover large ocean areas and keep cost–efficiency, the communication or telemetry range has to be enhanced to medium or long distances of tens or hundreds of kilometers. Thus, the counts of network bridges should be reduced to as low as possible.

4.1. Advances in medium- and long-range undersea communication

During the past decade, several deep-sea acoustic communication experiments have shown potential [14,25]. An experiment in deep water off the California coast achieved 1000 bits per second (bps) at 200 km range using 1 kHz central frequency and two receiving hydrophones. The product of the data rate and range reaches 200 breaking through the previous margin of 40 km·kbps. Another experiment using binary phase shift keying modulation and virtual time-reversal channel equalization achieved 100 bps at 1000 km using 100 Hz bandwidth (450–550 Hz). For deep sound channel communication, an experiment using a stationary source and a vertical hydrophone array both deployed around the channel axis (1000 m) achieved 400 bps and 600 km with a spectral efficiency of 4 bps·Hz^{-1}. For RAP communication, theoretical analysis has been carried out with promising results, while experimental verification is to be done later. It is observed from these experiments that deep-sea long-range communication is feasible, but the data rate is quite low. It is probably possible to further enhance the rate-range product if compression sensing techniques are utilized to consider the sparseness of both the communication signal and channel impulse response.

Jumping up outside the water column, on surface platform communication also faces medium- or far-distance problems. For very high frequency (VHF, 30–300 MHz), ultrahigh frequency (UHF, 300 MHz–3 GHz), and microwave bands, direct wave communication suffers from the curvature of the earth and over the horizon (OTH) communication is needed. Fortunately, the so-called evaporation duct (ED) provides a condition in favor of radio wave downwards refraction to make the duct effect possible. This duct is directly above the sea surface, where water vapor is generated by air/sea heat exchange. The upper height of the ED is approximately 20–30 m, as determined by weather conditions. Theoretical and experimental works show that microwaves in the ED can reach the OTH range of approximately several hundred kilometers [26].

4.2. Building cross-boundary data bridges

Technical approaches combating the air–water barrier are continuously searched for. Several promising methods have been found to potentially act as data bridges:

- First bridge, acoustic-radio telemetry buoys on the surface equipped with a receiving hydrophone or hydrophone array on its underwater part, a radio transmitter on the air part, and electronic signal processing circuits in between. Any surface platform with these functions can act as a bridge for underwater signals to pass through the interface and transmit into the air. A sort of miniature buoy is called a pop-up buoy, which can be housed in a sea-bottom autonomous station. In the case of sending a message, a pop-up buoy is released and runs to the water surface by its buoyancy and transmits a radio signal there.
- Second bridge, very low frequency (VLF) EM waves, which span the 3–30 kHz frequency band. It is quite suitable for closing seawater–air boundary transmission. Particularly when an underwater EM signal (including that transformed from an acoustic signal) at several or a few dozens of meters depth can directly penetrate the seawater surface and generate an airborne lateral wave. The lateral wave can horizontally propagate along the surface to medium-range destinations or relays [27]. The obvious merit of this approach is that it is not necessary to have a buoy or similar surface platform on the surface. This approach is particularly suitable for AUVs or other mobile vehicles. In addition, surface clash and acoustic interference are avoided. In some cases, a seawater–sediment–land path is possible, which is favorable in coastal areas. Other frequency bands are also usable. For example, VHF and ELF signals can find special applications. The VHF EM signal is suitable for short-range high data rate information transmission penetrating across the sea surface from water to air. The ELF EM signal is suitable for thousand miles of command transmission from a large land-based antenna to a sea-surface area where it penetrates down into the water [28]. An obvious advantage of the latter is that the ELF wave propagates mostly through a path in the air with near optical speed. Only the last portion of the propagation path, several hundred meters from the surface down to the receiver, involves low-speed propagation in seawater. The propagation speed of EM waves in conducting seawater media decreases at lower frequencies. As an example, for a frequency of 10 Hz, the speed drops down to approximately 5000 $m \cdot s^{-1}$. Even so, the time delay of ELF command transmission is approximately one-tenth of seconds, including the underwater path to an undersea receiver and several thousand kilometers of link in air. It is very important in practical applications with a time delay as such in comparison with the underwater acoustic transmission with several thousand seconds of time delay.
- Third bridge, mobile platforms maneuvering in the whole water column, can collect data from any acoustic detector and run to the water surface, transmitting data to a receiver in the air. Of course, there exists some time delay due to the running process. However, a batch scheme can be used. A large amount of data can be quickly collected in a very short range and transmitted into the air in a short time after the antenna exits the surface. In fact, optic data transmission using lasers can be considered in the data-collection phase for this scheme if the pointing problem of laser beams is properly solved. It is clear that AUVs, UUVs, remotely operated vehicles, and even manned underwater vehicles are eligible to conduct these functions.
- Fourth bridge, a newly found approach, performs microwave detection of surface fringes generated by underwater sound [29]. Recently, such an experiment in the laboratory conducted by a team from Massachusetts Institute of Technology (MIT) showed promising results. The fringe is mixed with strong wave turbulence, and it is very difficult to detect. Before the works from MIT, fringe detection above the water using a laser detector was proposed and succeeded in an underwater tank experiment in 2009 [30]. Although these are unilateral, the literature can be searched for to generate underwater acoustic signals by airborne lasers or microwave beams illuminating the water surface. The idea is to heat the water column under high-intensity illumination and explosively expand it into bubbles to generate impulses and vertically directive acoustic wave beams. However, waveform control is still an open problem. Another unilateral boundary-crossing method is that an airborne acoustic beam strikes onto the surface and directly penetrates the air–sea boundary to a moderate depth. It was reported decades ago that a submarine detected aircraft noise hundreds of kilometers away. Unfortunately, it is not feasible inversely in general except that the depth of underwater extremely low-frequency sound is smaller than its wavelength. In this specific condition, underwater acoustic waves may perfectly penetrate the boundary as if the boundary is transparent.

5. Prospect: Development united air–surface–undersea networks

From the discussion above, a vision is emerging. The approach for a united air–surface–undersea network becomes quite clear. First, the ubiquity of communication to the vast deep-water world at any place any time is feasible, since there are several beneficial channels that can be utilized, such as the deep sea acoustic channel, the RAP channel, the air/sea cross-boundary channel, and the underwater moving vehicle channel. In particular, frequent failure of link availability can be avoided by proper use of these important channels. For example, it is feasible to develop a link between a surface node and a node located in the "shadow zone" via RAP paths from the surface to the sea bottom and then to the "shadow zone," while current methods fail to get through. Second, underwater large time delay and low data rate problems can be greatly relaxed due to the combined use of underwater acoustic and airborne radio transmissions. This means that a full 6G rate is obtained as soon as underwater data are conveyed through the data bridges into the air. Meanwhile, acoustic communication itself can also be improved in spectrum efficiency by better use of the channel property and new concepts, such as orbital angular momentum modulation [31]. However, in consideration of the large difference in data rates for airborne and underwater communications, much research work should be done in data compression, data-file segmentation and remerging, time compression and stretching, AUV transportation of large quantities of stored data blocks. It is hoped that the low speed of underwater communication can be merged into the very high speed of 5G/6G in the air in this way. Third, further ubiquity can be achieved in comparison with fixed cable-connected undersea networks since the proposed unified air–surface–seawater network is wireless and distributed in addition to many moving components, as described in Section 4.1. A very deep impression of radio mobile phone communication in relation to a fixed telephone system makes us believe that a wireless and movable sea-based network may certainly provide tremendous newly appeared possibilities similarly. It is not to say that all the underwater fixed networks should be replaced. They may still have some unique merit in offshore or coastal shallow water areas. Thus, it is our view that underwater fixed networks may become complementary to wireless networks in the years to come.

At present, it is not immediately feasible yet to develop an ultimate united network for the underwater world similar to radio communication in land, air, and space. It is more realistic to encourage initiatives of a variety of different approaches for the goal. It is hoped that a large number of teams and projects appear to investigate different aspects of the united network depending on different application requirements, different propagation conditions, different scales of connections. Diversity, heterogeneity, scalable size, and different architectures are welcome. The R&D environment, investment, and management policies are particularly important to support at this stage. After a period of scattered development, rich results may be accumulated and sufficient to support the ultimate goal. We have reasons to believe one day that undersea video showing colorful fish activities could be observed on any family television screen; sea-bottom mineral exploitation machinery could be controlled at a land-based factory through undersea Internet of Things; an AUV could communicate with its mother-ship hundred miles away; extreme weather prediction data could reach to scientists as soon as possible; information from the underwater world could be accessed all over the world with acceptable time delay [32].

However, to be realistic, it may be nice to start with developing a local-area underwater wireless mobile acoustic network and connecting it to the radio system across the boundary as a test bed of concept [33]. It is better to be in deep water with links of medium to long ranges. The primary elements are sea-bottom base stations or sinks, deep-sea RAP propagation channels, mobile AUVs, and USVs running in the water column and surface to form a network across the boundary. The conception of the local-area underwater wireless mobile network is illustrated in Fig. 2. Radio 5G/6G techniques should be adopted if they are feasible and satisfy the undersea requirements. This test bed may provide a first glance of view for later development on a large scale. There has not been any demonstrative system to date. What were reported are the cabled sound surveillance system (SOSUS) and, more recently, the cabled multinode underwater network or "observatories." They are fixed installations, very expensive, less flexible, maintenance difficult, and relying on land facilities. However, our emphasis should be wireless, mobile, scalable, and cost-effective for good connectivity of seawater and air anywhere in the global oceans. So let us start to make test beds now without hesitation.

6. Concluding remarks

Apart from the great progress of 4G/5G and recent hot topics on 6G, wireless mobile communication and networking in the vast underwater world of oceans are far behind. The reason is an open scientific and technological problem that concerns the inability of radio transmission and the promise of acoustic transmission in seawater media. Based on the analysis of this problem, a solution and

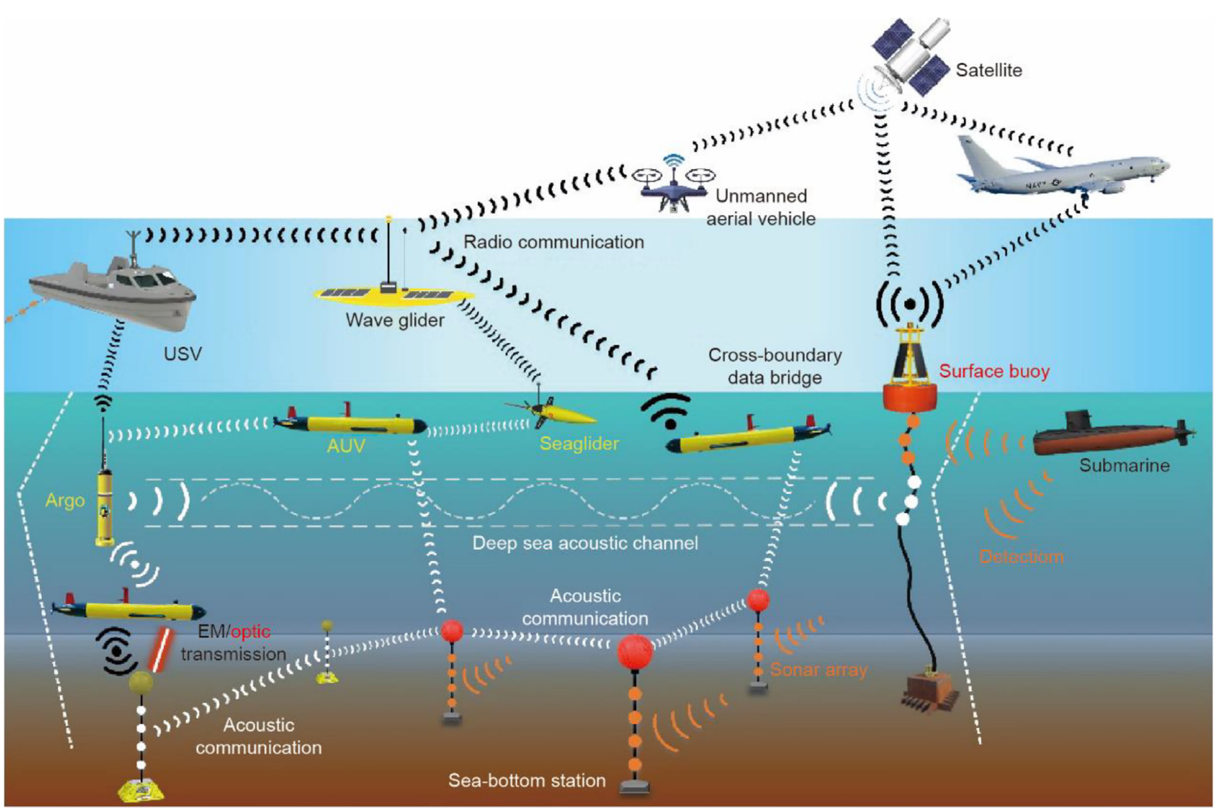

Fig. 2. The vision of united air–surface–undersea networks.

vision for it in view of 6G R&D are given. This paper summarized and analyzed the status and potential of wireless communication in oceans based on a comprehensive review of practical needs, bottleneck constraints, physical discoveries, scientific and technological breakthroughs, cross-disciplinary integration. Future developing conceptions and critical aspects are pointed out and discussed, such as full utilization of channel characteristics, development of diverse mobile platforms, and organizational structure of communication networks. For each key aspect, the application scenarios are analyzed and discussed in depth. To combine the merits of radio and acoustic communication, a new concept of building data bridges between the ocean and atmosphere is proposed, and feasible approaches are presented. It is shown that unified air–surface–undersea networks are feasible via these bridges. The vision is bright, but one has to start from test bed demonstrations for various application cases due to the sparseness and heterogeneous property of oceanic systems. In conclusion, 6G for the ocean world could be very different from that in the air and space. The ubiquity of 6G is still hopeful in the oceans but in a very special form. It will be extremely valuable and is in urgent need of development.

Large-scale underwater communication and networking share features in common with underground and deep space. They suffer constraints of physics, large latency time, transmedia, heterogeneous structure, and special protocol. They all have a strong demand-pull and supply (technology) pushes for innovation. Therefore, common communication problems in fundamental science concerning ground, sea, air, and space should be investigated coordinately. This may extend our present view further to a much broader field of 6G research.

Acknowledgments

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