

Hybrid Satellite-Terrestrial Communication Networks for the Maritime Internet of Things: Key Technologies, Opportunities, and Challenges

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Abstract—With the rapid development of marine activities, there has been an increasing number of Internet-of-Things (IoT) devices on the ocean. This leads to a growing demand for high-speed and ultrareliable maritime communications. It has been reported that a large performance loss is often inevitable if the existing fourth-generation (4G), fifth-generation (5G), or satellite communication technologies are used directly on the ocean. Hence, conventional theories and methods need to be tailored to this maritime scenario to match its unique characteristics, such as dynamic electromagnetic propagation environments, geometrically limited available base station (BS) sites and rigorous service demands from mission-critical applications. Toward this end, we provide a survey on the demand for maritime communications enabled by state-of-the-art hybrid satellite-terrestrial maritime communication networks (MCNs). We categorize the enabling technologies into three types based on their aims: 1) enhancing transmission efficiency; 2) extending network coverage; and 3) provisioning maritime-specific services. Future developments

and open issues are also discussed. Based on this discussion, we envision the use of external auxiliary information, such as sea state and atmosphere conditions, to build up an environment-aware, service-driven, and integrated satellite-air-ground MCN.

Index Terms—Knowledge library, maritime channel, maritime communication network (MCN), maritime service, satellite-air-ground integration.

I. INTRODUCTION

MARITIME activities, such as marine tourism, offshore aquaculture, and oceanic mineral exploration, have seen rapid development in recent years. With the increasing number of vessels, offshore platforms, buoys, etc., there has been a growing demand for high-speed and ultrareliable maritime communications to connect them [1]–[3]. For example, navigational information and operational data are required for the safe navigation of all vessels, and multimedia communication services are needed for passengers, crew, and fishermen onboard. Similarly, offshore drilling platforms require real-time operational data communications, and buoys also have a large amount of meteorological and hydrological data to upload [4]–[6]. For maritime rescue, in addition to information exchange using texts and voices, real-time videos are often required for better ship-to-ship and ship-to-shore coordination [7]. Therefore, building a broadband maritime communication network (MCN) for the maritime Internet of Things (IoT) is of great significance for marine transportation [8], [9], production safety [10], and emergency rescue [11].

Currently, mobile terminals on the ocean mainly rely on maritime satellites or base stations (BSs) on the coast/island to acquire services. Narrow-band satellites, represented by International Maritime Satellites (Inmarsats), mainly provide services, such as telephone, telegraph, and fax, at a low communication rate. For example, the annual throughput of Inmarsat was only 66 Gb/s in 2016, while the number of ships has exceeded 2 million. Thus, the average communication rate per ship is less than 33 kb/s [12]. To meet the demand for broadband satellite communication services, several companies have launched high-throughput satellites, such as EchoStar-19 (also known as Jupiter-2) by EchoStar and the Starlink project by SpaceX. In addition to maritime satellites, shore and island-based BSs are also used to extend the coverage of terrestrial fourth-generation (4G)/fifth-generation

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TABLE I
COMPARISON BETWEEN CELLULAR AND MARITIME COMMUNICATIONS

Characteristics	Cellular communications	Maritime communications
Single BS coverage	Small 4G: 500–2000 m for a single cell in urban area 5G: 100–300 m for a single cell in urban area (Achieved by building a large number of BSs)	Wide Shore-based MCN: 10–100 km for a single BS MCN using ship-borne/UAV-enabled BSs: 1–50 km for a single BS (Due to the limited number of geographically available BSs)
Wireless channel	Lower propagation loss (Due to small cell radius)	Higher propagation loss (Due to long-distance transmission)
	Mainly affected by blocks and scatterers	Mainly affected by sea surface conditions (such as tidal waves), and atmospheric conditions (such as temperature, humidity, and wind speed)
	Mostly multi-path channels (Rician channels in open areas)	Mostly Rician channels (with a direct path, a specularly reflected path, several diffusely reflected paths, and several atmospheric scattering paths)
One-way transmission delay	Low 4G: less than 10 ms 5G: less than 1 ms	High Onshore BSs: Similar to 4G/5G GEO: approx. 270 ms MEO: approx. 130 ms (e.g., for O3b) LEO: less than 40 ms (e.g., 10–30 ms for Globalstar)
Service	Mainly for mobile communications services	Mainly for maritime affairs, fisheries, ports, shipping, and coastal defence E.g., accurate and intelligent navigational communications for all vessels, real-time operational data communications for offshore drilling platforms, high-throughput multimedia downloading services for passenger/crew infotainment, and emergency communications with low-latency and high-reliability for maritime rescue

(5G) networks for maritime activities [13]. The existing shore-based communication systems, such as the navigation telex (NAVTEX) system and the automatic identification system (AIS), mainly provide services for information broadcasting, voice, and ship identification, but they cannot provide high-speed data services [14]. To improve the communication rate, several companies, such as Huawei and Ericsson, have carried out long-distance shore-to-ship transmission tests based on worldwide interoperability for microwave access (WiMAX) or long-term evolution (LTE) networks [15], [16]. However, the coverage of these systems is limited by the earth curvature and maritime environment.

To provide a practically affordable solution for broadband maritime communications, an efficient hybrid satellite-terrestrial MCN is urgently required to combine the advantage of satellites' wide coverage with shore-based systems' high capacity. It is believed that an arm-hand-like network architecture is beneficial to cover the widely but sparsely distributed maritime mobile terminals. In this framework, satellites and shore-based systems provide backhauls for dynamic global coverage (like the arms), while ship-to-ship interconnections and unmanned aerial vehicles (UAVs) can be exploited for enhancing local coverage (like the hands) [17]. However, different from terrestrial cellular networks, the MCN still faces many challenges due to the complicated electromagnetic propagation environment, network topology patterns, and service demands from mission-critical applications [18]–[25].

Transmission Efficiency: Compared with the terrestrial environment, the atmosphere over the sea surface is unevenly distributed due to the large amount of seawater evaporation. Shore-to-ship and ship-to-ship communications are very vulnerable to both sea surface conditions, such as tidal waves, and atmospheric conditions, such as temperature, humidity, and wind speed. In addition, the height and the angle of ship-borne antennas vary greatly with the ocean waves. Thus, the fading channel is particularly sensitive to parameters, such as antenna height and angle, which may cause frequent link interruption.

Therefore, the transmission efficiency in these applications is often low, due to these complicated time-varying factors.

Coverage Performance: In a terrestrial network, it is possible to increase the broadband coverage by installing more BSs. However, in an MCN, the available BS sites are very limited. Due to the limited onshore BS sites and the strong mobility of the ship-borne BSs, aerial BSs, and low-earth orbit (LEO) satellites, the topology of the hybrid satellite-terrestrial MCN is highly dynamic and irregular. Blind zones always exist in the planned coverage area. Additionally, if the BS covers remote users using high power, it will generate strong co-channel interference to the users served by neighboring BSs. The coverage performance of MCNs is thus restricted by blind zones and areas with severe interference.

Service Provisioning: Marine information network contains several industries, such as maritime affairs, fisheries, ports, shipping, and coastal defence. Their maritime application scenarios are also quite different with unique service requirements. Providing reliable services for all of these maritime-specific applications is a major challenge for the MCN.

In Table I, we illustrate the difference between traditional cellular communications and relevant maritime communications. To address the unique challenges in maritime communications, conventional communications and networking theories and methods need to be tailored for maritime scenarios, leading to an emerging area of communications. To date, a number of studies have been conducted on MCNs. To enhance the maritime transmission efficiency, various channel measurement and modeling projects have been performed to analyze the impact of important system parameters (frequency, antenna height, etc.) and maritime environments (sea state, weather conditions, etc.) on the maritime channel. Moreover, advanced resource allocation schemes, such as dynamical beamforming and user scheduling techniques, have been studied to adapt to the dynamic changes in maritime channels. In addition,

several studies have exploited the evaporation duct effect to improve the transmission efficiency, especially for remote ship-to-ship/shore transmissions. To expand the network coverage, various BSs have been utilized, including onshore BSs, ship-borne BSs, aerial BSs, and satellites. For these BSs, advanced beamforming and microwave scattering techniques have been studied to reduce the signal attenuation and extend the coverage. In addition, interference mitigation and satellite-terrestrial coordination schemes have been studied to overcome the interference due to the irregular network topology. To satisfy the unique maritime service requirements, different systems and their transmission and resource allocation techniques have been studied for different service requirements, such as bandwidth, latency, and criticality.

Although there have been a large number of works on the above topics, there are very few survey papers on MCNs. Additionally, most of them are focused on a specific issue, such as channel models [18]–[20], network management [21], or existing systems [22]–[25]. These issues are closely related to the characteristics of MCNs, but they were addressed separately without considering their interplays. For example, the surveys on maritime channel models have pointed out the challenges faced by environment-sensitive maritime channels but have not discussed any technologies to enhance transmission efficiency in such maritime scenarios. Moreover, many other important issues for MCNs, such as resource allocation, service provisioning and network integration, are not completely discussed by any of these surveys. Although the survey papers on some relevant topics, such as 5G channel measurements and models [26], space-air-ground integrated networks [27], and cognitive-radio-based IoT [28], could shed light on the development of an efficient hybrid satellite-terrestrial MCN, in general they have not specialized in maritime scenarios. To the best of the authors' knowledge, a survey paper dedicated to hybrid satellite-terrestrial MCNs with a complete picture of maritime communications is not available in the literature but is crucial to pave the way for the understanding of the unique features of MCNs. To fill in the gap, this article provides a survey on maritime communications, which not only includes the topics that have not been previously covered, such as maritime service provisioning, but also extends the existing surveys by addressing the unique features of MCNs and the inner connections among the topics.

This article provides a survey on the demand, state of the art, major challenges and key technical approaches in maritime communications. In particular, it focuses on the unique characteristics of maritime communications that are not seen in terrestrial or satellite communications. It discusses the major challenges of MCNs due to unique meteorological conditions and geographical environments, as well as heterogeneous service requirements. Consequently, it illustrates the corresponding solutions from link-level, network-level, and service-level perspectives. Finally, it makes recommendations on developing an environment-aware, service-driven, and satellite-air-ground integrated MCN, which is smart enough to utilize the external auxiliary information, e.g., the sea state conditions. The relevant open issues are also pointed out.

The remainder of this article is organized as follows. Section II briefly reviews the state-of-the-art MCNs, including satellite-based, shore-based, island-based, vessel-based, air-based, and underwater MCNs. In Section III, we introduce the key technologies to enhance maritime transmission efficiency. Section IV introduces the key technologies to extend the coverage of MCNs. The demand for maritime communications, and key technologies for providing maritime-specific services, such as low-power communications and cross-layer design, are discussed in Section V. In Section VI, we suggest the architecture and features of future smart MCNs, as well as suggesting future research topics. Section VII concludes this article.

II. STATE-OF-THE-ART MARITIME COMMUNICATIONS

Maritime communications began at the turn of the 20th century, pioneered by Marconi's work on long-distance radio transmissions. In 1897, Marconi established a 6-km communication link across the Bristol Channel, which is the first wireless communication over open sea. In 1899, he initiated the transmission across the English channel, from Wimereux, France to Dover, England, approximately 50-km away. In the same year, Marconi and his assistants installed wireless equipment on the Saint Paul, a trans-Atlantic passenger liner, and successfully received telegrams from the coast station 122-km away. In 1901, Marconi achieved trans-Atlantic communications with a transmission distance of over 3000 km, using a 20-kW high-power transmitter and a receiving antenna with a height of 150 m [29]–[31]. Marconi's experiments aroused great interest from the shipping industry in Europe and North America. From then on, many countries began to install coast stations and ship-borne radio stations. Narrowband communication services, such as telegraph, telephone and fax were provided using data transmissions via intermediate frequency (MF, 0.3–3 MHz), high frequency (HF, 3–30 MHz), very high frequency (VHF, 30–300 MHz), and ultra high frequency (UHF, 0.3–3 GHz) bands. Among them, VHF is mostly used for radio and television broadcast. It is also a licensed band for aviation and navigation, which is important for the safe navigation of ships within 25 nautical miles along the coast. VHF terminals have been widely used on merchant ships, fishing boats, official ships, yachts, and lifeboats. It is the most popular communication equipment for marine vessels [32]–[34].

Presently, several works have been conducted on broadband MCNs. Norway and Portugal launched the MARCOM project and the BLUECOM+ project, respectively, to provide broadband communications for remote areas by using Wi-Fi, general packet radio service (GPRS), universal mobile telecommunications system (UMTS), LTE technologies or their combination [35], [36]. Singapore launched the TRITON project, where a wireless multihop network is formed between adjacent vessels, maritime beacons, and buoys, to ensure wide-area coverage [37]. In addition, Jiang [38], Adarsh *et al.* [39], and Cankar and Stanovnik [40] discussed methods to achieve maritime communications through collaborative heterogeneous wireless networks using terrestrial networks, satellite networks, and other types of wireless networks.

The history of the development of MCNs is depicted in Fig. 1. Based on the network architecture, MCNs can

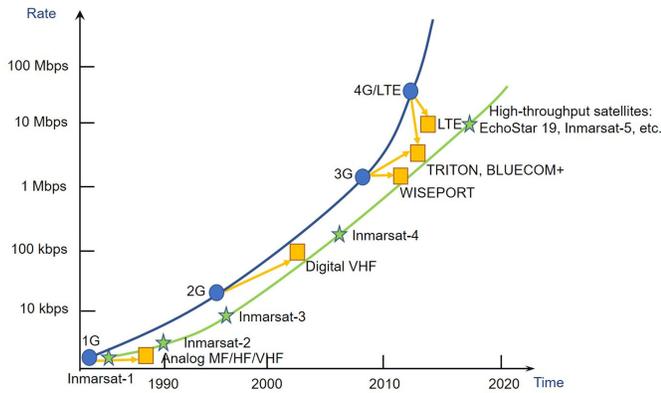


Fig. 1. Developing route of MCNs.

be categorized into satellite-based, shore-based, island-based, vessel-based, and air-based networks. They will be discussed in the following sections.

A. Satellite-Based Maritime Communications

Inmarsat is an international geostationary Earth orbit (GEO) satellite communications system. It aims to provide worldwide voice and data services for various applications, such as ocean transport, air traffic control, and emergency rescue [41]. The first generation of Inmarsat systems (Inmarsat-1) was put into use in 1982. The system is composed of several satellites and transponders rented from other companies and organizations, mainly providing analogue voice, fax, and low-speed data services [42]. The second-generation system (Inmarsat-2) was put into use in 1990. It has a total of four satellites, each of which is equipped with a single global beam, providing digital voice, fax, and low/medium-speed data services [43], [44]. The third-generation system (Inmarsat-3) was put into use in 1996. There are five satellites, and each satellite has 4–6 regional spot beams in addition to the global beam. Inmarsat-3 can support mobile packet data service (MPDS), with a capacity 8 times that of Inmarsat-2 [45]–[47]. The state-of-the-art Inmarsat-4 system consists of 3 satellites. Each satellite has a global beam, 19 regional beams, and approximately 200 narrow spot beams. Inmarsat-4 can provide Internet services with a peak rate of 492 kb/s [48], [49]. The future Inmarsat-5 system, also known as Global Xpress, aims to provide worldwide customers with downlink services at 50 Mb/s and uplink services at 5 Mb/s [50].

O3b is the first medium Earth orbit (MEO) satellite communications system that has been commercially used. It consists of 16 active satellites, providing standard and limited services for areas within latitudes of 45° and 62°, respectively. Presently, the O3b company is actively promoting maritime satellite communication services and has installed O3b satellite communication terminals on several Royal Caribbean cruise ships. The maximum data rate of a single ship is 700 Mb/s, while the delay is approximately 140 ms [51].

Iridium is an LEO satellite communications system providing voice and low-speed data services for users with satellite phones and pagers. The second generation of Iridium satellite constellations, Iridium Next, started in 2017. It consists of 66 active satellites, 9 in-orbit spare satellites, and 6 on-ground

spare satellites. Presently, Iridium Next provides data services of up to 128 kb/s to mobile terminals and up to 1.5 Mb/s to Iridium Pilot marine terminals. In the future, it will support more bandwidth and higher rate, reaching a transmission rate of 1.4 Mb/s for mobile terminals and up to 30 Mb/s for high-speed data services when large user terminals are available [52].

Tiantong-1 is China's first mobile satellite communications system, which is also known as the Chinese "Inmarsat." The system was launched into orbit in 2016 and put into commercial use in 2018. It mainly covers the Asia-Pacific region, including most of the Pacific Ocean and the Indian Ocean. It provides voice, short message, and low-speed data services, with a peak rate of 9.6 kb/s [53].

The Shijian-13 communications satellite is China's first high-throughput communication satellite. It is a multibeam broadband communication system using the Ka-band, and its total communication capacity is more than 20 Gb/s, approximately 10 times higher than before. The satellite is designed with 26 user spot beams, covering nearly 200 km of China's offshore areas [54].

Another high-throughput satellite EchoStar-19 has a capacity of more than 200 Gb/s and is equipped with 138 customer communications beams and 22 gateway beams. The satellite provides users in North America with high-speed Internet services and emergency response. In addition, Ka-band-based airborne broadband services will be available on the EchoStar-19 satellite [55].

The satellite-based communication systems have wide coverage and can provide low-speed or high-speed data services depending the bandwidth. However, satellite-based communications are easily affected by climate and the marine environment, resulting in low reliability [56]–[59]. In addition, the cost of ship-borne equipment and the communication charges are also very high. For example, the cost of installing ship-borne equipment for Inmarsat (Fleet 77) is approximately \$28000, including the antenna, terminal, handset, manuals, SIM card and power supply, and the data service costs \$2.8 per minute [60]. Data from the AIS show that there are nearly 80 000 ships sailing simultaneously around the world, less than 25 000 of which are high-end ships (with a load of more than 10 000 tons) that may afford the ship-borne equipment for high-throughput satellite communications.

B. Shore-Based Maritime Communications

The NAVTEX system is a narrow-band system with data rates of 300 bps, providing direct-printing services for ships within 200 nautical miles offshore. It operates at the MF band, using the 518-kHz band to broadcast international information and the 490-kHz band for local messages [61]. The NAVTEX system delivers navigational messages, meteorological warnings and forecasts and emergency information to enhance marine safety, but it cannot provide broadband communication services or obtain real-time information from users [23].

The PACTOR system is also a narrow-band system, which operates at the HF band, using frequencies between 1 and 30 MHz [62]. The first generation of PACTOR (PACTOR-I)

was built to provide a combination of direct-printing and packet radio services. Adaptive modulation methods and orthogonal frequency division multiplexing (OFDM) technologies were applied to PACTOR-II and PACTOR-III, respectively, in order to improve the spectral efficiency [63]. The state-of-the-art PACTOR-IV system uses adaptive channel equalization, channel coding, and source compression techniques, and has proven to be suitable for channels with severe multipath. PACTOR-IV can provide text-only e-mail services for ships thousands of kilometres away from the land with a data rate of up to 10.5 kb/s, using a bandwidth of 2.4 kHz [64]. Similar to NAVTEX, the PACTOR system cannot provide real-time communication services due to a large transmission delay.

As wireless communications technologies advance, several broadband MCNs have been constructed. The world's first offshore LTE network was jointly developed by Tampnet in Norway and Huawei in China. It covers the platforms, tankers, and floating production storage and offloading (FPSO) facilities from 20 to 50 km offshore on the North Sea, providing voice and data services of 1-Mb/s uplink and 2-Mb/s downlink. It also supports video surveillance data uploading and wireless trunking services [65].

Ericsson has also been working on connecting vessels at sea with shore-based BSs. It aims to enable maritime services that facilitate crew infotainment, cargo monitoring, and shipping route optimization. Ericsson and China Mobile have constructed a TD-LTE trial network for maritime coverage in Qingdao, China. The network operates at the 2.6 GHz band, covering areas up to 30-km offshore with a peak rate of 7 Mb/s. It can provide broadband services for offshore applications, such as maritime transportation and offshore fisheries [66].

The shore-based MCNs, as extensions of terrestrial networks, can provide broadband communications services for offshore applications, such as multimedia file downloading and video surveillance data uploading. However, the shore-based MCNs have limited coverage compared with satellite networks, and the coverage performance depends largely on the geometrically available BS sites. Shore-based communications are suitable for maritime applications that are densely clustered in a small area.

C. Island-Based Maritime Communications

For the remote islands on the sea, high-quality communications can not only provide service for the islanders but also provide strong support for the timely communications and interconnection of border information. In 2015, the U.S. wireless provider Verizon Communications enhanced 4G LTE network coverage on Rhode Island. It can provide the islanders and nearby vessels with Web browsing and file downloading services [67]. In 2016, China Mobile set up a 4G BS on the Yongshu Reef, which is more than 1400 km from mainland China. By building satellite ground stations on the island, the signals from the island can be transmitted to the satellites, then to the backbone gateway on the mainland. The transmission rate often reaches 10 Mb/s on the island and 15 Mb/s using nearby ship-borne communication equipment.

In 2017, China Telecom set up four 4G BSs on the Nansha Islands, which were connected to the mainland using underwater cables. The BSs provide coverage for the islands and reefs, such as Yongshu Reef, Qibi Reef, Meiji Reef and nearby sea areas, enhancing broadband communication services [68].

The construction of island-based BSs further expands the coverage of terrestrial mobile signals. Island-based MCNs can support clear voice and video calls from the coast to the island and provide high-quality communication services for the surrounding ships and fishermen. On the other hand, island-based BSs are more vulnerable to extreme climate events, such as typhoons and rainstorms. Their coverage is also limited.

D. Vessel-Based Maritime Communications

The Japanese Ministry of Internal Affairs and Communications has developed a maritime mobile *ad hoc* network (Maritime-MANET) to expand the coverage of shore/island-based MCNs via ship-to-ship communications. The network uses 27 MHz and 40-MHz frequency bands, covering areas of up to 70-km offshore. However, the supported rate is only 1.2 kb/s, supporting mainly narrowband communication services, such as the short message service (SMS) [69].

Singapore has launched the TRITON project to develop a wireless mesh network to expand the coverage area. In this network, each vessel, maritime beacon, or buoy serves as a mesh node, which can route traffic for other nearby nodes. The network operates at the 5.8-GHz band, covering areas up to 27-km away from the shore, with a coverage of 98.91%. It can provide broadband communication services of 6 Mb/s for offshore applications but cannot cover the high seas [37].

The vessel-based mesh or *ad hoc* networks can provide broadband communication services for most vessels and platforms along the coast. However, the link stability of vessel-based MCNs is restricted by the frequent change of the sea surface and marine weather conditions. In addition, the mesh architecture requires a high density of vessels, and each vessel needs to install expensive equipment. Therefore, more reliable network protocols and more cost-effective ship-borne terminals are required for vessel-based maritime communications.

E. Air-Based Maritime Communications

The Internet.org project was launched by Facebook in 2013, aiming to provide free Internet access for users in remote areas, including marine users. The project utilizes UAVs at altitudes of 55–82 km to serve as aerial BSs and form a network via laser communications. Until now, Facebook has teamed up with a set of mobile operators and handset manufacturers and has found a number of sites for deploying UAVs to cover impoverished areas in Latin America, Asia, and Africa [70].

The BLUECOM+ project also uses tethered balloons as routers to extend land-based communications to remote ocean areas. It exploits the TV white spaces for long-range wireless communications and uses multihop relaying techniques to extend the coverage. Simulation results have shown that the BLUECOM+ solution can cover the ocean areas up to 150 km

TABLE II
EXISTING MARITIME COMMUNICATION NETWORKS

Project/System	Sponsor	Frequency	Maximum rate	Coverage	Feature
WISEPORT	Singapore	5.8 GHz	5 Mbps	15 km	WiMAX
TRITON	Singapore	5.8 GHz	6 Mbps	27 km	mesh
Maritime-MANET	Japan	27/40 MHz	1.2 kbps	70 km	Ad Hoc
BLUECOM+	Portugal	500/800 MHz	3 Mbps	100 km	balloons, 2-hop
Digital VHF TMR	Norway	87.5-108/174-240 MHz	21/133 kbps	130 km	broadcasting
Qingdao TD-LTE Trial Network	China Mobile & Ericsson	2.6 GHz	7 Mbps	30 km	LTE
Norwegian Offshore LTE Network	Tampnet & Huawei	1785-1805 MHz	2 Mbps	50 km	LTE
Internet.org	Facebook	laser	unknown	wide	UAVs & laser
Inmarsat-4	Inmarsat	L/S band	492 kbps	wide	GEO
Iridium NEXT	Iridium & Motorola	L band	30 Mbps	wide	LEO
Tiantong-1	China	S band	9.6 kbps	wide	GEO

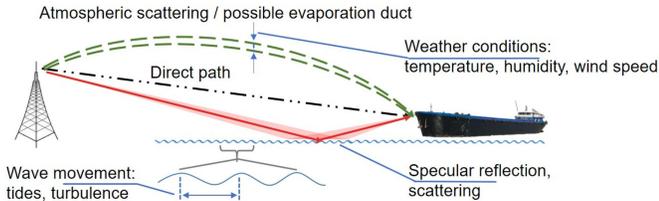


Fig. 2. Illustration of typical shore-to-ship propagation rays, which are affected by sea state and atmosphere conditions.

from shore, providing broadband communication services at 3 Mb/s [35], [36].

In general, the air-based MCNs can cover a wider area than the vessel-based MCNs, as the BSs are high above the ocean surface. They can provide remote users with high-rate and low-reliability communication services. On the other hand, aerial BSs, such as UAVs and balloons, are easily damaged by severe weather.

The key performance indicators of existing MCNs are compared in Table II. For satellite communications, narrow-band satellites mainly provide services, such as telephone, telegraph and fax, and the communication rate is low. The newly launched high-throughput satellites enable broadband maritime coverage. However, the cost of ship-borne equipment is very high. In addition to satellites, shore & island-based BSs can be built to extend the maritime coverage of terrestrial networks. UAVs, high-end ships and offshore lighthouses can be exploited as well to extend the coverage further. The coverage performance of the MCN depends largely on the above-mentioned geometrically available BS sites, and the transmission efficiency of a single BS is affected by maritime weather conditions, e.g., wave fluctuations. The link stability is generally poorer than terrestrial networks. From the above, it is necessary to enhance the transmission efficiency in the complex and dynamical maritime environment, to extend the coverage by taking advantage of different methods, and to develop service-oriented transmission and coverage techniques to meet the unique service requirements from maritime applications. We begin with the key technologies for transmission efficiency enhancement in the following section.

III. ENHANCING MARITIME TRANSMISSION EFFICIENCY

Compared with the terrestrial environment, the atmosphere over the sea surface is unevenly distributed due to seawater evaporation. Thus, the electromagnetic propagation over sea

is susceptible to sea surface conditions (tidal waves, etc.) and atmospheric conditions (temperature, humidity, wind speed, etc.), as depicted in Fig. 2. In addition, the height and angle of ship-borne antennas can change rapidly with the fluctuation of the sea surface. A representative insight on this issue can be found in [71], where the impact of sea waves to radio propagation and the communications link quality has been comprehensively discussed. Hence, maritime channel fading is particularly sensitive to parameters, such as antenna height and angle, which may cause frequent link interruption. These complex time-varying factors reduce the transmission efficiency in maritime scenarios.

To enhance the transmission efficiency, it is necessary to understand and take advantage of the characteristics of the wireless propagation environments over sea. Compared with terrestrial scenarios, electromagnetic propagation over sea is affected by various weather conditions, such as sea surface conditions and atmospheric conditions. These are unique for maritime channels. Therefore, the measurement and modeling of the maritime channel is very important for the design of MCNs [18]. On the other hand, advanced resource allocation schemes, such as dynamic beamforming and user scheduling techniques, need to be studied to utilize the dynamic changes of maritime channels. In addition, evaporation ducts may exist due to uneven atmospheric humidity above the sea surface, which can trap the signal inside and greatly reduce the transmission loss. It is possible to exploit the evaporation duct effect to improve the transmission efficiency, especially for remote transmissions. We start with the characteristics and models for maritime channels.

A. Characteristics and Models of Maritime Channels

Various channel measurements and modeling works have been conducted to analyze the impact of system parameters (frequency, antenna height, etc.) and maritime environments (sea state, weather conditions, etc.) on maritime channel fading [72]–[102]. According to the rate of change of these parameters over time, maritime channel fading can be classified as large-scale fading and small-scale fading. The large-scale fading varies slowly on the same order as the user location change. The small-scale fading is much faster due to the rapid fluctuations in signal amplitude, phase, or multipath delay over a signal wavelength.

For the large-scale fading, Bai *et al.* [72] studied the influence of ground curvature on the signal propagation characteristics of the maritime environment and calculated the link budget for wideband code division multiple access (WCDMA) systems. Yang *et al.* [73] studied the possibility of adapting several terrestrial channel models to the maritime environment in the 2-GHz band and found that the model from the International Telecommunication Union Radiocommunication Group (ITU-R) agrees well with the measurement results. However, the ITU-R model uses simple corrections for different terrains and therefore does not truly reflect the complex maritime variations, such as sea reflections and evaporation ducts.

Considering the impact of sea surface reflections, some recent works [74]–[77] studied the two-ray channel model and proposed several modified models. Among them, Zhao *et al.* [74] considered factors, such as sea surface reflection and antenna height, and proposed a two-ray model suitable for maritime channels. The model assumes that the maritime channel mainly consists of a direct path and a reflection path, and its path loss can be expressed as

$$L_{2\text{-ray}} = -10\log_{10} \left\{ \left(\frac{\lambda}{4\pi d} \right)^2 \left[2 \sin \left(\frac{2\pi H_1 H_2}{\lambda d} \right) \right]^2 \right\} \quad (1)$$

where λ is the carrier wavelength, d is the distance between the transmitting antenna and the receiving antenna, H_1 and H_2 represent the heights of the transmitter antenna and the receiver antenna, respectively.

Additionally, Reyes-Guerrero *et al.* measured the maritime channel in nonline-of-sight (NLOS) scenarios and proposed a simplified two-path model by using a geometrical approximation method. Compared with the free-space model and the two-ray model, this model is only appropriate for transmission over a short distance [75]. Mehrnia and Ozdemir [76] introduced the index correction coefficient in the two-ray model formula and obtained better channel prediction in the 5-GHz band. Lee *et al.* [77] studied large-scale fading characteristics and small-scale fading characteristics in the 2.4-GHz band and found that the two-ray model considering the wave height is more consistent with the experimental data in general. This modified two-ray model can achieve good accuracy under certain scenarios but is only applicable to offshore areas within a short distance.

In the marine atmosphere, special atmospheric refractive index structures easily form evaporation ducts, so that the electromagnetic wave has an extra scattering energy gain, enabling it to propagate to more distant areas. The evaporation duct effect is necessary for communications at a longer distance. Lee *et al.* measured the near-shore channel in the line-of-sight (LOS) scenario. The analysis shows that, when the distance between the transmitter and receiver exceeds a certain threshold (relative to the antenna heights), the presence of the evaporation duct will affect the path loss. In addition, Lee *et al.* [78] proposed a three-ray path loss model, which is closely related to the heights of the evaporation duct and the transmitting and receiving antennas. The height of the evaporation duct can be estimated using the Paulus–Jeske

empirical model (P–J model). Coker *et al.* [79] simulated and analyzed the effect of evaporation duct height on signal attenuation and diversity. More recently, Wang *et al.* [80] proposed a way to estimate the evaporation duct height using a novel refractivity profile model. Under proper sea conditions, the 3-ray model considering the evaporation duct has considerable advantages over the 2-ray model, and its path loss can be expressed as

$$L_{3\text{-ray}} = \begin{cases} -10\log_{10} \left\{ \left(\frac{\lambda}{4\pi d} \right)^2 \left[2 \sin \left(\frac{2\pi H_1 H_2}{\lambda d} \right) \right]^2 \right\}, & d < d_{\text{break}} \\ -10\log_{10} \left\{ \left(\frac{\lambda}{4\pi d} \right)^2 [2(1 + \Delta)]^2 \right\}, & d > d_{\text{break}} \end{cases} \quad (2)$$

where $\Delta = 2 \sin([2\pi H_1 H_2]/\lambda d) \sin([2\pi(H_e - H_1)(H_e - H_2)]/\lambda d)$, $d_{\text{break}} = [4H_1 H_2]/\lambda$, and H_e denotes the height of evaporation duct layer.

In addition to path loss, the maritime channel model needs to consider small-scale fading caused by sea-level fluctuation and atmospheric scattering. Hu *et al.* [81] pointed out that multipath reflection on the sea surface can be divided into coherent specular reflection and noncoherent diffuse reflection, and the concept of effective reflection area was proposed. Dong *et al.* [82] used the Rayleigh roughness decision criterion to prove that the diffuse reflection from the sea surface is negligible when the wave height is less than 4 m and the grazing angle is less than 5° . Haspert and Tuley [83] proposed a theoretical approximation modeling method that can be applied to multipath channels containing specular and diffuse reflection components. Yang *et al.* [84] measured the channel between the transmitting antenna on the far sea and the receiving antenna on the shore, and analyzed the important influence of the antenna position on signal propagation based on the received signal level (RSL) and the power delay profile (PDP). Lee and Meng analyzed the probability density function (PDF) of the small-scale fading and pointed out that the PDF is more approximate to the Rice distribution than the Nakagami- m distribution and the Rayleigh distribution. Yang *et al.* [86] analyzed the Doppler shift. Huang *et al.* [87] considered the smooth sea surface and the rough sea surface. The impulse response of a multipath channel, composed of the direct path, reflected paths, and scattering paths, was obtained. The model is suitable for different carrier frequencies, transmission distances, and sea states. More recently, Dahman *et al.* [88] performed ship-to-shore propagation measurements at the 1.39-GHz band and the 4.5-GHz band, and proposed a model to capture the behavior of small-scale fading at different frequency bands.

Focusing on the influence of various factors, such as waves, tides, and evaporating ducts on the maritime channel, we conducted a maritime channel measurement experiment at the 5.8-GHz band on the East Sea of China. The bandwidth of the measured signal is 20 MHz and the maximum distance is 33 km. The transmitter is set at the top of the teachers' apartment of the Qidong Campus of Nantong University, and the height is approximately 22 m. The receiver is arranged on the top of the fishing boat cabin and the height is approximately 4 m.

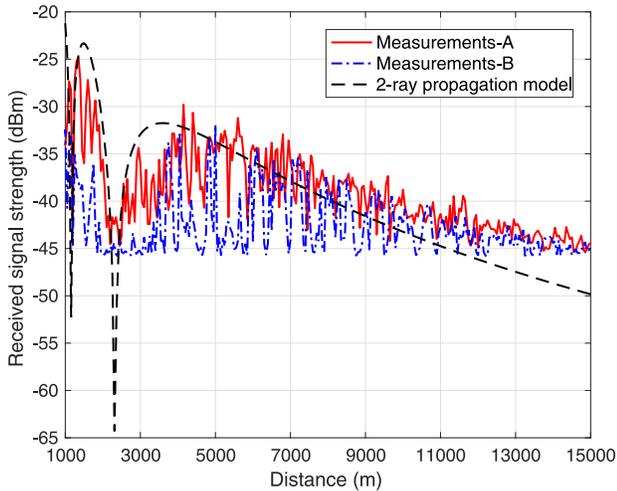


Fig. 3. Received signal strength results of channel measurements conducted on East China Sea and a two-ray channel model.

The vessel travels in a straight line in the East China Sea to the east at a constant speed of 10 knots. Parameters that affect the large-scale channel fading include the carrier frequency, the antenna heights, and the distance between the transmitting antenna and the receiving antenna. In particular, in the maritime environment, the height of the wave changes slowly due to the tide phenomenon, which changes the height of the shipborne antennas consequently [89]. It affects the received signal strength in duplicate measurements according to the two-ray model, as shown in Fig. 3. The small-scale fading characteristics of the channel can be observed by deriving the probability density distribution from the measurement data of the path loss, which can be described by the Rician distribution in LOS due to the existence of direct path and multiple sea surface reflection paths. However, the measurement results deviate greatly from the Rician distribution, and the small-scale fading model of the maritime channel needs further exploration.

For satellite channels, the channel fading consists of free space loss, ionospheric scintillation effect, atmospheric absorption loss, multipath fading and shadowing effects. When the weather is good, the signal is not blocked by clouds when it is transmitted over the channel. The signal received by the terminal includes scattering and direct components. In this case, the received signal envelope follows the Rice distribution. When the weather conditions are poor, the signal is affected by both shadowing effect and multipath without direct signal. It can be described using the Suzuki model as

$$p(a) = \int_0^{\infty} \frac{a}{\sigma^2} \exp\left(-\frac{a^2}{2\sigma^2}\right) \frac{1}{\sqrt{2\pi}\sigma\sigma_1} \times \exp\left(-\frac{(\ln \sigma - \mu)^2}{2\sigma_1^2}\right) d\sigma \quad (3)$$

where σ is the standard deviation of each Gaussian component, μ and σ_1 are the mean and standard deviations of signals that follow the Log-normal distribution, respectively. For maritime satellite channels, Hagenauer *et al.* [90] measured the channel fading with different antenna types and elevation angles and compared the performance of several modulation schemes.

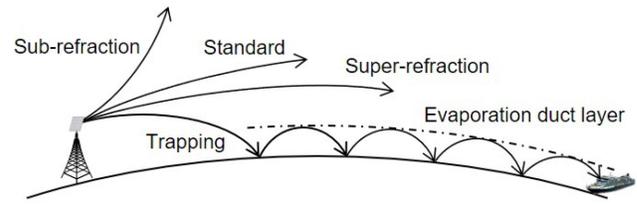


Fig. 4. Illustration of the four possible propagation paths due to atmospheric refraction and the evaporation duct.

Amaya and Rogers [91] and [92] analyzed the characteristics of rain fading on the Ka-band using the statistics extracted from the satellite-to-beacon propagation measurements.

The channel parameters from representative maritime channel measurements and modeling works are listed in Table III. The maritime channel model is determined not only by parameters, such as signal frequency, transmission distance, antenna height and moving speed but also by oceanic weather and sea surface fluctuations [98]–[102]. The above studies have considered several specific factors and measured the relevant received signal strengths under specific experimental setups and marine environments. However, their combined effect is still unknown. For the design of a practical MCN, link budget is necessary based on channel measurement results, which changes greatly from spring to winter, from day to night, and from sunny days to windy days. Therefore, network design ignoring the environmental factors will largely reduce the transmission efficiency and degrade the coverage performance of MCNs. On the other hand, the transmission efficiency in MCNs is envisioned to be enhanced by using some promising 5G technologies, such as massive multiple-input–multiple-output (MIMO) technologies, millimetre wave (mmWave) communications, and vehicle-to-vehicle (V2V) communications [103]. Until now, many massive MIMO channel models [104]–[107], mmWave channel models [108], [109], V2V channel models [110], [111], and high-mobility channel models [112]–[115] have been proposed, and a general 5G channel model can be used to simulate the channels [116]. However, these models are mostly based on the channel measurements in terrestrial scenarios and may not be suitable for the environment-sensitive maritime channels [26]. Therefore, it is necessary to carry out further measurements and modeling studies on maritime channels.

B. Reducing Transmission Loss: Exploiting Evaporation Duct for Remote Transmissions

The atmospheric refractive index over the sea surface varies with the maritime environment. Electromagnetic waves have different propagation paths depending on the rate at which the refractive index changes with height. When the rate meets certain conditions, atmospheric ducts will be formed, and signals will be trapped therein, as depicted in Fig. 4 [117]. Atmospheric ducts can be utilized to improve transmission efficiency, as the propagation loss in the duct layer is much smaller than that in free space [118].

Three types of atmospheric ducts often appear over the sea surface, namely, surface duct, elevated duct, and evaporation duct. The evaporation duct, formed by a large

TABLE III
MARITIME CHANNEL MEASUREMENTS AND MODELS

Ref.	Scenario	Frequency (GHz)	Tx-Rx Distance (km)	Tx/Rx Antenna Heights (m)	Channel Statistics	Environmental Factors Considered	Channel Model
[74]	ship to shore	2.1	13-41	10,25,50,100/10	PL	earth curvature	FSPL model
[75]	ship to shore	2.075	45	9.5/11.2	RSL, PDP, SC	not mentioned	ITU-R model
[77]	buoy to ship	5.8	10	1.7/9.8	PL	not mentioned	modified 2-ray model
[78]	ship to ship	35/94	20	5/9.7	PDP, PL, RMS-DS	not mentioned	FSPL model, modified 2-ray model
[79]	shore to ship	2.4	2	3/4.5	RSL, PL	not mentioned	FSPL, ITU-R, and 2-ray models
[80]	ship to shore	5.15	10	3-4/7.6,10,20	PL	evaporation duct	FSPL, 2-ray, and 3-ray models
[86]	ship to shore	2.075	45	9.5/11.2	RSL, PDP, SC	not mentioned	ITU-R model
[87]	air to ground	5.7	10	370,1830/2,1,7.65	PL	evaporation duct	FSPL model, 2-ray model
[88]	ship to shore	2.075	15.5	6.5/23	RSL, PDP, DFO, SRC	sea state	2-ray model
[95]	shore to ship	1.95	16	22/2.5	RSL, PL	not mentioned	FSPL model
[96]	flight to ship	5.7	27.7	1000/5.5	PL	evaporation duct	ducting-induced enhancement model
[97]	island to island	0.248/0.341	33.3,48	18.5/16,14	RSL, PL	sea state	FSPL model, ITU-R model
[98]	buoy to ship	5800	0.2	1.9/3.3	PDP, RMS-DS	not mentioned	not mentioned
[99]	ship to ship	1900	5-30	8/8	PDP, PL	not mentioned	log-distance PL model

Tx: transmitter; Rx: receiver; PL: path loss; RSL: received signal level; PDP: power delay profile; SC: spatial correlation; RMS-DS: root-mean-square delay spread; DFO: Doppler frequency offset; SRC: sea reflection coefficient; FSPL: free-space path loss

amount of seawater evaporated approximately 0–40 m above sea level, is the most common type of atmospheric duct and only occurs in the oceanic atmosphere [117]. Using the evaporation duct, several radio links have been set up for beyond-LOS maritime communications, such as the 78-km link from the Australian mainland to the Great Barrier Reef [118], and the 100-km link between Malaysian shores [119], [120].

It should be noted that the height of the evaporation duct layer depends on various environmental factors, such as air-sea temperature difference, humidity, air pressure, wind speed, and wave height [121]. Although the P-J formulation can be used to calculate the duct height, it may lose the prediction accuracy due to its sensitivity to the weather information. The utilization of evaporation duct for maritime communications is still in the early stage. To promote the development of MCNs, more meteorological instruments are needed to collect the vertical weather information, and more accurate models are required to predict the channel state information (CSI).

C. Improving Resource Utilization: Resource Management and Allocation Schemes

The transmission efficiency of MCNs depends on the channel environment. Therefore, advanced resource allocation schemes, such as dynamic beamforming and user scheduling techniques, can be used to take advantage of the dynamic changes of maritime channels. For random and rapidly changing wireless channels, traditional resource allocation and utilization methods based on service statistics and characteristics are inefficient, as they lead to a significant decrease in the overall performance of the network. To deal with the dynamic changes in maritime channels from sea surface and weather conditions, it is necessary to fully exploit the characteristics of the MCN.

Raulefs *et al.* [122] used vertically spaced multiple antennas at the receiver side and proposed a frequency and time synchronization and scheduling scheme to overcome deep fading, assuming the two-path characteristic of maritime channels. Kidston and Labbe [123] proposed a service-oriented framework for the management of MCNs and developed three policy-based routing schemes using the framework. In addition

to the above works, WiMAX and delay-tolerant networking (DTN) technologies have been widely discussed for maritime communications [124]. Lin *et al.* [125] used the WiMAX-based mesh technology for ship-to-ship communications with DTN features and compared the performances of different routing schemes. Yang *et al.* [126] studied the scheduling of data traffic tasks to optimize the network throughput and energy sustainability. Jiang *et al.* [127] proposed a joint backhaul and access link resource management scheme for the maritime mesh network to maximize the network capacity.

In contrast to terrestrial networks, user behavior characteristics are useful in MCNs to improve its transmission efficiency, since most marine users, such as passenger ships and cargo vessels, follow specific shipping lanes [128]–[130]. Qin *et al.* [131] derived a model of ship encounter probability and used the model to analyze the data delivery ratio. Kolios and Lambrinos [132] proposed an architecture of delay-tolerant MCNs where the AIS is integrated to obtain the trip-related data of ships, and they optimized the routing performance utilizing ship contact opportunities. Yang *et al.* [133], [134] proposed energy-and-content-aware scheduling algorithms for video uploading in MCNs based on the deterministic network topology and the ship route traces, respectively.

The studies in Section III-A have suggested that maritime channels consist of only a few strong propagation paths due to the limited number of scatterers, making the large-scale channel fading more dominant. Thus, it is promising to allocate resources using the large-scale CSI only, which can be conveniently acquired from the location information in the MCN [135]. Previous studies have explored the performance gain achieved by power allocation [136] and user scheduling [137] techniques using only large-scale CSI and suggested that coordinated transmission with large-scale CSI is effective in practical MIMO or distributed MIMO systems to improve the spectral efficiency and energy efficiency [138].

In Table IV, we summarize the technologies to enhance transmission efficiency for MCNs, as well as the unique characteristics of maritime communications that have been utilized. From the table, we can see that it is promising to utilize the unique features of MCNs in terms of electromagnetic

TABLE IV
TECHNOLOGIES TO ENHANCE TRANSMISSION EFFICIENCY FOR MCNS

Goal	Scheme	Characteristics of MCNs Used	Contributions
reducing transmission loss	microwave scattering	evaporation duct over sea	setting up beyond-LOS maritime communications: 78-km [120], 100-km [121][122]
	frequency-time scheduling	two-path maritime channels	exploiting vertically spaced multiple antennas at the Rx. to overcome deep fading [124]
reducing transmission delay	routing	delay-tolerant maritime services	a service-oriented framework and three policy-based routing schemes [125], DTN technologies [126][127]
improving network throughput	traffic scheduling	content-aware maritime applications	data traffic task scheduling [128]
	resource allocation	heterogeneous networking	joint backhaul and access link resource management [129]
improving data delivery ratio	routing	user behaviours (such as shipping lanes)	a model of ship encounter probability [133], an architecture integrating the AIS [134]
improving energy efficiency	traffic scheduling		energy-and-content-aware scheduling algorithms for video uploading based on the deterministic network topology [135] and the ship route traces [136]

propagation environment, service requirement and vessel movement for more efficient transmission. Specifically, since maritime channels are susceptible to sea surface conditions and atmospheric conditions, future MCNs need to be able to perceive environmental information, such as the sea level, temperature, humidity, and wind speed, to make more accurate prediction of the CSI and then intelligently utilize the dynamic changes of maritime channels for more efficient transmission.

IV. INCREASING BROADBAND COVERAGE

The previous section has focused on enhancing the transmission efficiency for the MCN from the link-level perspective. However, due to the quite limited BS sites in an MCN, only link-level enhancement is not enough to ensure seamless wide-area coverage. For this reason, we focus on the utilization and coordination of all available wireless coverage approaches, and introduce the key technologies for increasing broadband coverage from a system/network-level perspective in this section.

In addition to maritime satellites, shore & island-based BSs can be built to extend the coverage of terrestrial networks to the ocean. UAVs, high-end ships and offshore lighthouses can be exploited as well to serve as maritime BSs. The coverage performance of the MCN depends largely on the above-mentioned geometrically available BS sites. Due to the limited onshore BS sites and the high mobility of the ship-borne BSs, aerial BSs and users, the topology of the MCN is highly irregular. There always exist blind zones within the coverage area. When the BS increases its transmission power, it will also generate strong co-channel interference to users served by the neighboring BSs.

Considering these problems, the MCN has to make full use of the available BSs, including onshore BSs, ship-borne BSs, aerial BSs and satellites, as depicted in Fig. 5. By using multihop wireless networking and satellite-terrestrial integration technologies, the BSs can work cooperatively to increase broadband coverage. Advanced transmission techniques, such as dynamic beamforming and microwave scattering, can also be used to reduce the signal attenuation and extend the coverage of a single BS.

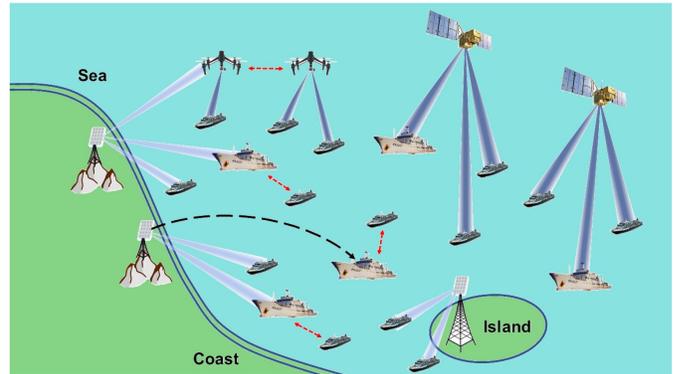


Fig. 5. Exploiting onshore BSs, ship-borne BSs, aerial BSs, and satellites to extend the maritime coverage.

A. Building and Exploiting Offshore BSs: Multihop Networking of Ship-Borne and UAV-Enabled BSs

To achieve wider coverage for MCNs, Laarhuis [139] and Kim *et al.* [140] proposed the *ad hoc* networks Maritime-MANET and Nautical *Ad hoc* Network (NANET), respectively. Similarly, Lin *et al.* [125] proposed a WiMAX-based mesh network to provide delay-tolerant maritime communication services. To improve the efficiency of ship-to-ship communications in these MCNs, Laarhuis [139] used multiple directional antennas, Zaidi *et al.* [141] used virtual MIMO technologies, and [142] and [143] used two relaying schemes. Additionally, in [144], a novel handover protocol was proposed. In [145], a distributed adaptive time slot allocation scheme was proposed, while in [146], a cognition-enhanced mesh medium access control (MAC) protocol was proposed. Furthermore, Du *et al.* [147] proposed an integrated MCN consisting of NANETs, terrestrial cellular networks, and satellite networks, in order to meet the requirements of various services.

Various routing methods and protocols have been proposed for terrestrial delay-tolerant *ad hoc* networks [148], [149], such as epidemic routing [150], probabilistic routing [151], spray and wait [152], network coding schemes [153], [154], optimized link state routing (OLSR) [155], *ad hoc* on demand distance vector (AODV) Routing [156]–[158], and *ad hoc* on demand multipath distance vector (AOMDV) [159]. However,

TABLE V
ROUTING PROTOCOLS FOR MARITIME COMMUNICATIONS

Reference	Protocol	Feature	Applicable Scenario
[150]	Routing Application for Parallel Computation of Discharge (RAPID)	Replica-based (flooding)	Ships in low density
[152]	Epidemic Routing (ER)	Replica-based (flooding)	Ships in low density
[153]	Probabilistic Routing (PR)	Replica-based (flooding)	Ships in low density
[154]	Spray and Wait (SaW)	Replica-based (flooding)	Ships in low density
[155]	Estimation Based Erasure Coding (EBEC)	Coding based	Ships in low density
[156]	Hybrid Erasure coding (HEC)	Coding based	Ships in low density
[157]	Optimized Link State Routing (OLSR)	Regular	Ships in good density
[158]	Ad Hoc On Demand Distance Vector (AODV)	Regular	Ships in good density
[161]	Ad Hoc On Demand Multi-path Distance Vector (AOMDV)	Regular	Ships in good density
[166]	Lane-Based Opportunistic Routing (LanePost)	Knowledge based	Ships in low density
[170]	Geographical Routing (GR)	Knowledge based	Ships in low density
[171]	Gradient Routing Based on Link Metrics (GR-LM)	Knowledge based	Ships in low density

these schemes have poor performances in maritime communications, due to the large delivery delay and low delivery ratio from the lower user density [160]. Therefore, routing protocols custom-made for maritime mesh networks are required [161]–[163].

Geng *et al.* [164] proposed an opportunistic routing scheme for delay-tolerant MCNs based on lane intersecting opportunities. Yang *et al.* [133] proposed three offline scheduling algorithms for video uploading in MCNs based on the deterministic network topology. Hu *et al.* [165] proposed a route maintenance method for maritime sensor networks based on ring broadcast mechanism. In addition, Glissa *et al.* [166] and Bouaziz *et al.* [167] proposed two secure and efficient routing protocols for the Internet of Mobile Things based on movement prediction. These studies utilized the predictability and stability of user movement but did not take full advantage of the physical characteristics of maritime channels. Different features and applicable scenarios of representative routing protocols for maritime communications are listed in Table V. Note that the height and angle of the ship-borne antenna are rapidly changing due to the fluctuation of the sea surface. In addition, maritime channel fading is sensitive to antenna height and angle [89]. To solve this problem, we need to establish a sensitivity model for the received signal strength, the height of the ship-borne antennas, and the sea surface fluctuation intensity, based on which we can optimize the routing algorithm in MCNs to reduce the packet loss rate and network delay.

Moreover, marine traffic also fluctuates over time, resulting in changes in BS loading. Using BS switching, the MCN can shut down some low-loaded BSs when the traffic is low to not only support current users but also save energy and reduce interference to neighboring users. Presently, the switch selection methods applicable to terrestrial fixed BSs are based on BS performance indicators, such as coverage, cell load, and neighboring cell interference, to provide a BS deployment scheme and a switching method. Unlike terrestrial BSs, a ship-borne BS has the following two characteristics. First, the power resources are limited, so it is more important to save energy. Second, the onboard BS has high mobility. If the switch selection method for terrestrial fixed BS is applied to maritime communications, either the BS switch operation will be too frequent or the BS switch configuration for a period of time will not meet the user needs. Therefore, existing BS switch selection methods do not apply to the

onboard BS. Switch selection methods for ship-borne BSs in maritime communications need to be investigated. For example, Xiao *et al.* [170] proposed a ship-borne BS sleeping control and power allocation scheme for the MCN based on the sailing route to enhance the robustness of dynamic coverage.

UAVs are believed to be useful and efficient for promoting connectivity in vehicular *ad hoc* networks [171]. In addition to ship-borne BSs, UAVs can be exploited to serve as aerial maritime BSs, or relay nodes to extend the coverage of the MCN. Specifically, the coordination among UAVs can provide a multihop network, such as a mesh network, where the flight trajectory, routing strategy and transmission method are optimized. Chen *et al.* [172] focused on the reliability, and optimized the altitude of the UAV as a relaying station. Feng *et al.* [173] considered UAV-aided data collection for the maritime IoT and optimized the transmit power and duration of all devices to maximize the data collection efficiency. Due to their agile manoeuvrability, UAVs are considered effective tools to achieve dynamic and flexible coverage for MCN. Despite that, utilizing UAVs for maritime IoT applications (such as data gathering) still faces challenges. For example, it is difficult to recharge battery-equipped maritime IoT devices, so the energy constraint must be considered to optimize the communication strategy. In addition, it is difficult to acquire perfect CSI (including the random small-scale CSI) due to the sea wave movement.

B. Utilizing High-Throughput Satellites: Multispot Beams and Satellite-Terrestrial Cooperation

In addition to building a mesh network using ship-borne BSs and UAVs, satellites can also be exploited to extend the coverage of MCNs. The utilization of satellite communications for maritime coverage has been widely reported in the literature [174]–[185]. Although satellite communications have a wide coverage, they are limited by their high latency and low data rate. To enhance broadband coverage of maritime satellites, spot beam and frequency reuse technologies have been studied. Since a narrower beam width leads to a higher antenna gain, the use of spot beam technologies can increase the spectral efficiency, and allow maritime users to use smaller satellite terminals [174]–[176]. Furthermore, the use of multispot beams allows beams that are far apart to reuse frequency. Frequency reuse is an effective way

to improve spectral efficiency, but it may generate strong interbeam interference due to the nonzero side lobes [177]. Therefore, side lobe suppression technologies are required for the use of multispot beams, and there is a tradeoff between the number of spot beams and the distance between frequency-reuse beams [178], [179]. It should be noted that, in maritime communications, the density of vessels/platforms/islands is low, while the users are clustered thereon. Therefore, using multispot beams is an effective way to enhance broadband coverage for MCNs [180], [181].

Since terrestrial networks in general have high capacity but limited coverage, while satellites have wide coverage but a low data rate, an integrated satellite-terrestrial network (ISTN) is a promising way to enable seamless broadband coverage, taking advantage of both networks [182]. Specifically, for maritime communications, Boreli *et al.* [183] proposed intelligent middleware and link-specific protocols for the coordination of maritime mesh networks and satellite communication networks. Kessab *et al.* [184] considered a hybrid Satellite-MANET consisting of GEO, MEO, and LEO satellites and terrestrial MANET. They analyzed the distribution of coverage radius for full connection and proposed a multihop routing protocol to minimize the end-to-end delay. Dhivvy *et al.* [185] proposed an OceanNet Backhaul Link Selection (OBLS) algorithm to select the optimal backhaul links with the best signal-to-noise ratio (SNR). Furthermore, the authors implemented the proposed algorithm in a hardware testbed.

It should be noted that the round-trip time in satellite communications is much longer than cellular communications. This will greatly degrade the Quality of Service (QoS) and Quality of Experience (QoE), especially for real-time video needed in marine rescue. To tackle this problem, Shaat and Perez-Neira [186] proposed a backhaul activation scheme to minimize the traffic delivery time for a multihop ISTN. In addition, caching strategies have been adopted to reduce the accumulative delay. Li *et al.* [187] proposed a back-tracing partition based on-path caching algorithm for ISTNs to reduce the overheads and access delay. Zhong *et al.* [188] proposed a QoE-driven caching placement scheme for video streaming in the ISTN, considering the social relationship among users. Romano and Roseti [189] presented a secure hybrid in-network caching scheme for multimedia content streaming in the ISTN.

It is also possible to increase the broadband coverage for MCNs by building large-scale LEO satellite constellations. SpaceX plans to launch approximately 12 000 Starlink LEO satellites. There will be two Starlink satellite constellations: one containing 4409 satellites and the other containing 7518 satellites. SpaceX plans to provide affordable Internet services with delays between 25 and 35 ms, which will make its services comparable to cable and fiber optics. In addition to SpaceX, many companies, such as OneWeb, TeleSat, and Amazon hope to provide Internet access services to more people by deploying small LEO satellite networks [190]–[193]. There are many challenges for large-scale LEO satellite constellations, such as mobility management, resource allocation, and security. For example, conventional Internet protocols have large signalling overhead and handover delay due to the frequent changes of LEO satellites' Point of Attachment (PoA) in the ISTN, and methods of installing mobility logic in the

software-defined network (SDN) controller to address the PoA variation need to be studied.

C. Reducing Signal Attenuation: Phased-Array Antennas and Beam Scheduling Techniques

Directional beams are commonly used to widen the coverage area. The concept of beamforming was introduced in 5G, where the beamforming vectors are calculated based on the MIMO CSI [194]. In the scenario of maritime communications, the density of vessels is low and the users are clustered in a small area (ship/platform), which makes it easy to determine the beam directions according to the users' geographical location. Thus, it is convenient for MCNs to use phased array antennas with analogue beamforming to reduce the cost. The use of phased array antennas can effectively increase the coverage of MCNs with a lower cost based on the existing LTE networks [195], as the directions of antennas can be determined according to the location of users.

The user location information can be obtained from the AIS. The BS receives the location information and steers the antennas to point to the selected directions [196]. Note that directional beams can point to a narrower range of directions than omni-directional beams to decrease the signal attenuation, and the beams need to be dynamically scheduled, for higher throughput or wider coverage [197]–[199].

D. Exploiting Microwave Scattering for Over-the-Horizon Coverage of Islands/Platforms

The earth's atmosphere can be divided into the ionosphere, the stratosphere, and the troposphere. The troposphere is the atmosphere from earth surface to an average altitude of 10–12 km. The turbulence and the inhomogeneous medium in the troposphere can scatter incident microwaves to allow over-the-horizon communications. Microwave scattering communications have the advantages of long distance, large capacity, high security, and high flexibility. Therefore, microwave scattering is very suitable for providing communication services for users in environmentally harsh areas, such as mountains, deserts, and oceans [200]–[202].

The number of scatterers in the troposphere over the oceans is much larger than that in the troposphere over the ground, due to more frequent atmospheric flows. Thus, the transmission distance using microwave scattering in maritime communications is larger than that in terrestrial communications [203], [204]. Until now, many experimental links have been set up for over-the-horizon maritime communications using microwave frequency band, such as the 5.8-GHz band [200], and the 2.2-GHz band [202].

High-power microwave antennas or large-scale antenna arrays often require compensation for the transmission loss. Therefore, microwave scattering communications may not be cost effective and are mainly used for the coverage of islands, warships, and drilling platforms [205].

E. Interference Alleviation for Irregular Network Topology

Due to the limited spectrum resources, some systems and beams of the MCN have to be frequency-multiplexed, and the interference model is complicated. Traditional methods

TABLE VI
TECHNOLOGIES TO INCREASE BROADBAND COVERAGE FOR MCNS

Approach	Goal	Scheme	Technology
exploiting ship-borne BSs	providing delay-tolerant maritime communication services	network architecture	WiMAX-based mesh network [127]
			Maritime MANET [141]
			Nautical ad hoc network [142]
		resource allocation	dynamic subnet relay [144]
			energy-efficient handover [146]
	improving the efficiency of ship-to-ship communications	multiple antennas	multiple directional antennas [141]
			virtual MIMO technologies [143]
		resource allocation	distributed adaptive time slot allocation [147], cognition-enhanced mesh MAC protocol [148] ship-borne BS sleeping control and power allocation [172]
utilizing high-throughput satellites	improving the throughput of satellite-to-ship communications	smart antennas	smart satellite terminals [177][178] phased array antennas [181]–[183]
	satellite-MANET coordination	network protocol	intelligent middleware and link-specific protocol [185]
			multi-hop routing protocol [186]
			backhaul link selection algorithm [187]
	extending the coverage of a single BS	reducing propagation loss	directional beams
achieving over-the-horizon communications		microwave scattering	experimental microwave links [203]
			novel lightweight antennas [204]
interference alleviation	interference analysis	interference modelling	modelling of interferences on other satellites in maritime satellite communications [179]
		interference simulation	analysis and simulation of interference produced to the fixed service receivers by the mobile satellite service [180]
			analysing the co-channel interference from maritime mobile earth station to 5G mobile service [212][213]
	interference coordination	resource allocation	pilot scheduling and power allocation [216]
			radio resource block allocation [218]

often deal with the intersystem interference and intrasystem interference independently. However, the MCN often has an irregular topology, and its coupling between the systems and the intrasystem interference is very strong [206]–[208]. To solve this problem, one can either schedule the beam resources between the satellite and the terrestrial network, study the optimal beam design method, or suppress inter-beam interference. In [209], an antenna selection algorithm was proposed for hierarchical maritime radio networks toward better coverage and cost effectiveness. Aoyagi *et al.* [177] investigated the impact of diffracted waves from the structures of a ship on the RSLs and found a relationship between the clearance angles and interference. Koletta *et al.* [178] focused on the interference between the mobile satellite service and the fixed service in a maritime environment in the Ku band, and analyzed the mobile earth station's transmit power, antenna gain, speed, and the propagation environment. More recently, Son and Chong [210] and Kim *et al.* [211] analyzed the co-channel interference from maritime mobile earth station to 5G mobile service and suggested that a separation distance should be set to guarantee the QoS for 5G outdoor environments.

Due to the long distance required to cover the sea surface, the propagation path needs to take into account the influence of the curvature of the earth. For sea surface coverage, the wireless signal travels very far due to the small loss of radio wave transmission. At this point, the influence of the

curvature of the earth on the sea surface must be considered, and the sea surface cannot be regarded as a plane. Therefore, the height of the antenna is directly related to the coverage distance [212], [213]. If the antenna height is too low, it will reduce the coverage of the BS. If the antenna height is too high, it will cause pilot contamination between neighboring cells. Therefore, the antenna height must be carefully adjusted for maritime communications.

On the other hand, when the BS covers the remote users with high power, it will generate strong interference to users served by the neighboring BSs, causing the near-far effect. The removal of interference requires the CSI, but the pilot transmitted by the nearby users also generates strong interference to the pilot transmitted by the remote user, resulting in inaccurate channel estimation. Thus, the pilots need to be carefully designed [214].

Up to now, the key technologies to extend the coverage of MCNs, such as multihop wireless networking of ship-borne BSs and UAVs, satellite-terrestrial cooperation, dynamic beam scheduling, microwave scattering, and interference management, have been studied. We summarize the technologies in Table VI. To give full play to the advantages of the above-mentioned methods, a heterogeneous network can be formed by coordinating maritime satellites, shore & island-based BSs, ship-borne BSs and UAVs. In particular, narrowband systems that provide position information or transmit control signals,

such as the VHF Data Exchange System (VDES), may also be integrated for intelligent configuration of the heterogeneous MCN. Additionally, it is essential to effectively allocate spectrum and power resources based on the characteristics of different service requirements [215]–[217]. Typical maritime communication services, such as geographic information services for safe navigation and video downloading services for passenger infotainment, have various requirements for bandwidth, latency and reliability. We will discuss the key technologies for service provisioning in detail in the following section.

V. SERVICE PROVISIONING FOR MARITIME APPLICATIONS

A. Demand for Maritime Communications

If one takes a bird's-eye view over the ocean, one will find various types of marine users requiring communication services. For sailing vessels, navigational and operational communication services are required for safe navigation. For passengers, crew, fishermen and offshore workers, Web browsing and multimedia downloading services are needed for their entertainment. The beacons are deployed to collect and upload meteorological and hydrological information, and platforms for oil exploitation require real-time operational data services. In particular, when a marine accident happens, real-time video communications will be of great help for rescue.

In industrial applications, marine informatization management requires wireless data services, such as video surveillance, video conferencing, and navigational data services. Other marine industries, such as marine fisheries and offshore oil exploration, also have a large amount of data for uploading. For marine tourism applications, multimedia services are needed to satisfy the passengers and the crew, and Internet services are required to keep them connected at any time. For all of the applications described above, low-cost high-speed maritime communications are beneficial [4]–[6].

On the other hand, for maritime rescue, real-time and high-reliability maritime communication services are required to enable coordination between ships and between ship and shore. In addition to text and voice, real-time video communications will be very helpful for conducting rescue operations in a more accurate manner. Real-time and high-reliability services are also required for maritime military applications, e.g., for communication and coordination between warships and between fleets and land. A higher level of security is also required in these applications to prevent the data transmission from being intercepted by eavesdroppers [218].

Based on the nature of the communication network organization and service demands, maritime communication services can be classified as secure communications, dedicated communications and public communications [14]. Secure communications include voyage reports and severe weather warnings to ensure safe navigation, as well as communications for help, search and rescue in the event of a shipwreck. Dedicated communications allow the navigation department or the maritime enterprise to establish internal communication protocols, and set up communication links between a self-designed or leased coast station and its own ships according to the application

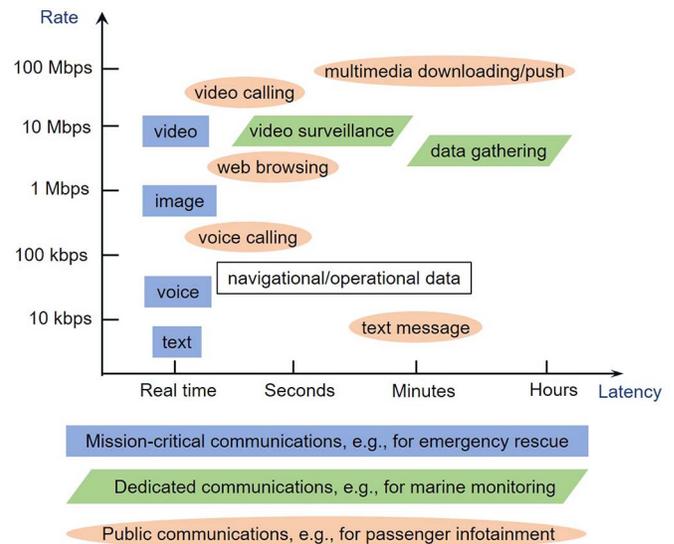


Fig. 6. Three types of maritime communication services and their required rate and latency.

requirements. Public communications refer to the communications between ship personnel, passengers, and any users of the land-based public communication network [60].

Typical maritime communication services are depicted in Fig. 6, according to their requirements for rate and latency [219]. Navigational and operational communication services, such as ship reporting, voyage reporting, electronic navigational chart (ENC) updates, coast state notification, and environment notification, are required by all vessels. These services do not require large bandwidth and can be provided by coast stations or maritime satellites [220], [221]. Secure communications services, such as those for emergency rescue and military missions, have a critical demand for latency. There have been increasing demands for real-time video communications in addition to voice services in such mission-critical maritime activities [222]–[224]. Dedicated communications usually require a large bandwidth but tolerate high latency. Public communications, such as Web browsing and video downloading services, are mainly for passenger and crew infotainment. For public communications, a great deal of bandwidth is required, while the demand for latency varies from real-time to minutes.

B. Service Provisioning for Typical Maritime Applications

Different services have different requirements for bandwidth, latency and reliability, as depicted in Fig. 7. For example, the data services for maritime rescue and operation of oil platforms have a critical demand for real-time video and high reliability. The multimedia downloading and data gathering services usually require a large bandwidth but tolerate high latency. One unique property of maritime services is that the density of vessels is low, while the users (passengers/crew/fishermen/offshore workers) are clustered in a small area (ship/platform). Therefore, the passenger/crew infotainment services are sparsely distributed on the sea, but densely clustered in each vessel.

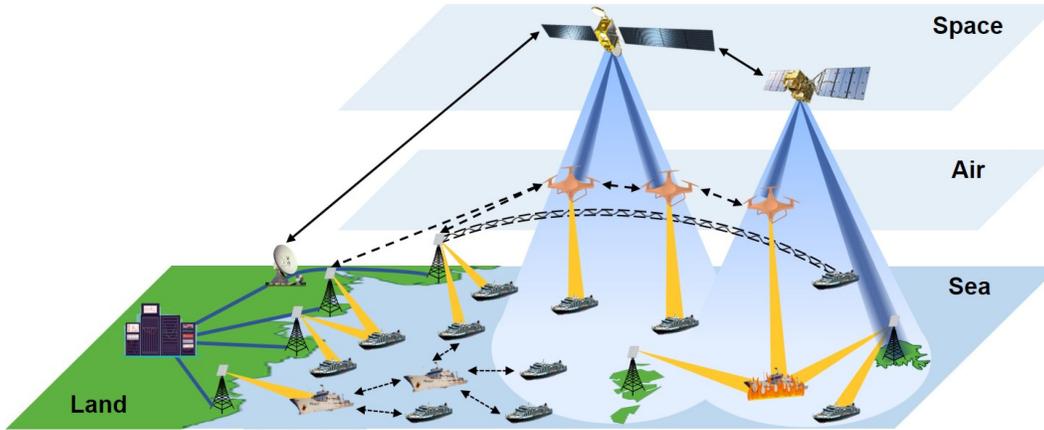


Fig. 7. Future MCNs: satellite-air-ground integrated, environment aware, and service driven.

In view of this, next we will introduce the existing and potential schemes to provide maritime-specific services. In addition to the intelligent navigational communication services required by all vessels, the clustered distribution services, delay/reliability-sensitive maritime services, as well as delay-tolerant maritime services will be discussed.

1) *Intelligent Navigational Communication Services*: To achieve safe navigation and improve shipping efficiency, sailing ships need to be provided with real-time and accurate maritime traffic information in the fastest and most efficient way. Stove *et al.* [225] considered the feasibility of utilizing illuminators sent by Inmarsat for maritime surveillance and navigation, especially for marine obstacle avoidance. Holsten [226] introduced the utilization of satellite-based AIS receivers to extend traffic monitoring zones to open seas, as well as collision avoidance in high traffic zones. More recently, Jayasimha *et al.* [227] proposed a parallel signal processing architecture and algorithms for satellite-based AIS to cope with the message collision in dense maritime zones and reduce the downlink power, bandwidth, and latency. Similar to satellite-based AIS, the long-range identification and tracking (LRIT) system is a real-time reporting system that allows for ship detection and identification from space [228].

In addition to using the above-mentioned satellite-based systems, navigational communication services can also be provided by shore-based systems, such as terrestrial AIS and coastal radars [229]. Shore-based radar systems can promote safe navigation by collision monitoring and grounding prevention. Particularly, Braca *et al.* [230] reported the experimental performance assessment of high frequency surface wave (HFSW) radars, which have wider coverage than conventional microwave radars. The detection capabilities of HFSW radars were evaluated and enhanced using spectrum analysis techniques in [231]. In short, an intelligent maritime transportation network is currently formed by making full use of the geographic information system (GIS), the global positioning system (GPS), remote sensing (RS), and other technologies [232]–[237].

2) *Passenger/Crew Infotainment–Clustered Distribution Services*: Different from the terrestrial scenario, where users are scattered on the land, in the MCN, the density of vessels

is low, while the users (passengers/crew/fishermen/offshore workers) are clustered in a small area (ship/platform) [238]. Therefore, the passenger/crew infotainment services are sparsely distributed on the sea, but densely clustered in each vessel. To provide such services, phased array antennas and beamforming techniques can be used. The direction of beams can be controlled according to the location of vessels, which can be obtained from the AIS [239]. Xu *et al.* [217] proposed a user-centric communication structure and an antenna selection scheme based on distributed antennas. Li *et al.* [199] proposed a location-aware dynamic beam scheduling scheme to provide users in each ship with guaranteed QoS to strike a balance between the throughput and fairness among different ships.

3) *Mission-Critical Services With Low Latency and High Reliability*: When a marine accident happens, real-time and high-reliability communication services are important for maritime search and rescue. The emergency communication systems based on UAVs and low-orbit satellites can provide real-time transmissions of voice, image, video, etc., and help improve the communication security in the remote area. In addition, underwater emergency communications can also provide communication and location services for underwater rescue, wreck positioning, as well as search and salvage [240].

For ship-to-ship communications between the rescue team and the ship with accident, it is worth mentioning that the height and angle of the ship-borne antenna are rapidly changing with the fluctuation of the sea surface. Thus, the maritime channel fading is particularly sensitive to antenna height and angle, which may cause frequent link interruption. To cope with this challenge, antenna switching techniques have been proposed in [241]. In this article, when the rocking angle of a ship is more than a threshold, antenna switching will be triggered to improve link stability and packet delivery ratio.

4) *Multimedia Downloading and Data Gathering–Delay-Tolerant Services*: The downloading of multimedia and the uploading of hydro-meteorological information require broadband communications and high latency tolerance [242]. To provide this kind of delay-tolerant services, several resource scheduling methods for maritime communications have been

TABLE VII
TECHNOLOGIES FOR GUARANTEEING TYPICAL MARITIME COMMUNICATION SERVICES

Service	Characteristics	Solutions	Technologies
intelligent navigation and emergency rescue	real-time, high reliability, high accuracy	using satellite-based positioning and geographic information systems	utilizing illuminating signals sent by Inmarsat for maritime surveillance and navigation [228]
			utilizing satellite-based AIS receivers to extend traffic monitoring zones [229]
			parallel signal processing for satellite-based AIS to cope with message collision [230]
		using shore-based positioning and geographic information systems	collecting and disseminating vessel position information via the self-reporting-based LRIT system [231]
			collision monitoring and grounding prevention using terrestrial AIS and coastal radar systems [232]
			experimental performance assessment of HFSW radars [233]
passenger and crew infotainment	low density of vessels, users clustered in a small area	generating directional beams according to the location of vessels	enhancing detection capabilities of HFSW radars using spectrum analysis techniques [234]
			fairness-oriented beam scheduling using phased-array antennas [201]
			antenna selection based on distributed antennas [219]
multimedia downloading and data gathering	large data volume, high latency tolerance	service scheduling based on the mobility of vessels	antenna tracking [242]
			offline scheduling based on the deterministic network topology [135]
			opportunistic routing based on lane intersecting opportunities [166]
			store-carry-and-forward scheduling [246]

proposed. In [164], an opportunistic routing scheme for delay-tolerant MCNs based on lane intersecting opportunities was proposed. In [133], three offline scheduling algorithms for video uploading in MCNs based on the deterministic network topology were proposed. These studies utilized the predictability and stability of marine user movement [243].

In Table VII, we summarize the technologies used to provide typical maritime communication services. The above work has designed different networks for different maritime service requirements. However, for maritime communications, due to the limited number of BSs, the best solution is to establish a network that supports all types of services at sea. To this end, network resources should be flexibly coordinated to present different performance gains according to different service requirements. Therefore, cross-layer design and joint optimization of the physical layer, MAC layer, and network layer are required for multiple service types and QoS requirements, such as different rates, delays, and reliability, with comprehensive consideration of channel status and service requirements.

C. Cross-Layer Design for QoS-Guaranteed Maritime Communications

It should be noted that the maritime application scenarios are quite different and that the marine service requirements are unique. To adapt to the different types of services and different requirements for QoS, it may be necessary to jointly consider the CSI and service requirements by designing cross-layer optimization schemes [244]. For example, potential synergies of exchanging information between different layers for real-time video streaming in *ad hoc* networks was explored in [245]. The joint design of physical, MAC, and network layers was considered for interference-limited wireless sensor networks in [246]. Hasan *et al.* [247] analyzed the cross-layer design of QoS-forward geographic wireless sensor network routing strategies in green IoT. In particular, service-driven methods can be used in MCNs to allocate resources, and user-centric transmissions can be used to implement rapid link-building services [248]. Resource conditions and service requirements can be exploited for flexible resource allocation for different services [249]. In addition, a programmable

architecture based on SDN is believed to be useful for the maritime IoT [250].

Using these service-driven schemes, it is possible to comprehensively address the dynamic changes in the location and demand of marine users, as well as the wide range of maritime network coverage with severely limited resources. Moreover, a new framework for joint optimization of service scheduling and BS transmission can be built. For example, a proxy can be set up for each user, and the agent collects and combines information, such as the user location, shipping route, service demand, and link resource status of the BS, along with the sea status. The resource scheduling is performed by estimating user location and CSI, and then these data are sent to the BSs and to the users.

VI. ARCHITECTURE AND FEATURES OF FUTURE MCNs

In the last three sections, we have discussed the key technologies for enhancing transmission efficiency, increasing broadband coverage, and providing domain-specific services for the MCN. As discussed in Section IV, a heterogeneous network is useful which requires the coordination of terrestrial and nonterrestrial BSs [251]. In this network, the terrestrial BSs mainly cover the offshore waters, and the satellites mainly cover the ocean areas. At the same time, the ship-borne BSs on the sea can be used as relay nodes to serve nearby vessels. To facilitate the use of the above-mentioned BSs, advanced hardware needs to be developed, such as new antennas with higher directivity and lower complexity, radio frequency (RF) amplifiers with higher linearity and lower noise, as well as airborne and shipborne equipment with lighter weight and lower power consumption [252], [253]. Future MCNs should enhance the transmission efficiency in the complex and varied maritime environment, extend the coverage by taking advantage of and overcoming the shortcomings of different coverage methods, and develop service-specific transmission and coverage techniques to meet the unique service requirements of marine users.

A. Requirements and Characteristics of Future MCNs

To improve transmission efficiency, future MCNs need to be aware of the environment, such as the sea level, temperature, humidity, and wind speed, and use this awareness to obtain

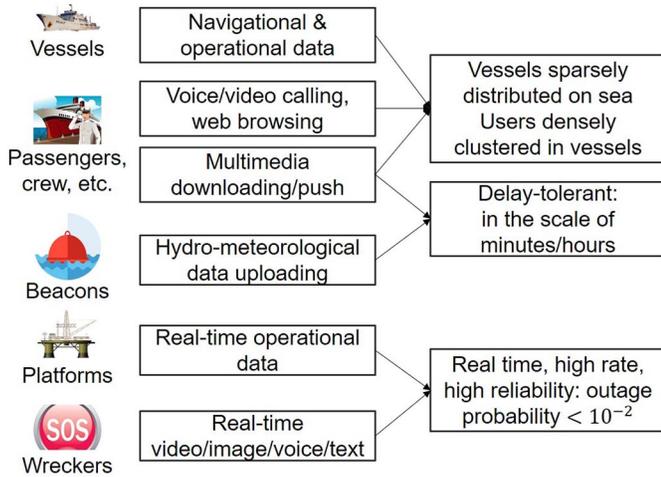


Fig. 8. Maritime-specific communication services and their features.

more accurate prediction of the CSI and adopt more efficient transmission techniques that counteract the dynamic changes in maritime channels [254]. In addition, future MCNs need to be able to provide flexible services based on resource conditions and service requirements. This can address the dynamic changes in the location and demand of marine users and thus allow the provision of dynamic and on-demand coverage using limited resources.

As depicted in Fig. 8, future MCNs can adopt more flexible coverage modes and service patterns by utilizing the unique maritime channels and service characteristics. Specifically, the environmental information, positional information and service information can be collected by narrowband systems and exploited by the central processor (and BSs serving as edge processors [255], [256]) to design integrated satellite-air-ground systems. For example, a long-distance communication link can be dynamically established, depending on whether the user is in an environment that satisfies the conditions under which the evaporating duct exists. When high-speed and high-reliability communication services are required for rescuing a vessel on fire, the nearby vessels and UAVs can gather together to provide ship-borne and air-borne services.

B. Exploiting the Knowledge Library for Intelligent MCNs

Following the discussion in Section VII-A, it is recommended to establish a knowledge library that contains all environmental information for future MCNs. The knowledge library is used to portray the complex signal propagation environment, network topology, and service characteristics, based on which the transmission efficiency and coverage performance can be improved through optimization. The knowledge library comes from both internal information on the communication process, such as the CSI, and external information, such as the maritime environment, network node position, and user behavior characteristics. The external information can be gathered by buoys, ship-borne sensors, etc., and then uploaded to the central processor via narrowband

systems. In the machine learning and optimization platform with the central processor, machine learning techniques can be adopted to jointly process the internal and external information and establish the knowledge library, including the hierarchical maritime channel model, the network topology evolution model, and the service model. The available BSs with extra storage capacity and computing power can be exploited to serve as edge processors. Neural network structures [257] and federated learning technologies [258] being discussed for the sixth-generation (6G) network may contribute to the above process.

Utilizing the knowledge library, the machine learning and optimization platform will further perform transmission optimization, network management, and service scheduling for the MCN. For example, in transmission optimization, using the meteorological and hydrological information gathered by maritime buoys and weather satellites, the machine learning and optimization platform can model the temporal-spatial distribution of maritime channels and add it to the knowledge library. Then, the MCN can predict the existence of deep-fading channels due to the 2-ray/3-ray propagation characteristic in maritime scenarios and overcome the deep fading using diversity techniques. The MCN can also estimate when and where an evaporation duct will exist and dynamically configure the network and allocate resources for more efficient transmissions.

In network management, the BSs are often static in traditional schemes. Hence, they fail to adapt to the dynamic network topology in the MCN. Using the knowledge of network node mobility, such as the shipping lane information obtained from the AIS, and the attitudes of satellites and UAVs, the machine learning and optimization platform can construct a network topology evolution model from BS/user position prediction. Based on that, the network can be dynamically and intelligently configured for wider coverage, as represented by the irregularly configured heterogeneous network in Fig. 8.

In service scheduling, based on user interest and mission goals, the machine learning and optimization platform can establish a personalized service model, characterizing the distribution of service occurrence time, the length of service duration, and the service requirement. Using the knowledge library, the network can perform service forecasting, provide user-specific services, and dynamically adjust the allocation of resources in the case of emergency. In general, statistical service models can be applied for resource allocation to greatly improve the service capabilities of the MCN.

C. Open Problems

Based on the lessons from Section III-V, to facilitate the construction of future MCNs supporting more intelligent coverage and transmission, as well as providing higher QoS, it is important to address the environment-sensitive maritime channels, to make coordination of all available coverage methods, and to adapt to the service demands from maritime applications. In particular, the external auxiliary information can be exploited to establish an intelligent MCN to achieve on-demand agile coverage and efficient transmissions. On the

other hand, this new framework also poses challenges for both communications theories and practices. We list some open issues as follows.

First, the new maritime channel model is essential for transmission efficiency enhancement. In most traditional applications, we deal with wireless channels from a mathematical perspective, e.g., we treat the channel coefficient as a random variable and use lots of measurements to derive a statistical channel model. For the intelligent MCN framework, we need to treat the wireless channel from a more physical perspective. An environment-sensitive maritime channel considering sea surface conditions and atmospheric conditions is required [259]. Toward this end, a new channel measuring method is needed, which has to synchronize the channel measurement with meteorological observation. Based on that, the physical model of the meteorological information can be integrated into mathematical statistical analysis to obtain an external auxiliary information-driven maritime channel model. There exists hierarchy in the new channel model, and accordingly, structural modeling is a potential solution to integrate both the physical and the mathematical features. Structural processing is also a potential solution to realize environment-aware transmission enhancement by matching the hierarchy of the channel.

Second, the coordination of all available wireless techniques is another important open issue. It is desired to integrate satellites and high-altitude platforms into 6G to expand its coverage, which may facilitate the development of MCNs [260]. In general, satellites, UAVs and terrestrial BSs are quite different in terms of both mobility and transmission performance. The satellite follows the dynamics of orbits, leading to relatively static GEOs and fast moving LEOs. The movement of the UAV is more agile than satellites. However, its mobility may be significantly restricted by weather conditions over the sea. When the terrestrial BS is equipped on vessels, it can move, but its mobility is determined by the fixed shipping lane of the corresponding vessel. All these issues make the stochastic topology of MCNs a challenge [261], [262]. Moreover, the transmission delay and rate are also quite different for satellites, UAVs and terrestrial BSs. This further complicates the network control of MCN. To solve this problem, new coverage metrics can first be established theoretically. Different from traditional cellular networks, the coverage performance cannot be calculated by the sum of the achievable rate in different cells because the cellular structure may not hold in the maritime scenario. The coverage metric of a noncellular MCN can also consider the distribution of users from a practical perspective. As maritime users are sparsely distributed on the ocean, it is not efficient to cover the whole geographical area as the cellular architecture does. A user distribution-aware coverage performance metric is desired, which needs both theoretical and practical research.

Third, new marine services also pose challenges in the design of intelligent MCNs. Due to the limited BS sites, the optimal solution is to build one network supporting all services over the sea. This is quite different from the terrestrial network, where we have already had a number of different networks for different services, e.g., the 4G/5G cellular network, the Wi-Fi network,

as well as a variety of private networks. To achieve this, the intelligent MCN needs to be flexible enough to support both existing and upcoming communication services. Taking the fast-developing Maritime Autonomous Surface Ships (MASS) as an example, it requires both high-speed multimedia services for video surveillance and ultrareliable services for remote control. This is challenging when using only one system. The 5G cellular network could support three usage scenarios with different service types, including enhanced mobile broadband (eMBB), ultrareliable low-latency communication (URLLC), and mMTC [263]. In the future, the network resource ought to be orchestrated in a more flexible and agile manner, thus presenting different performance gains according to different requirements. Both mobile edge computing [264] and blockchain technologies [265], [266] being discussed for 6G can be used in this orchestration, although it remains open.

VII. CONCLUSION

This article has provided a comprehensive review of hybrid satellite-terrestrial MCNs for the maritime IoT, including the demand for maritime communications, state-of-the-art MCNs, and enabling technologies. It has been recognized that a large performance loss is usually inevitable if the existing 4G/5G and satellite communication technologies are used directly for the maritime scenario. Thus, conventional communication theories and methods need to be tailored to match the unique characteristics of MCNs in terms of dynamic electromagnetic propagation environments, geometrically limited available BS sites and rigorous service demands from mission-critical applications. Toward this end, we have categorized the enabling technologies into three types, i.e., enhancing transmission efficiency, extending network coverage, and provisioning maritime-specific services. We have illustrated and compared the technologies in terms of their objectives, methods, and characteristics of MCNs used. Facing the future, more research on communication and networking theories is still needed to avoid simple integration of existing networks. We have accordingly envisioned the use of external auxiliary information to build up an environment-aware, service-driven, and integrated satellite-air-ground MCN. The corresponding open issues have also been discussed.

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