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 ultra-reliable 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. Towards 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: enhancing transmission efficiency, extending network coverage, and 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—Maritime communication network, maritime channel, maritime service, satellite-air-ground integration, knowledge library.

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edge library.

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 ultra-reliable maritime communications to connect them [1]–[3]. For example, navigational information and operational data are required for the safe navigation of all vessels, and multi-media 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 (Inmarsat), mainly provide services such as telephone, telegraph, and fax, at a low communication rate. For example, the annual throughput of Inmarsat was only 66 Gbps in 2016, while the number of ships has exceeded 2 million. Thus, the average communication rate per ship is less than 33 kbps [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 & island-based BSs are also used to extend the coverage of terrestrial fourth-generation (4G)/fifth-generation (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

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 scatteres	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

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 neighbouring 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 modelling projects have been performed to analyse 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
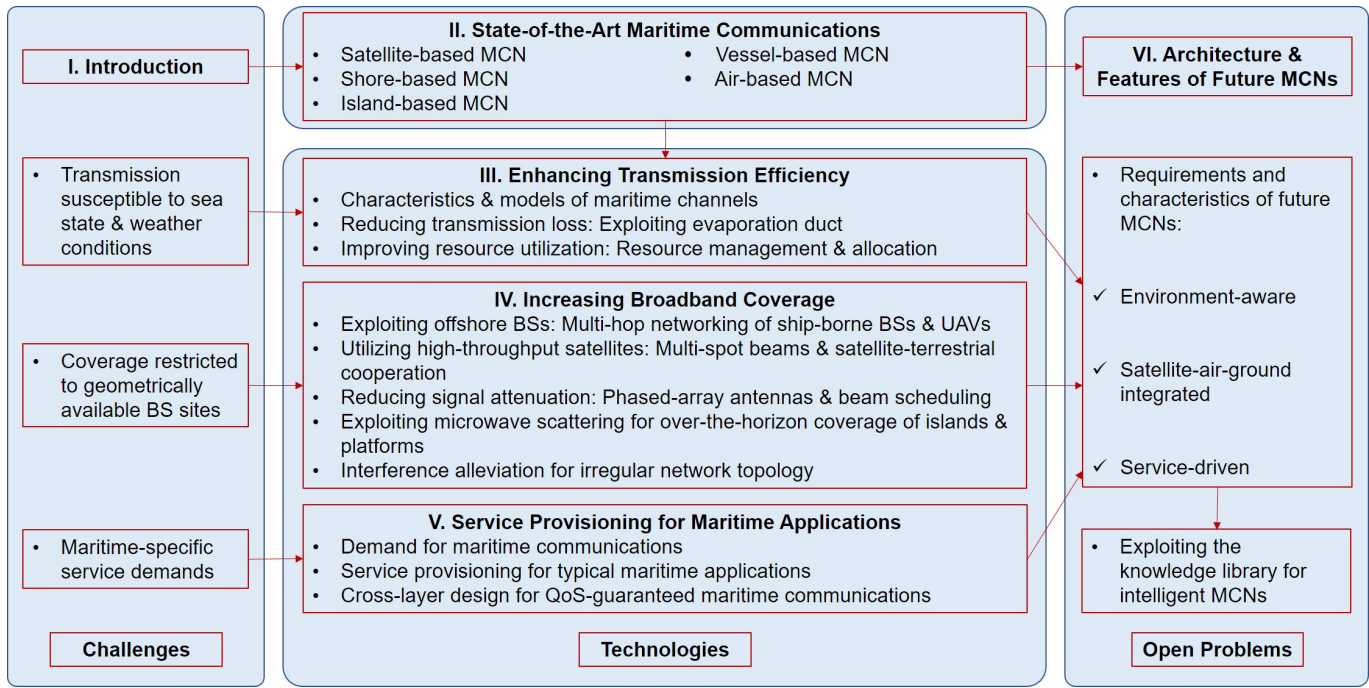
Fig. 1. The structure of this paper.

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 paper 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 paper 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 paper 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 paper. Figure 1 shows the outline of the paper.

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 metres [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. Narrow-band 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].

At present, 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 multi-hop network is formed between adjacent vessels, maritime beacons, and buoys, to ensure wide-area coverage [37]. In addition, the authors in [38]–[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 Figure 2. Based on the network architecture, MCNs can 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 5 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 kbps [48][49]. The future Inmarsat-5 system, also known as Global Xpress, aims to provide worldwide customers with downlink services at 50 Mbps and uplink services at 5 Mbps [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 degrees and 62 degrees, respectively. At present, 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 Mbps, 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. At present, Iridium Next provides data services of up to 128 kbps to mobile terminals and up to 1.5 Mbps to Iridium Pilot marine terminals. In the future, it will support more bandwidth and higher rate, reaching a transmission rate of 1.4 Mbps for mobile terminals and up to 30 Mbps 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 kbps [53].

The Shijian-13 communications satellite is China's first high-throughput communication satellite. It is a multi-beam broadband communication system using the Ka-band, and its total communication capacity is more than 20 Gbps, 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 Gbps 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].
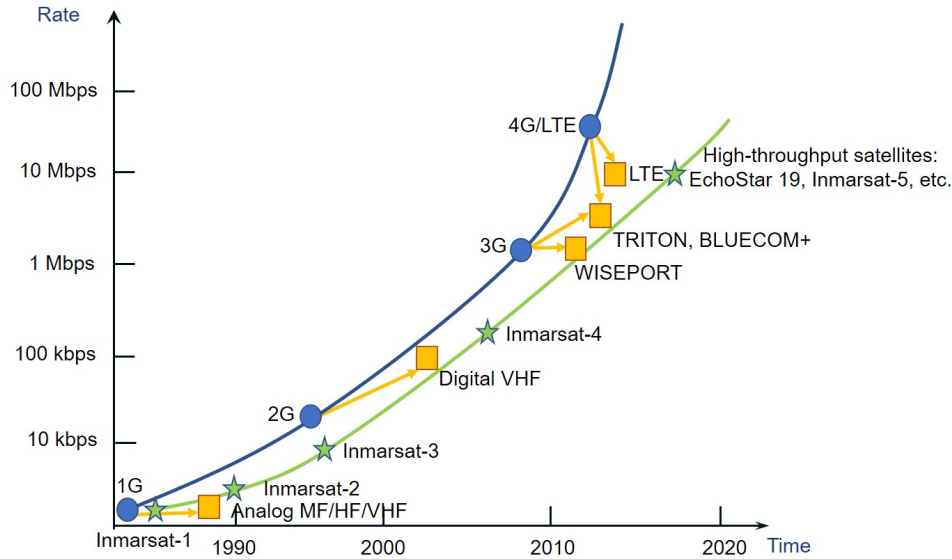
Fig. 2.   The developing route of MCNs.

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 MHz 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 multi-path. 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 kbps, 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 km to 50 km offshore on the North Sea, providing voice and data services of 1 Mbps uplink and 2 Mbps 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 Mbps. 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 1,400 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 Mbps on the island and 15 Mbps 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 kbps, 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 Mbps 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 manufactures and has found a number of sites for deploying UAVs to cover impoverished areas in Latin America, Asia and Africa [70].

The Loon project was initiated by Google in 2013, aiming to provide Internet access for users in the countryside and remote areas. The project uses super-pressure balloons at an altitude of 20 km to build a communication network. The network operates at the 2.4/5.8 GHz band and can provide communication services of 10 Mbps. Although the project is not commercial yet, it has provided emergency communication services for several areas suffering from natural disasters [71].

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 multi-hop relaying techniques to extend the coverage. Simulation results have shown that the BLUECOM+ solution can cover the ocean areas up to 150 km from shore, providing broadband communication services at 3 Mbps [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.

F. Sensing-Oriented Maritime IoT

DARPA launched the Maritime IoT project in 2017, which plans to deploy tens of thousands of small, low-cost smart floating objects to form a distributed sensor network to achieve continuous situational awareness of large areas of the sea. Each smart float will use a set of commercial sensors to collect environmental data such as sea temperature, sea conditions and location in the area, as well as activity data for commercial vessels, aircraft and even marine animals. These floats can periodically transmit data via satellite to the cloud for storage and real-time analysis. The first phase of the Maritime IoT mainly involves the initial designs and trials to verify concepts [72].

The key performance indicators of existing MCNs are compared in Table II. For satellite communications, narrowband 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 abovementioned geometrically available BS sites, and the

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
Norwagian Offshore LTE Network	Tampnet & Huawei	1785-1805 MHz	2 Mbps	50 km	LTE
Internet.org	Facebook	laser	unknown	wide	UAVs & laser
Loon	Google	2.4 GHz	10 Mbps	wide	balloons
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

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.

Fig. 3. Illustration of typical shore-to-ship propagation rays, which are affected by sea state and atmosphere conditions.

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 Figure 3. 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 [73], 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 modelling 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
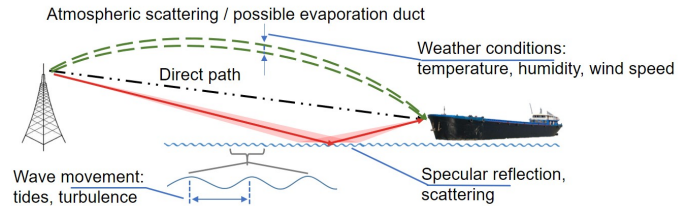
for remote transmissions. We start with the characteristics and models for maritime channels.

A. Characteristics and Models of Maritime Channels

Various channel measurements and modelling works have been conducted to analyse the impact of system parameters (frequency, antenna height, etc.) and maritime environments (sea state, weather conditions, etc.) on maritime channel fading [74]-[104]. 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 multi-path delay over a signal wavelength.

For the large-scale fading, Y. Bai et al. 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 [74]. K. Yang et al. 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 [75]. 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 [76]–[79] studied the two-ray channel model and proposed several modified models. Among them, Y. Zhao et al. considered factors, such as sea surface reflection and antenna height, and proposed a two-ray model suitable for maritime channels [76]. 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, J. C. Reyes-Guerrero *et al.* measured the maritime channel in non-line-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 [77]. N. Mehrnia *et al.* introduced the index correction coefficient in the two-ray model formula and obtained better channel prediction in the 5 GHz band [78]. Jae-Hyun Lee *et al.* 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 [79]. 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. Y. H. 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, Y. H. Lee *et al.* proposed a three-ray path loss model, which is closely related to the heights of the evaporation duct and the transmitting and receiving antennas [80]. The height of the evaporation duct can be estimated using the Paulus-Jeske empirical model (P-J model). A. Coker *et al.* simulated and analysed the effect of evaporation duct height on signal attenuation and diversity [81]. More recently, in [82], the authors 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

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

where $\Delta = 2\sin\left(\frac{2\pi H_1 H_2}{\lambda d}\right)\sin\left(\frac{2\pi(H_e-H_1)(H_e-H_2)}{\lambda d}\right)$, $d_{break} = \frac{4H_1 H_2}{\lambda}$, 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. X. Hu *et al.* pointed out that multi-path reflection on the sea surface can be divided into coherent specular reflection and non-coherent diffuse reflection, and the

concept of effective reflection area was proposed [83]. M. Dong *et al.* 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 metres and the grazing angle is less than 5 degrees [84]. K. Haspert *et al.* proposed a theoretical approximation modelling method that can be applied to multi-path channels containing specular and diffuse reflection components [85]. K. Yang *et al.* measured the channel between the transmitting antenna on the far sea and the receiving antenna on the shore, and analysed the important influence of the antenna position on signal propagation based on the received signal level (RSL) and the power delay profile (PDP) [86]. J. Lee *et al.* analysed 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 [87]. K. Yang *et al.* analysed the Doppler shift [88]. F. Huang *et al.* considered the smooth sea surface and the rough sea surface. The impulse response of a multi-path 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 [89]. More recently, in [90], the authors 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 behaviour 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. 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 ship-borne antennas consequently [91]. It affects the received signal strength in duplicate measurements according to the two-ray model, as shown in Figure 4. 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, multi-path 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
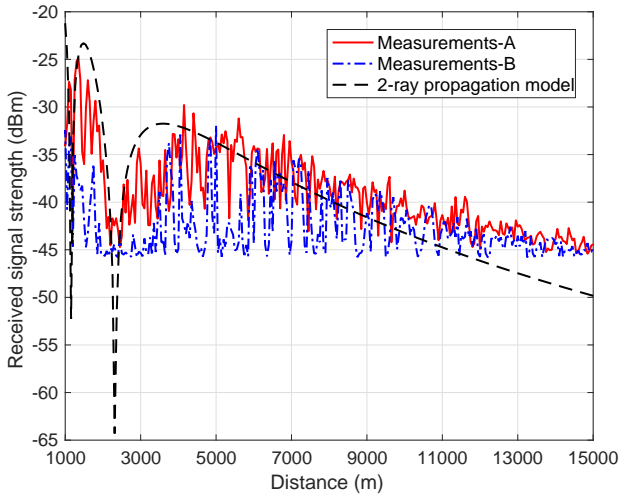
Fig. 4.   Received signal strength results of channel measurements conducted on East China Sea and a two-ray channel model.
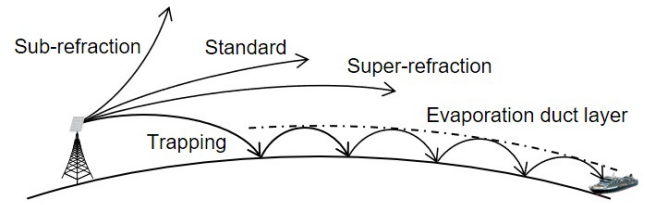

Fig. 5.   Illustration of the four possible propagation paths due to atmospheric refraction and the evaporation duct.

cations, and vehicle-to-vehicle (V2V) communications [105]. Until now, many massive MIMO channel models [106]–[109], mmWave channel models [110][111], V2V channel models [112][113], and high-mobility channel models [114]–[117] have been proposed, and a general 5G channel model can be used to simulate the channels [118]. 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 modelling studies on maritime channels.

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

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

where σ is the standard deviation of each Gaussian component, μ and σ_l are the mean and standard deviations of signals that follow the Log-normal distribution, respectively. For maritime satellite channels, the authors in [92] measured the channel fading with different antenna types and elevation angles and compared the performance of several modulation schemes. The authors in [93] and [94] analysed 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 modelling 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 [100]–[104]. 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) communi-

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 Figure 5 [119]. 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 [120].

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 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 [119]. 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 [120], and the 100-km link between Malaysian shores [121][122].

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 [123]. 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).

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

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.

The authors in [124] 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. The authors in [125] 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 [126]. The authors in [127] used the WiMAX-based mesh technology for ship-to-ship communications with DTN features and compared the performances of different routing schemes. The authors in [128] studied the scheduling of data traffic tasks to optimize the network throughput and energy sustainability. In [129], the authors 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 behaviour 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 [130]–[132]. The authors in [133] derived a model of ship encounter probability and used the model to analyse the data delivery ratio. The authors in [134] 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. In [135] and [136], the authors 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 [137]. Previous studies have explored the performance gain achieved by power allocation [138] and user scheduling [139] 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 [140].

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 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

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]
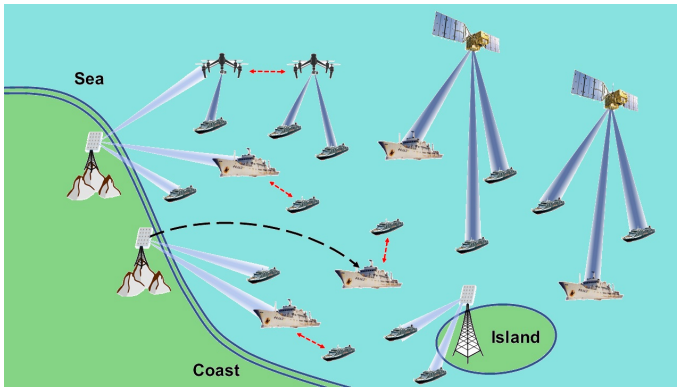
Fig. 6. Exploiting onshore BSs, ship-borne BSs, aerial BSs and satellites to extend the maritime coverage.

can be exploited as well to serve as maritime BSs. The coverage performance of the MCN depends largely on the abovementioned 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 neighbouring 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 Figure 6. By using multi-hop 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.

A. Building and Exploiting Offshore BSs: Multi-hop Networking of Ship-borne and UAV-enabled BSs

To achieve wider coverage for MCNs, the authors in [141] and [142] proposed the ad hoc networks Maritime-MANET and Nautical Ad hoc Network (NANET), respectively. Similarly, the authors in [127] 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, [141] used multiple directional antennas, [143] used virtual MIMO technologies, and [144] and [145] used two relaying schemes. Additionally, in [146], a novel handover protocol was proposed. In [147], a distributed adaptive time slot allocation scheme was proposed, while in [148], a cognition-enhanced mesh medium access control (MAC) protocol was proposed. Further, the authors in [149] 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 [150][151], such as epidemic routing [152], probabilistic routing [153], spray and wait [154], network coding schemes [155][156], Optimized Link State Routing (OLSR) [157], Ad Hoc On Demand Distance Vector (AODV) Routing [158]–[160], and Ad Hoc On Demand Multipath Distance Vector (AOMDV) [161]. However, these schemes have poor performances in maritime communications, due to the large delivery delay and low delivery ratio from the lower user density [162]. Therefore, routing protocols custom-made for maritime mesh networks are required [163]–[165].

In [166], the authors proposed an opportunistic routing scheme for delay-tolerant MCNs based on lane intersecting opportunities. In [135], the authors proposed three offline scheduling algorithms for video uploading in MCNs based on the deterministic network topology. In [167], the authors proposed a route maintenance method for maritime sensor networks based on ring broadcast mechanism. In addition, the authors of [168] and [169] 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 [91]. 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 neighbouring users. At present, the switch selection methods applicable to terrestrial fixed BSs are based on BS performance indicators such as coverage, cell load, and neighbouring 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 on-board 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, the authors in [172] 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 [173]. 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 multi-hop network, such as a mesh network, where the flight trajectory, routing strategy and transmission method are optimized. In [174], the authors focused on the reliability, and optimized the altitude of the UAV as a relaying station. In [175], the authors 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: Multi-spot 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 [176]–[187]. Although satellite communications have a wide coverage, they are limited by their high latency and low data
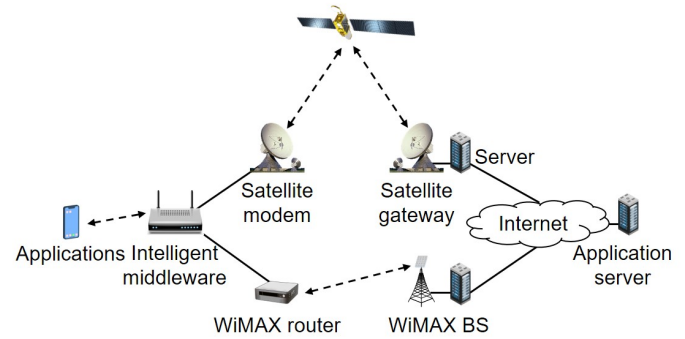

Fig. 7. Using intelligent middleware for satellite-terrestrial cooperation [185].

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 [176]–[178]. Further, the use of multi-spot 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 inter-beam interference due to the non-zero side lobes [179]. Therefore, side lobe suppression technologies are required for the use of multi-spot beams, and there is a trade-off between the number of spot beams and the distance between frequency-reuse beams [180][181]. It should be noted that, in maritime communications, the density of vessels/platforms/islands is low, while the users are clustered thereon. Therefore, using multi-spot beams is an effective way to enhance broadband coverage for MCNs [182][183].

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 [184]. Specifically, for maritime communications, the authors in [185] proposed intelligent middleware and link-specific protocols for the coordination of maritime mesh networks and satellite communication networks, as depicted in Figure 7. The authors in [186] considered a hybrid Satellite-MANET consisting of GEO, MEO, and LEO satellites and terrestrial MANET. They analysed the distribution of coverage radius for full connection and proposed a multi-hop routing protocol to minimize the end-to-end delay. The authors in [187] proposed an OceanNet Backhaul Link Selection (OBLS) algorithm to select the optimal backhaul links with the best signal to noise ratio (SNR). Further, the authors implemented the proposed algorithm in a hardware test-bed.

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, the authors in [188] proposed a backhaul activation scheme to minimize the traffic delivery time for a multi-hop ISTN. In addition, caching

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

strategies have been adopted to reduce the accumulative delay. In [189], the authors proposed a back-tracing partition based on-path caching algorithm for ISTNs to reduce the overheads and access delay. In [190], the authors proposed a QoE-driven caching placement scheme for video streaming in the ISTN, considering the social relationship among users. In [191], the authors 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 4,409 satellites and the other containing 7,518 satellites. SpaceX plans to provide affordable Internet services with delays between 25 ms 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 [192]–[195]. 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 [196]. 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 [197], 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 [198]. 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 [199]–[201].

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 [202]–[204].

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 [205][206]. 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 [202], and the 2.2 GHz band [204].

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 [207].

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 often deal with the inter-system interference and intra-system interference independently. However, the MCN often has an irregular topology, and its coupling between the systems and the intra-system interference is very strong [208]–[210]. To solve this problem, one can either schedule the beam resources

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]
			routing (shown in Table V)
	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	MIMO transmit diversity and multiplexing [200]
			location-aware dynamic beam scheduling [201]
	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]

between the satellite and the terrestrial network, study the optimal beam design method, or suppress inter-beam interference. In [211], an antenna selection algorithm was proposed for hierarchical maritime radio networks towards better coverage and cost-effectiveness. In [179], the authors investigated the impact of diffracted waves from the structures of a ship on the received signal levels and found a relationship between the clearance angles and interference. In [180], the authors focused on the interference between the mobile satellite service and the fixed service in a maritime environment in the Ku band, and analysed the mobile earth station's transmit power, antenna gain, speed, and the propagation environment. More recently, the authors in [212] and [213] analysed 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 [214][215]. 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 neighbouring 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 neighbouring 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 [216].

Up to now, the key technologies to extend the coverage of MCNs, such as multi-hop 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 abovementioned methods, a heterogeneous network can be formed by coordinating maritime satellites, shore & island-based BSs, ship-borne BSs and UAVs. In particular, narrow-band 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 [217]–

[219]. 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

The demand for maritime communications emerged in the early 20th century. Due to several maritime accidents, such as the sinking of the Titanic in 1912, the maritime community was awakened to the need for maritime communications in the event of search and rescue and to ensure the safety of ships and lives on the sea. In 1914, the International Convention on the Safety of Life at Sea (SOLAS) was developed. It mandates that ships sailing at sea must have battery-powered transceivers for transmitting and receiving radio alarm signals [220]. After that, maritime communications played an important role in distress communication and rescue. In this case, low-speed maritime communication services were enough to meet the demand for emergency rescue.

The number of maritime activities has increased dramatically since the beginning of the 21st century, owing to the development of the world's economies and the prosperity of the modern shipping industry. Maritime activities, such as marine tourism, offshore aquaculture and oceanic mineral exploration, have generated huge demand for high-speed and ultra-reliable maritime communication services. For example, the annual throughput of communication services provided by maritime satellites was less than 5 Gbps in 2005, while this number increased to approximately 66 Gbps in 2016 [12].

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 multi-media 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 [221].

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 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 Figure 8, according to their requirements for rate and latency [222]. 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 [223][224]. 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 [225]–[227]. 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 Figure 9. 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.

In view of this, next we will introduce the existing and potential schemes to provide maritime-specific services. In
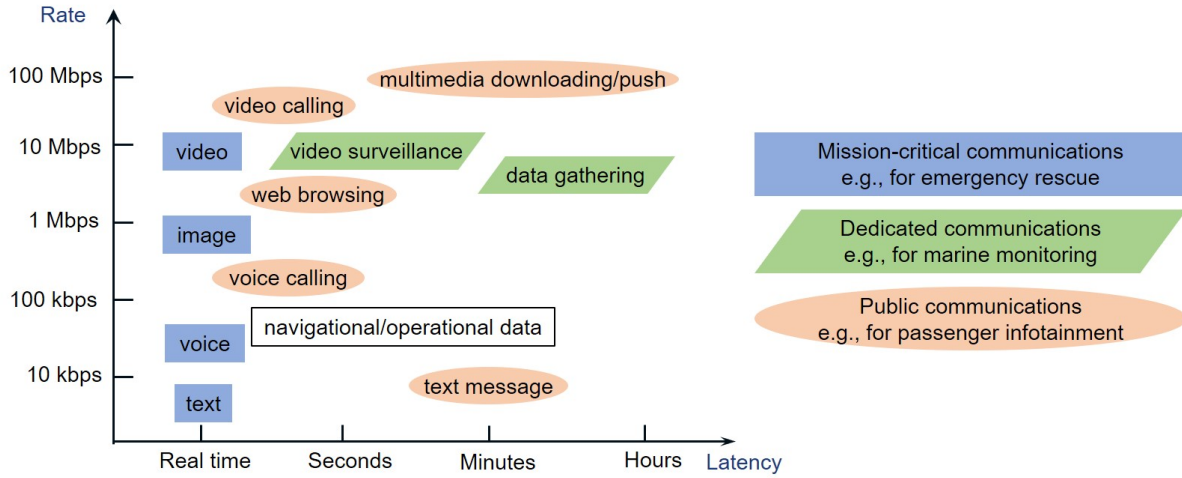
Fig. 8.   Three types of maritime communication services and their required rate and latency.

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. In [228], the authors considered the feasibility of utilizing illuminators sent by Inmarsat for maritime surveillance and navigation, especially for marine obstacle avoidance. In [229], the authors 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, the authors of [230] 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 [231].

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 [232]. Shore-based radar systems can promote safe navigation by collision monitoring and grounding prevention. Particularly, the authors of [233] 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 [234]. 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 [235]–[240].

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) [241]. 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 [242]. In [219], the authors proposed a user-centric communication structure and an antenna selection scheme based on distributed antennas. In [201], the authors 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 [243].

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 [244]. In this paper, 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 multi-media and the uploading of hydro-meteorological information require broad-

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]
			collecting and disseminating vessel position information via the self-reporting-based LRIT system [231]
		using shore-based positioning and geographic information systems	collision monitoring and grounding prevention using terrestrial AIS and coastal radar systems [232]
			experimental performance assessment of HFSW radars [233]
			enhancing detection capabilities of HFSW radars using spectrum analysis techniques [234]
passenger and crew infotainment	low density of vessels, users clustered in a small area	generating directional beams according to the location of vessels	fairness-oriented beam scheduling using phased-array antennas [201]
			antenna selection based on distributed antennas [219]
			antenna tracking [242]
multimedia downloading and data gathering	large data volume, high latency tolerance	service scheduling based on the mobility of vessels	offline scheduling based on the deterministic network topology [135]
			opportunistic routing based on lane intersecting opportunities [166]
			store-carry-and-forward scheduling [246]

band communications and high latency tolerance [245]. To provide this kind of delay-tolerant services, several resource scheduling methods for maritime communications have been proposed. In [166], an opportunistic routing scheme for delay-tolerant MCNs based on lane intersecting opportunities was proposed. In [135], 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 [246].

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. Low Power Communications for Maritime IoT

The Low-Power Wide-Area Network (LPWAN) is designed for low-bandwidth, low-power, long-range, and massively connected IoT applications, which can support data collection from sensors up to several tens of kilometres from shore [247]. LPWAN has wider coverage than other wireless connection technologies (such as Bluetooth and Wi-Fi) and lower power consumption than cellular technologies (such as 4G/5G). LPWAN can be divided into two categories: one using unlicensed spectrum, such as LoRa and SigFox, and the other using licensed spectrum, such as NB-IoT. NB-IoT has higher-reliability due to less interference in the licensed band, while its power consumption is higher than the other two technologies with a coverage of approximately 10 km [248]. The role of LPWAN in cellular IoT to support massive

machine-type communications (mMTC) is being discussed for beyond 5G networks, while it remains to be seen whether its coverage can be further expanded for maritime IoT [249].

D. 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 [250]. For example, potential synergies of exchanging information between different layers for real-time video streaming in ad hoc networks was explored in [251]. The joint design of physical, MAC, and network layers was considered for interference-limited wireless sensor networks in [252]. Reference [253] analysed 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 [254]. Resource conditions and service requirements can be exploited for flexible resource allocation for different services [255]. In addition, a programmable architecture based on SDN is believed to be useful for the maritime IoT [256].

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.
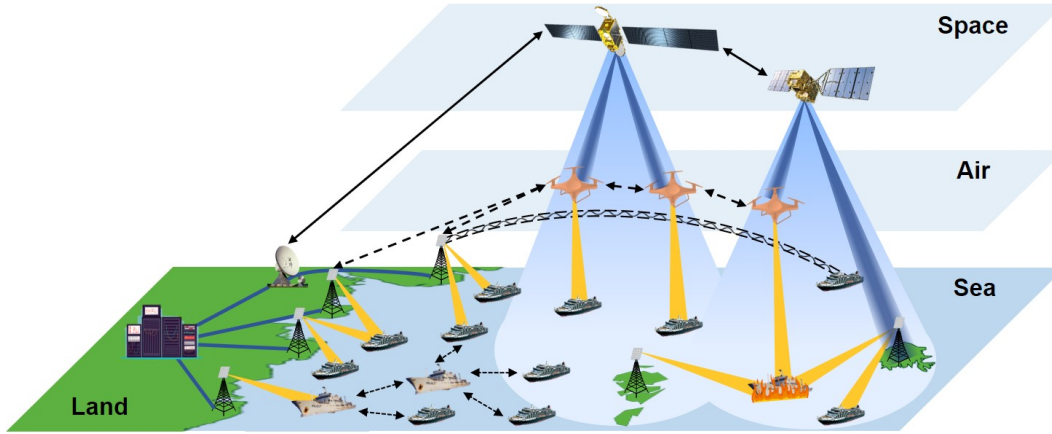
Fig. 9.   Future MCNs: satellite-air-ground integrated, environment-aware and service-driven.
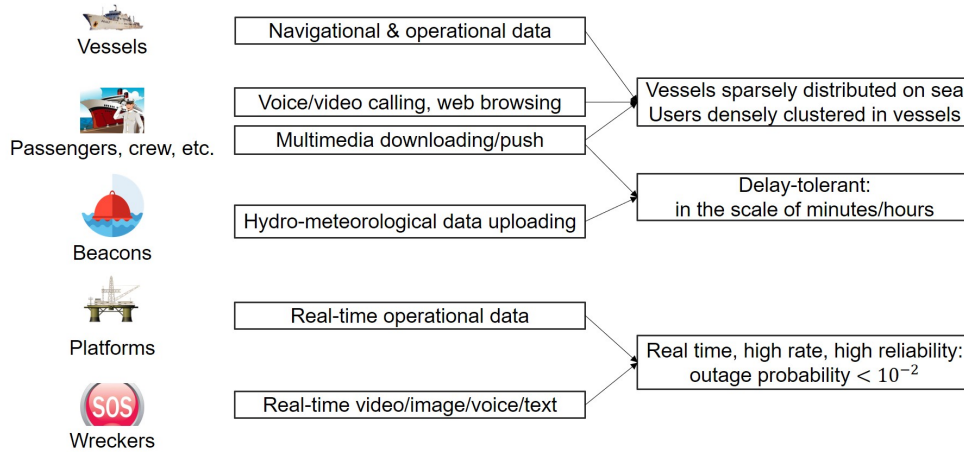

Fig. 10.   Maritime-specific communication services and their features.

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 non-terrestrial BSs [257]. 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 abovementioned 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 [258][259]. 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 more accurate prediction of the CSI and adopt more efficient transmission techniques that counteract the dynamic changes in maritime channels [260]. 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 Figure 10, 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 [261][262]) 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 behaviour characteristics, as depicted in Figure 11. 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 [263] and federated learning technologies [264] 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 Figure 10.

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. Figure 11 shows all the scenarios discussed.

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 [265]. Towards 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 modelling 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 [266]. 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
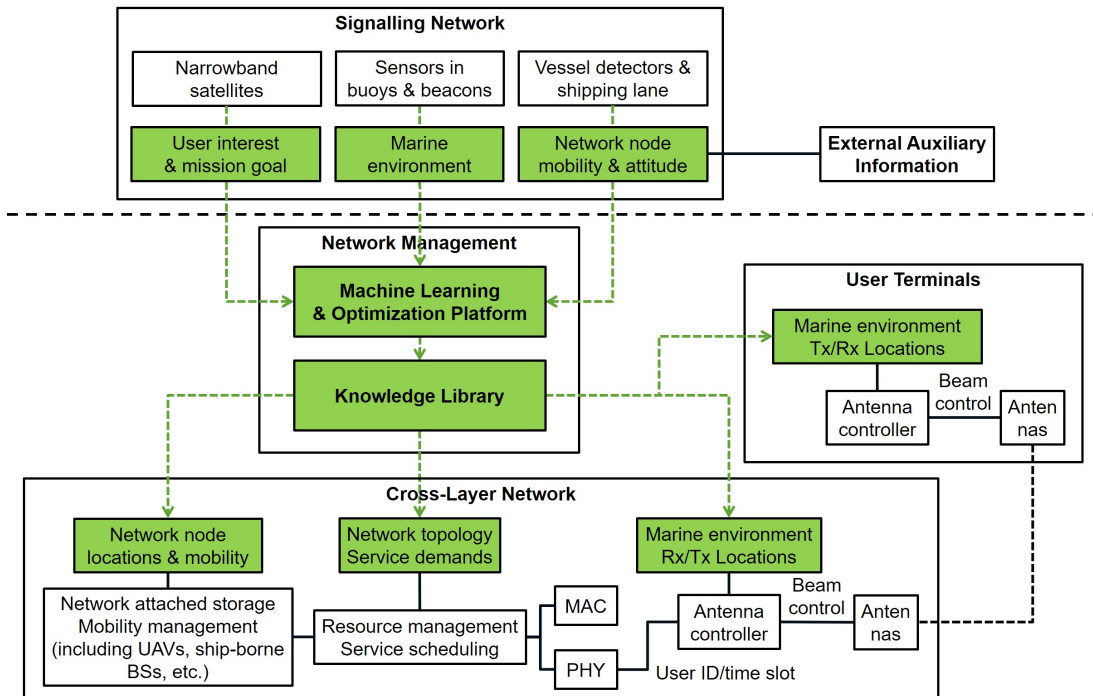
Fig. 11.   Exploiting the knowledge library for intelligent coverage and transmission in the future MCN.

the fixed shipping lane of the corresponding vessel. All these issues make the stochastic topology of MCNs a challenge [267][268]. 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 non-cellular 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 ultra-reliable 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), ultra-reliable low-latency communication (URLLC), and mMTC [269]. 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 [270] and block-chain technologies [271][272] being discussed for 6G can be used in this orchestration, although it remains open.

VII. CONCLUSIONS

This paper 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. Towards 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.

References

[1] H. Wang, O. L. Osen, G. Li, W. Li, H. Dai, and W. Zeng, "Big data and industrial Internet of Things for the maritime industry in Northwestern Norway", in *Proc. IEEE Region 10 Conf.*, Macao, China, Nov. 2015, pp. 1–5.

[2] T. Xia, M. M. Wang, J. Zhang, and L. Wang, "Maritime Internet of Things: Challenges and solutions", *IEEE Wireless Commun.*, vol. 27, no. 2, pp. 188–196, Apr. 2020.

[3] J. Zhang, M. M. Wang, T. Xia, and L. Wang, "Maritime IoT: An Architectural and radio spectrum perspective," *IEEE Access*, vol. 8, pp. 93109–93122, 2020.

[4] W. Ejaz, K. Manzoor, H. J. Kim, B. T. Jang, G. Jin, and H. S. Kim, "Two-state routing protocol for maritime multi-hop wireless networks," *Computers & Electrical Engineering*, vol.39, no.6, pp. 1854–1866, Aug. 2013.

[5] T. Roste, K. Yang, and F. Bekkadal, "Coastal coverage for maritime broadband communications," in *Proc. Oceans*, Bergen, Norway, Jun. 2013, pp. 1–8.

[6] L. Lambrinos and C. Djouvas, "Creating a maritime wireless mesh infrastructure for real-time applications," in *Proc. IEEE GLOBECOM Workshops*, Houston, TX, USA, Dec. 2011, pp. 529–532.

[7] T. D. Ta, T. D. Tran, D. D. Do, H. V. Nguyen, Y. V. Vu, and N. X. Tran, "GPS-based wireless ad hoc network for marine monitoring, search and rescue (MSnR)," in *Proc. Intern. Conf. Intelligent Systems, Modelling & Simulation*, Kuala Lumpur, Malaysia, Mar. 2011, pp. 350–354.

[8] J. Wozniak, K. Gierlowski, and M. Hoeft, "Broadband communication solutions for maritime ITSs: Wider and faster deployment of new e-navigation services," in *Proc. Intern. Conf. ITS Telecommun*, Warsaw, Poland, May 2017, pp. 1–11.

[9] J. S. Jeong, G. Park, and J. Kim, "Prediction table to improve maritime situation awareness by VTS operator," in *Proc. Intern. Conf. Fuzzy Theory & Applications*, Taipei, Taiwan, Dec. 2013, pp. 479–481.

[10] Y. M. Dai and K. S. Liu, "TACSA: A web-service based system for coastal surveillance and situational awareness," in *Proc. Intern. Carnahan Conf. Security Tech.*, Taipei, Taiwan, Sep. 2015, pp. 409–413.

[11] T. Tares, H. Greidanus, G. Jurquet, and P. Helie, "Wide Maritime Area Airborne Surveillance SoS," in *Proc. Intern. Systems Conf.*, Vancouver, BC, Canada, Mar. 2009, pp. 123–126.

[12] Q. Zhuang and C. Zheng, "Research on INMARSAT based on Ka band and applications," in *Proc. Intern. Conf. Information, Cybernetics & Computational Social Systems*, Dalian, China, Jul. 2017, pp. 127–129.

[13] J. Mashino, K. Tateishi, K. Muraoka, D. Kurita, S. Suyama, and Y. Kishiyama, "Maritime 5G experiment in windsurfing World Cup by using 28 GHz band massive MIMO," in *Proc. IEEE Intern. Symp. Personal, Indoor & Mobile Radio Commun.*, Bologna, Italy, Sep. 2018, pp. 1134–1135.

[14] F. Bekkadal, "Innovative maritime communications technologies," in *Proc. Intern. Conf. Micromaves, Rader, & Wireless Commun.*, Vilnius, Lithuania, Jun. 2010, pp. 1–6.

[15] H. Seo, J. Shim, S. Ha, Y. S. Kim, and J. Jeong, "Ultra long range LTE ocean coverage solution," in *Proc. Intern. Conf. Telecommun.*, Limassol, Cyprus, May 2017, pp. 1–5.

[16] Huawei Technologies Co., Ltd.: Huawei eWBB LTE Solution, 2013. [Online]. Available: http://www.huawei.com/ilink/enenterprise/download/HW203747. [Accessed: Dec. 15, 2018].

[17] R. Huang, "Maritime intelligent real-time control system based on UAV," in *Proc. Intern. Conf. Robots & Intell. System*, Changsha, China, May 2018, pp. 10–12.

[18] S. Balkees, K. Sasidhar, and S. Rao, "A survey based analysis of propagation models over the sea," in *Proc. Intern. Conf. Advances in Computing, Commun. & Informatics*, Kochi, India, Aug. 2015, pp. 69–75.

[19] J. Wang et al., "Wireless channel models for maritime communications," *IEEE Access*, vol. 6, pp. 68070–68088, Nov. 2018.

[20] A. Habib and S. Moh, "A survey on channel models for radio propagation over the sea surface," in *Proc. Intern. Conf. Internet*, Phnom Penh, Cambodia, Dec. 2018, pp. 1–3.

[21] D. Kidston and T. Kunz, "Challenges and opportunities in managing maritime networks," *IEEE Commun. Mag.*, vol. 46, no. 10, pp. 162–168, Oct. 2008.

[22] F. Bekkadal and K. Yang, "Novel maritime communications technologies," in *Proc. Mediterranean Microwave Symp.*, Guzelyurt, Cyprus, Aug. 2010, pp. 338–341.

[23] F. Bekkadal, "Emerging maritime communications technologies," in *Proc. Intern. Conf. Intell. Transport Systems Telecommun.*, Lille, France, Oct. 2009, pp. 358–363.

[24] L. Robinson, T. Newe, J. Burke, G. Dooly, J. Coleman, and D. Toal, "High bandwidth maritime communication systems: Review of existing solutions and new proposals," in *Proc. URSI Atlantic Radio Sci. Meeting*, Meloneras, Spain, Jun. 2018, pp. 1–3.

[25] F. Bekkadal, "Future maritime communications technologies," in *Proc. Oceans*, Bremen, Germany, May 2009, pp. 1–6.

[26] C.-X. Wang, J. Bian, J. Sun, W. Zhang, and M. Zhang, "A survey of 5G channel measurements and models," *IEEE Commun. Surveys & Tuts.*, vol. 20, no. 4, pp. 3142–3168, 4th Quart., 2018.

[27] J. Liu, Y. Shi, Z. M. Fadlullah, and N. Kato, "Space-air-ground integrated network: A survey," *IEEE Commun. Surveys & Tuts.*, vol. 20, no. 4, pp. 2714–2741, May 2018.

[28] A. A. Khan, M. H Rehmani, and A. Rachedi, "Cognitive-radio-based Internet of Things: applications, architectures, spectrum related functionalities, and future research directions," *IEEE Wireless Commun.*, vol. 24, no. 3, pp. 17–25, 2017.

[29] G. Falciasecca and B. Valotti, "Guglielmo Marconi: The pioneer of wireless communications," in *Proc. European Microwave Conf.*, Rome, Italy, Sep. 2009, pp. 544–546.

[30] J. S. Belrose, "Fessenden and Marconi: their differing technologies and transatlantic experiments during the first decade of this century," in *Proc. Intern. Conf. 100 Years Radio*, London, UK, Sep. 1995, pp. 32–43.

[31] A. Sinha, S. A. Saoudy, and B. P. Sinha, "An investigation of Marconi's transmitter during the 1901 transatlantic experiment," in *Proc. Symp. Antenna Tech. & Applied Electromagnetics*, Ottawa, Canada, Aug. 1998, pp. 29–32.

[32] S. J. Lee, H. K. Kwon, G. Y. Park, H. Hwang, D. Kim, and B. Park, "Development of an ASM2.0 RF system for maritime communications of high-data-rate in the VHF band," in *Proc. Asia-Pacific Microwave Conf.*, Nanjing, China, Dec. 2015, pp. 1–3.

[33] D. Palma, "Enabling the maritime Internet of Things: CoAP and 6LoWPAN performance over VHF links," *IEEE Internet Things J.*, vol. 5, no. 6, pp. 5205–5212, Sep. 2018.

[34] Q. Hu, X. Jing, L. Xu, J. Huang, and Z. Sun, "Performance specifications of filtered multitone modulation for the roll-off factor and filter order in the maritime VHF data exchange system," in *Proc. IEEE Intern. Conf. Smart IoT*, Xi'an, China, Aug. 2018, pp. 87–92.

[35] R. Campos, T. Oliveira, N. Cruz, A. Matos, and J. M. Almeida, "BLUECOM+: Cost-effective broadband communications at remote ocean areas," in *Proc. Oceans*, Shanghai, China, Apr. 2016, pp. 1–6.

[36] BLUECOM+: Innovative communications solution for broadband, cost-effective Internet access at remote ocean areas, 2019. [Online]. Available: http://bluecomplus.inesctec.pt. [Accessed: July. 4, 2019].

[37] M. Zhou, V. D. Hoang, H. Harada, J. S. Pathmasuntharam, H. Wang, P. Kong, C. Ang, Y. Ge, and S. Wen, "TRITON: high-speed maritime wireless mesh network," *IEEE Wireless Commun.*, vol. 20, no. 5, pp. 134–142, Nov. 2013.

[38] S. Jiang and H. Chen, "A possible development of marine Internet: A large scale cooperative heterogeneous wireless network," in *Proc. Conf. Smart Spaces*, Petersburg, Russia, Aug. 2015, pp. 481–495.

[39] K. Adarsh, K. M. P. Akshay, J. P. Dhivvya, K. J. Harikrishna, S. Simi, and S. N. Rao, "Analysis of long range wi-fi backhaul link in maritime environment," in *Proc. Intern. Conf. Commun. & Signal Process.*, Chennai, India, Apr. 2018, pp. 569–573.

[40] M. Cankar and S. Stanovnik, "Maritime IoT solutions in fog and cloud," in *Proc. IEEE/ACM Intern. Conf. Utility & Cloud Computing Companion*, Dec. 2018, Zurich, Switzerland, pp. 284–289.

[41] J. Wang and C. Liu, "Development and application of INMARSAT satellite communication system," in *Proc. Intern. Conf. Instrumentation, Measurement, Computer, Commun. & Control*, Beijing, China, Oct. 2011, pp. 619–621.

[42] V. V. Spiridonov, "Inmarsat systems and services," in *Proc. Intern. Conf. Satellite Commun.*, Moscow, Russia, Oct. 1994, pp. 45–52.

[43] E. Gambaruto, "Inmarsat Second Generation Satellites for Maritime Communications," in *Proc. Oceans*, Seattle, WA, USA, Sep. 1989, pp. 920–925.

[44] D. K. Banks, E. Gambaruto, and B. Krinsky, "The Inmarsat second generation communications payload," in *Proc. European Microwave Conf.*, London, UK, Sep. 1989, pp. 781–788.

[45] S. W. Wong, "An evaluation of 6.4 kbit/s speech codecs for Inmarsat-M system," in *Proc. Intern. Conf. Acoustics, Speech & Signal Process.*, Toronto, Ontario, Canada, Apr. 1991, pp. 629–632.

[46] G. V. Kinal, J. Nagle, and D. W. Lipke, "INMARSAT integrity channels for global navigation satellite systems," *IEEE Aerospace & Electronic Systems Mag.*, vol. 7, no. 8, pp. 22–25, Aug. 1992.

[47] G. V. Kinal, J. Nagle, and D. W. Lipke, "Inmarsat integrity channels for global navigation satellite systems," in *Proc. National Telesystems Conf.*, Washington, DC, USA, May 1992, pp. 1–4.

[48] A. Franchi, E. Trachtman, L. Christodoulides, and J. Sengupta, "Multimedia via Inmarsat," *IEEE MultiMedia*, vol. 6, no. 4, pp. 15–19, Dec. 1999.

[49] A. Franchi, A. Howell, and J. Sengupta, "Broadband mobile via satellite: Inmarsat BGAN," in *Proc. IEE Seminar Broadband Satellite*, Oct. 2000, pp. 1–7.

[50] P. J. Hadinger, "Inmarsat Global Xpress: The design, implementation, and activation of a global Ka-band network," in *Proc. AIAA Intern. Commun. Satellite Systems Conf. & Exhibition.*, Queensland, Australia, Sep. 2015, pp. 1–8.

[51] M. Breiling et al., "LTE backhauling over MEO-satellites," in *Proc. Advanced Satellite Multimedia Systems Conf. & Signal Process. Space Commun. Workshop*, Livorno, Italy, Sep. 2014, pp. 1–8.

[52] K. Sekiguchi, "Iridium contributes to maritime safety," in *Proc. Techno-Ocean*, Kobe, Japan, Oct. 2016, pp. 90–92.

[53] F. Wei, B. Chen, R. Jia, T. Wang, and L. Wang, "Research on maritime leapfrog emergency communication coverage technology based on satellite relay," *J. Phys.: Conf. Ser.*, vol. 1087, no. 4, p. 042064, Sep. 2018.

[54] Xinhua News Agency: China launches 1st high-throughput communications satellite, 2017. [Online]. Available: http://silkroad.news.cn/2017/0413/16398.shtml. [Accessed: Feb. 3, 2019].

[55] Spaceflight101: EchoStar 19 Satellite Overview, 2019. [Online]. Available: http://spaceflight101.com/atlas-v-echostar-19/echostar-19. [Accessed: Feb. 11, 2019].

[56] O. Lundberg, "The way ahead for maritime satellite communications," *Radio & Electronic Engineer*, vol. 53, no. 7, pp. 254–256, Jul. 1983.

[57] T. Aoyagi, K. Suzaki, Y. Suzuki, T. Hirose, and T. Sugiyama, "Wave propagation simulations for considering the installation of the maritime mobile satellite communication antennas," in *Proc. Asia-Pacific Microwave Conf.*, Kaohsiung, Taiwan, Dec. 2012, pp. 346–348.

[58] M. Kuwabara, K. Nishino, and H. Sugihara, "Satellite repeater arrangement in a new maritime mobile telephone system," *IEEE Trans. Veh. Tech.*, vol. 18, no. 3, pp. 116–123, Nov. 1969.

[59] D. Wright, "International maritime satellite communication," *Electronics and Power*, vol. 29, no. 9, pp. 623–626, Sep. 1983.

[60] O. J. Roseth, B. Kvamstad, A. Tjora, and F. Drezet, "Ship-shore communication requirements," FLAGSHIP, Brussels, Belgium, Tech. Rep. TIP5-CT-2006-031406, 2009.

[61] S. Lee and J. Lee, "An implementation of NAVTEX application on android mobile device," in *Proc. Intern. Conf. Info. Science & Applications*, Suwon, South Korea, Jun. 2013, pp. 1–3.

[62] M. Y. A. Razak, N. Zainal, and A. R. M. Sidek, "Performance of 8FSK base on PACTOR I protocol over AWGN channels," in *Proc. Intern. Conf. Info. Tech., Computer & Electrical Engineering*, Semarang, Indonesia, Sep. 2018, pp. 1–5.

[63] S. Valcic, Z. Mrak, and D. Kezic, "Comparison of new technologies for data exchange in the maritime HF frequency band," in *Proc. Intern. Convention Info. & Commun. Tech., Electronics & Microelectronics*, Opatija, Croatia, May 2013, pp. 498–502.

[64] Special Communications Systems (SCS): PACTOR-4, 2018. [Online]. Available: https://www.scs-ptc.com/en/PACTOR-4.html. [Accessed: July. 4, 2019].

[65] Huawei Technologies Co., Ltd.: North Sea: Worlds First Offshore LTE Network, 2013. [Online]. Available: https://e.huawei.com/hk/case-studies/global/older/hw_258225. [Accessed: Feb. 11, 2019].

[66] Ericsson: Maritime ICT Cloud enables ships to join the Networked Society, 2015. [Online]. Available: https://www.ericsson.com/en/press-releases/2015/1/maritime-ict-cloud-enables-ships-to-join-the-networked-society. [Accessed: Feb. 11, 2019].

[67] Verizon Communications : Wireless : Announces 4G LTE Coverage Enhancements in Rhode Island, 2015. [Online]. Available: https://www.marketscreener.com/VERIZON-COMMUNICATIONS-IN-4830/news/Verizon-Communications-Wireless-Announces-4G-LTE-Coverage-Enhancements-in-Rhode-Island-20135125. [Accessed: Feb. 11, 2019].

[68] Chinadaily: Telecoms extend 4G service to Nansha Islands, 2016. [Online]. Available: http://www.newsgd.com/news/2016-07/20/content_151841840.htm. [Accessed: Feb. 11, 2019].

[69] T. Yoshikawa, S. Kawasaki, M. Takase, Y. Hiraoka, Y. Takaki, C. Ohta, and T. Inoue, "Development of 27MHz/40MHz bands maritime wireless ad-hoc networks," in *Proc. Intern. Conf. Ubiquitous & Future Networks*, Jeju, South Korea, Jun. 2010, pp. 177–182.

[70] M. L. Best, "The Internet that Facebook built," *ACM Commun.*, vol.57, no.12, pp. 21–23, Dec. 2014.

[71] M. Engel, "Google's Project Loon hovers over the satellite industry," *Via Satellite*, vol. 28, no. 8, p. 13, Aug. 2013.

[72] Ryan Maass, United Press International: DARPA's Sea Network Project Completes First Phase, 2017. [Online]. Available: https://www.ecnmag.com/news/2017/01/darpas-sea-network-project-completes-first-phase?cmpid=horizontalcontent. [Accessed: July. 4, 2019].

[73] Y. Huo, X. Dong, and S. Beatty, "Cellular communications in ocean waves for maritime Internet of Things," *IEEE IoT. J.*, to appear, 2020. DOI: 10.1109/JIOT.2020.2988634.

[74] Y. Bai, W. Du, and C. Shen, "Over-the-sea radio propagation and integrated wireless networking for ocean fishery vessels," in *Proc. Intern. Conf. Wireless Commun. & Applications*, Sanya, China, Aug. 2011, pp. 180–190.

[75] K. Yang, T. Roste, F. Bekkadal, K. Husby, and O. Trandem, "Long-distance propagation measurements of mobile radio channel over sea at 2 GHz," in *Proc. Veh. Tech. Conf.*, San Francisco, CA, USA, Sep. 2011, pp. 1–5.

[76] Y. Zhao, J. Ren, and X. Chi, "Maritime mobile channel transmission model based on ITM," in *Proc. Intern. Symp. Computer, Commun., Control & Automation*, Singapore, Dec. 2013, pp. 378–383.

[77] J. C. Reyes-Guerrero, M. Bruno, L. A. Mariscal, and A. Medouri, "Buoy-to-ship experimental measurements over sea at 5.8 GHz near urban environments," in *Proc. Mediterranean Microwave Symp.*, Hammamet, Tunisia, Sep. 2011, pp. 320–324.

[78] N. Mehrnia and M. K. Ozdemir, "Novel maritime channel models for millimeter radiowaves," in *Proc. Intern. Conf. Software, Telecommun. & Computer Networks*, Split, Croatia, Sep. 2016, pp. 405–410.

[79] J. Lee, J. Choi, W. Lee, J. Choi, and S. Kim, "Measurement and analysis on land-to-ship offshore wireless channel in 2.4 GHz," *IEEE Wireless Commun. Lett.*, vol.6, no.2, pp. 222–225, Feb. 2017.

[80] Y. H. Lee, F. Dong, and Y. S. Meng, "Near sea-surface mobile radiowave propagation at 5 GHz: measurements and modeling," *Radioengineering*, vol. 23, no. 3, pp. 824–830, Sep. 2014.

[81] A. Coker, L. Straatemeier, T. Rogers, P. Valdez, D. Cooksey, and K. Griendling, "Maritime channel modeling and simulation for efficient wideband communications between autonomous unmanned surface vehicles," in *Proc. Oceans*, San Diego, CA, USA, Sep. 2013, pp. 1–9.

[82] Q. Wang et al., "Estimation of evaporation duct and surface-based duct parameters from a combined refractivity model," in *Proc. IEEE Intern. Symp. Antennas & Propagation*, Boston, USA, Jul. 2018, pp. 879–880.

[83] X. Hu, J. Chen, and Y. Wang, "Research on metre-wave radar height-finding multipath model," *Chinese J. Radio Science*, vol. 23, no. 4, pp. 651–657, Apr. 2008.

[84] M. Dong, Y. Zhao, and S. Zhang, "The analysis of the multipath model under the VHF band and at sea," *Acta Electronica Sinica*, vol. 36, no. 6, pp. 1373–1377, Jun. 2009.

[85] K. Haspert and M. Tuley, "Comparison of predicted and measured multipath impulse responses," *IEEE Trans. Aerospace & Electronic Systems*, vol. 47, no. 3, pp. 1696–1709, Jul. 2011.

[86] K. Yang, T. Roste, F. Bekkadal, and T. Ekman, "Channel characterization of mobile radio channel over sea at 2 GHz," in *Proc. Mediterranean Microwave Symp.*, Guzelyurt, Cyprus, Aug. 2010, pp. 389–392.

[87] Y. H. Lee and Y. S. Meng, "Analysis of ducting effects on air-to-ground propagation channel over sea surface at C-band," in *Proc. Asia-Pacific Microwave Conf.*, Melbourne, VIC, USA, Dec. 2011, pp. 1678–1681.

[88] K. Yang, T. Roste, F. Bekkadal, and T. Ekman, "Channel characterization including path loss and Doppler effects with sea reflections for mobile radio propagation over sea at 2 GHz," in *Proc. Intern. Conf. Wireless Commun. & Signal Process.*, Suzhou, China, Oct. 2010, pp. 1–6.

[89] F. Huang, X. Liao, and Y. Bai, "Multipath channel model for radio propagation over sea surface," *Wireless Personal Commun.*, vol. 90, no. 1, pp. 245–257, Sep. 2016.

[90] G. Dahman, D. Couillard, M.-E. Grandmaison, G. Poitau, and F. Gagnon, "Improved 2-Ray model for overwater propagation channels: modeling the instantaneous variations in the received signal strength," *IEEE Wireless Commun. Lett.*, vol. 8, no, 3, pp. 865–868, Jun. 2019.

[91] C. Ang and S. Wen, "Signal strength sensitivity and its effects on routing in maritime wireless networks," in *Proc. IEEE Conf. Local Computer Networks*, Montreal, Canada, Oct. 2008, pp. 192–199.

[92] J. Hagenauer, F. Dolainsky, E. Lutz, W. Papke, and R. Schweikert, "The maritime satellite communication channel–channel model, performance of modulation and coding," *IEEE J. Sel. Areas Commun.*, vol. 5, no. 4, pp. 701–713, May 1987.

[93] C. Amaya and D. V. Rogers, "Characteristics of rain fading on Ka-band satellite-earth links in a Pacific maritime climate," *IEEE Trans. Microwave Theory & Tech.*, vol. 50, no. 1, pp. 41–45, Aug. 2002.

[94] C. Amaya and D. V. Rogers, "Characteristics of rain fading on Ka-band satellite-Earth links in a Pacific maritime climate," in *Proc. Intern. Microwave & Optoelectronics Conf.*, Rio de Janeiro, Brazil, Aug. 1999, pp. 308–311.

[95] D. Y. Choi, "Measurement of radio propagation path loss over the sea for wireless multimedia," in *Proc. Intern. Ifip-tc6 Conf. Networking*, Coimbra, Portugal, May 2006, pp. 525–532.

[96] Y. H. Lee and Y. S. Meng, "Empirical modeling of ducting effects on a mobile microwave link over a sea surface," *Radioengineering*, vol. 21, no. 4, pp. 1054-1059, Dec. 2012.

[97] C. Y. D. Sim, "The propagation of vhf and uhf radio waves over sea paths," Ph.D. dissertation, University of Leicester, 2002.

[98] J. C. Reyes-Guerrero and L. A. Mariscal, "Experimental time dispersion parameters of wireless channels over sea at 5.8 GHz," in *Proc. ELMAR*, Zadar, Croatia, Sep. 2012, pp. 89–92.

[99] K. Maliatsos, P. Loulis, M. Chronopoulos, P. Constantinou, P. Dallas, and M. Ikonomou, "Measurements and wideband channel characterization for over-the-sea propagation," in *Proc. Intern. Conf. Wireless & Mobile Computing, Networking & Commun.*, Montreal, Canada, Jun. 2006, pp. 237–244.

[100] P. Sobieski, A. Guissard, C. Baufays, and P. Siraut, "Sea surface scattering calculations in maritime satellite communications," *IEEE Trans. Commun.*, vol. 41, no. 10, pp. 1525–1533, Oct. 1993.

[101] S. Song, S. Lee, H. Kim, and C. Kim, "Digital communication channel model analysis for AUV in maritime environment," in *Proc. Oceans*, Yeosu, South Korea, May 2012, pp. 1–4.

[102] M. J. Lopes, F. Teixeira, J. B. Mamede, and R. Campos, "Wi-Fi broadband maritime communications using 5.8 GHz band," in *Proc. Underwater Commun. & Networking*, Sestri Levante, Italy, Sep. 2014, pp. 1–5.

[103] M. Cvijetic and M. Li, "Characterization of free space optical channels for terrestrial and maritime air conditions," in *Proc. Intern. Conf. Transparent Optical Networks*, Girona, Spain, Jul. 2017, pp. 1–5.

[104] H. Wang, W. Jia, and G. Min, "Effective channel exploitation in IEEE 802.16j networks for maritime communications," in *Proc. Intern. Conf. Distributed Computing Systems*, Minneapolis, USA, Jun. 2011, pp. 162–171.

[105] C.-X. Wang, F. Haider, X. Gao, X.-H. You, Y. Yang, D. Yuan, H. Aggoune, H. Haas, S. Fletcher, and E. Hepsaydir, "Cellular architecture and key technologies for 5G wireless communication networks," *IEEE Commun. Mag.*, vol. 52, no. 2, pp. 122–130, Feb. 2014.

[106] S. Wu, C.-X. Wang, H. Aggoune, M. M. Alwakeel, and Y. He, "A non-stationary 3D wideband twin-cluster model for 5G massive MIMO channels," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 6, pp. 1207–1218, June 2014.

[107] S. Wu, C.-X. Wang, H. Haas, H. Aggoune, M. M. Alwakeel, and B. Ai, "A non-stationary wideband channel model for massive MIMO communication systems," *IEEE Trans. Wireless Commun.*, vol. 14, no. 3, pp. 1434–1446, Mar. 2015.

[108] C.-X. Wang, S. Wu, L. Bai, X. You, J. Wang, and C.-L. I, "Recent advances and future challenges for massive MIMO channel measurements and models," *Sci. China Inf. Sci.*, vol. 59, no. 2, pp. 1–16, Feb. 2016.

[109] C. F. Lopez and C.-X. Wang, "Novel 3D non-stationary wideband models for massive MIMO channels," *IEEE Trans. Wireless Commun.*, vol. 17, no. 5, pp. 2893–2905, May 2018.

[110] J. Huang, C.-X. Wang, R. Feng, J. Sun, W. Zhang, and Y. Yang, "Multi-frequency MmWave massive MIMO channel measurements and characterization for 5G wireless communication systems," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 7, pp. 1591–1605, July 2017.

[111] J. Huang, C.-X. Wang, Y. Liu, J. Sun, and W. Zhang, "A novel 3D GBSM for mmWave MIMO channels," *Sci. China Inf. Sci.*, vol. 61, no. 10, Oct. 2018.

[112] Y. Yuan, C.-X. Wang, Y. He, M. M. Alwakeel, and H. Aggoune, "3D wideband non-stationary geometry-based stochastic models for non-isotropic MIMO vehicle-to-vehicle channels," *IEEE Trans. Wireless Commun.*, vol. 14, no. 12, pp. 6883–6895, Dec. 2015.

[113] X. Cheng, C.-X. Wang, B. Ai, and H. Aggoune, "Envelope level crossing rate and average fade duration of non-isotropic vehicle-to-vehicle Ricean fading channels," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 1, pp. 62–72, Feb. 2014.

[114] C.-X. Wang, A. Ghazal, B. Ai, P. Fan, and Y. Liu, "Channel measurements and models for high-speed train communication systems: a survey," *IEEE Commun. Surveys & Tuts.*, vol. 18, no. 2, pp. 974–987, 2nd Quart., 2016.

[115] A. Ghazal, C.-X. Wang, B. Ai, D. Yuan, and H. Haas, "A non-stationary wideband MIMO channel model for high-mobility intelligent transportation systems," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 2, pp. 885–897, Apr. 2015.

[116] Y. Liu, C.-X. Wang, J. Huang, J. Sun, and W. Zhang, "Novel 3-D nonstationary mmWave massive MIMO channel models for 5G high-speed train wireless communications," *IEEE Trans. Veh. Tech.*, vol. 68, no. 3, pp. 2077–2086, Mar. 2019.

[117] J. Bian, J. Sun, C.-X. Wang, R. Feng, J. Huang, Y. Yang, and M. Zhang, "A WINNER+ based 3D non-stationary wideband MIMO channel model," *IEEE Trans. Wireless Commun.*, vol. 17, no. 3, pp. 1755–1767, Mar. 2018.

[118] S. Wu, C.-X. Wang, H. Aggoune, M. M. Alwakeel, and X. You, "A general 3D non-stationary 5G wireless channel model," *IEEE Trans. Commun.*, vol. 66, no. 7, pp. 3065–3078, July 2018.

[119] Z. Yao, B. Zhao, W. Li, Y. Zhu, J. Du, and F. Dai, "Analysis on characteristics of atmospheric duct and its effects on the propagation of electromagnetic wave," *Acta. Meteor. Sin.*, vol. 15, no. 2, pp. 605–616, Feb. 2001.

[120] G. S. Woods, A. Ruxton, C. H. Holmes, and G. Gigan, "High-capacity, long-range, over ocean microwave link using the evaporation duct," *IEEE J. Ocean Eng.*, vol. 34, no. 3, pp. 323–330, Jul. 2009.

[121] A. Iqbal and V. Jeoti, "Feasibility study of radio links using evaporation duct over sea off Malaysian shores," in *Proc. Intern. Conf. Intell. Advanced Systems*, Manila, Philippines, Jun. 2010, pp. 1–5.

[122] W. L. Patterson, "Advanced refractive effects prediction system (AREP-S)," in *Proc. IEEE Radar Conf.*, Boston, USA, Apr. 2007, pp. 891–895.

[123] R. A. Paulus, "Practical application of an evaporation duct model," *Radio Science*, vol. 20, no. 4, pp. 887–896, Jul. 1985.

[124] R. Raulefs, M. Wirsing, and W. Wang, "Increasing long range coverage by multiple antennas for maritime broadband communications," in *Proc. Oceans*, Charleston, SC, USA, Oct. 2018, pp. 1–6.

[125] D. Kidston and I. Labbe, "A service oriented framework for policy-based management of maritime mobile networks," in *Proc. IEEE Military Commun. Conf.*, Washington, USA, Oct. 2006, pp. 1–7.

[126] S. Burleig, A. Hooke, L. Torgerson, et al., "Delay-tolerant networking: an approach to interplanetary Internet," *IEEE Commun. Mag.*, vol. 41, no. 6, pp. 128–136, Jun. 2003.

[127] H. Lin, Y. Ge, A. Pang, and J. S. Pathmasuntharam, "Performance study on delay tolerant networks in maritime communication environments," in *Proc. OCEANS*, Sydney, Australia, May 2010, pp. 1–6.

[128] T. Yang, Z. Zheng, H. Liang, et al., "Green energy and content aware data transmission in maritime wireless communication network," *IEEE Trans. Intell. Transport. Syst.*, vol. 16, no. 2, pp. 751–762, Apr. 2015.

[129] C. Jiang, C. Jiang, L. Yin, and Y. Qian, "Joint backhaul and access link resource management in maritime communication network," in *Proc. IEEE Global Commun. Conf.*, Abu Dhabi, United Arab Emirates, Dec. 2018, pp. 1–6.

[130] A. Alessandrini, M. Alvarez, H. Greidanus, V. Gammieri, V. F. Arguedas, F. Mazzarella, C. Santamaria, M. Stasolla, D. Tarchi, and M. Vespe, "Mining vessel tracking data for maritime domain applications," in *Proc. Intern. Conf. Data Mining Workshops*, Barcelona, Spain, Dec. 2016, pp. 361–367.

[131] Y. T. Wen, C. H. Lai, P. R. Lei, and W. C. Peng, "RouteMiner: Mining ship routes from a massive maritime trajectories," in *Proc. Intern. Conf. Mobile Data Management*, Brisbane, Australia, Jul. 2014, pp. 353–356.

[132] V. F. Arguedas, G. Pallotta, and M. Vespe, "Maritime traffic networks: From historical positioning data to unsupervised maritime traffic monitoring," *IEEE Trans. Intell. Transportation Systems*, vol. 19, no. 3, pp. 722–732, Mar. 2018.

[133] S. Qin, G. Feng, W. Qin, et al., "Performance modeling of data transmission in maritime delay-tolerant-networks," in *Proc. IEEE Wireless Commun. & Networking Conf.*, Shanghai, China, Apr. 2013, pp. 1109–1114.

[134] P. Kolios and L. Lambrinos, "Optimising file delivery in a maritime environment through inter-vessel connectivity predictions," in *Proc. IEEE Intern. Conf. Wireless & Mobile Computing, Networking & Commun.*, Barcelona, Spain, Oct. 2012, pp. 777–783.

[135] T. Yang, H. Liang, N. Cheng, R. Deng, and X. Shen, "Efficient scheduling for video transmissions in maritime wireless communication

networks," *IEEE Trans. Veh. Tech.*, vol. 64, no. 9, pp. 4215–4229, Sep. 2015.

[136] T. Yang and X. Shen, *Maritime wideband communication networks: Video transmission scheduling*, Berlin: Springer, 2014, pp. 15–31.

[137] S. M. Mun, J. Y. Son, W. R. Jo, and W. B. Lee, "An implementation of AIS-based Ad hoc routing (AAR) protocol for maritime data communication networks," in *Proc. Intern. Conf. Natural Computation*, Chongqing, China, May 2012, pp. 1007–1010.

[138] W. Feng, Y. Wang, N. Ge, J. Lu, and J. Zhang, "Virtual MIMO in multi-cell distributed antenna systems: coordinated transmissions with large-scale CSIT," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 10, pp. 2067–2081, Oct. 2013.

[139] W. Feng, Y. Wang, D. Lin, N. Ge, J. Lu, and S. Li, "When mmWave communications meet network densification: a scalable interference coordination perspective," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 7, pp. 1459–1471, Jul. 2017.

[140] W. Feng, Y. Chen, N. Ge, and J. Lu, "Optimal energy-efficient power allocation for distributed antenna systems with imperfect CSI," *IEEE Trans. Veh. Tech.*, vol. 65, no. 9, pp. 7759–7763, Sep. 2016.

[141] J. H. Laarhuis, "MaritimeManet: mobile ad-hoc networking at sea," in *Waterside Security Conf.*, Carrara, Italy, Nov. 2010, pp. 1–6.

[142] Y. Kim, J. Kim, Y. Wang, K. Chang, J. W. Park, and Y. Lim, "Application scenarios of nautical ad-hoc network for maritime communications," in *Proc. Oceans*, Biloxi, MS, USA, Oct. 2009, pp. 1–4.

[143] K. S. Zaidi, V. Jeoti, A. Awang, and M. Drieberg, "High reliability using virtual MIMO based mesh network for maritime wireless communication," in *Proc. Intern. Conf. Intell. & Advanced Systems*, Kuala Lumpur, Malaysia, Aug. 2016, pp. 1–5.

[144] M. Jorgenson, C. Reichelt, and T. Johnson, "Operation of the dynamic TDMA subnet relay system with HF bearers," in *Proc. IEEE Military Commun. Conf.*, Atlantic City, USA, Oct. 2005, pp. 338–343.

[145] R. Duan, J. Wang, H. Zhang, C. Jiang, Y. Ren, and T. Q. S. Quek, "Touch the sea: energy efficient relay design for maritime multi-hop multicast systems," in *Proc. IEEE Global Commun. Conf.*, Abu Dhabi, United Arab Emirates, Dec. 2018, pp. 1–6.

[146] V. D. Hoang, M. Ma, R. Miura, and M. Fujise, "A novel way for handover in maritime WiMAX mesh network," in *Proc. IEEE Conf. ITS Telecommun.*, Sophia Antipolis, France, Jun. 2007, pp. 1–4.

[147] P. Kong, H. Wang, Y. Ge, C. Ang, J. S. Pathmasuntharam, W. Su, M. Zhou, and H. Harada, "Distributed adaptive time slot allocation for WiMAX based maritime wireless mesh networks," in *Proc. IEEE Wireless Commun. & Networking Conf.*, Budapest, Hungary, Apr. 2009, pp. 1–6.

[148] M. Zhou and H. Harada, "Cognitive maritime wireless mesh/ad hoc networks," *J. Network & Computer Applications*, vol. 35, no.2, pp. 518–526, Mar. 2012.

[149] W. Du, Z. Ma, Y. Bai, C. Shen, B. Chen, and Y. Zhou, "Integrated wireless networking architecture for maritime communications," in *Proc. ACIS Intern. Conf. Software Engineering, Artificial Intell., Networking & Parallel/Distributed Computing*, London, UK , Jun. 2010, pp. 134–138.

[150] A. Balasubramanian, B. Levine, and A. Venkataramani, "DTN routing as a resource allocation problem," in *Proc. Conf. Applications, Tech., Architectures & Protocols Computer Commun.*, New York, USA, 2007, pp. 373–384.

[151] G. Pei, M. Gerla, and T. Chen, "Fisheye state routing: A routing scheme for ad hoc wireless networks," in *Proc. IEEE Intern. Conf. Commun.*, New Orleans, USA, Jun. 2000, pp. 70–74.

[152] R. Ramanathan, R. Hansen, P. Basu, R. Rosales-Hain, and R. Krishnan, "Prioritized epidemic routing for opportunistic networks," in *Proc. Intern. MobiSys Workshop Mobile Opportunistic Networking*, New York, USA, Jun. 2007, pp. 62–66.

[153] A. Lindgren, A. Doria, and O. Schelen, "Probabilistic routing in intermittently connected networks," *SIGMOBILE Mob. Comput. Commun. Rev.*, vol. 7, no. 3, pp. 19–20, Jul. 2003.

[154] T. Spyropoulos, K. Psounis, and C. S. Raghavendra, "Spray and focus: Efficient mobility-assisted routing for heterogeneous and correlated mobility," in *Proc. IEEE Intern. Conf. Pervasive Computing & Commun. Workshops*, White Plains, NY, USA, Mar. 2007, pp. 79–85.

[155] Y. Liao, K. Tan, Z. Zhang, and L. Gao, "Estimation based erasure-coding routing in delay tolerant networks," in *Proc. IWCMC*, New York, USA, Jan. 2006, pp. 557–562.

[156] L. Chen, C. Yu, T. Sun, Y. Chen, and H. Chu, "A hybrid routing approach for opportunistic networks," in *Proc. SIGCOMM Workshop Challenged Networks*, Pisa, Italy, Sep. 2006, pp. 213–220.

[157] P. Jacquet, P. Muhlethaler, T. Clausen, A. Laouiti, A. Qayyum, and L. Viennot, "Optimized link state routing protocol for ad hoc networks," in *Proc. IEEE INMIC*, Lahore, Pakistan, Dec. 2001, pp. 62–68.

[158] C. E. Perkins and E. M. Royer, "Ad-hoc on-demand distance vector routing," in *Proc. IEEE Workshop Mobile Computing Systems & Applications*, New Orleans, LA, USA, Feb. 1999, pp. 90–100.

[159] K. Devarajan and V. Padmathilagam, "An enhanced cluster gateway switch routing protocol (ECGSR) for congestion control using AODV algorithm in MANET," *Intern. J. Computer Applications*, vol. 123, no. 3, pp. 37–42, Aug. 2015.

[160] Y. Choi and Y. Lim, "Geographical AODV protocol for multi-hop maritime communications," in *Proc. Oceans*, Bergen, Norway, Jun. 2013, pp. 1–3.

[161] M. K. Marina and S. R. Das, "On-demand multipath distance vector routing in ad hoc networks," *Proc. Intern. Conf. Network Protocols*, Riverside, CA, USA, Nov. 2001, pp. 14–23.

[162] L. Lambrinos, C. Djouvas, and C. Chrysostomou, "Applying delay tolerant networking routing algorithms in maritime communications," in *Proc. IEEE Intern. Symp. & Workshops Wireless, Mobile & Multimedia Networks*, Madrid, Spain, Jun. 2013, pp. 1–6.

[163] P. Kong, H. Wang, Y. Ge, C. Ang, S. Wen, J. S. Pathmasuntharam, M. Zhou, and H. V. Dien, "A performance comparison of routing protocols for maritime wireless mesh networks," *Proc. IEEE Wireless Commun. & Networking Conf.*, Las Vegas, NV, USA, Mar. 2008, pp. 2170–2175.

[164] M. Manoufali, H. Alshaer, P. Kong, and S. Jimaa, "Technologies and networks supporting maritime wireless mesh communications," in *Proc. Joint IFIP Wireless & Mobile Networking Conf.*, Dubai, United Arab Emirates, Apr. 2013, pp. 1–8.

[165] S. Ali, J. Qadir, and A. Baig, "Routing protocols in delay tolerant networks–a survey," in *Proc. Intern. Conf. Emerging Tech.*, Islamabad, Pakistan, Oct. 2010, pp. 70–75.

[166] X. Geng, Y. Wang, H. Feng, and L. Zhang, "Lanepost: lane-based optimal routing protocol for delay-tolerant maritime networks," *China Commun.*, vol. 14, no. 2, pp. 65–78, Feb. 2017.

[167] Y. Hu, Y. Zheng, H. Liu, Y. Hu, "A route maintenance method for marine mobile sensor network based on ring broadcast mechanism," in *IEEE Intern. Conf. Commun. Tech.*, Chongqing, China, Oct. 2018, pp. 533–537.

[168] G. Glissa, A. Rachedi, and A. Meddeb, "A secure routing protocol based on RPL for Internet of Things," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, pp. 1–7, 2016.

[169] M. Bouaziz, A. Rachedi, and A. Belghith, EKF-MRPL: Advanced mobility support routing protocol for Internet of Mobile Things: movement prediction approach," *Future Generation Computer Systems*, vol. 93, pp. 822–832, 2019.

[170] P. Cheng, K. C. Lee, M. Gerla, and J. Hrri, "GeoDTN+Nav: Geographic DTN routing with navigator prediction for urban vehicular environments," *Mobile Networks & Applications*, vol. 15, no. 1, pp. 61–82, Jun. 2009.

[171] E. P. C. Jones, L. Li, J. K. Schmidtke, and P. A. S. Ward, "Practical routing in delay-tolerant networks," *IEEE Trans. Mobile Computing*, vol. 6, no. 8, pp. 943–959, Aug. 2007.

[172] A. Xiao, N. Ge, L. Yin, C. Jiang, and S. Zhao, "Adaptive shipborne base station sleeping control for dynamic broadband maritime communications," in *Proc. Asia-Pacific Network Operations & Management Symp.*, Seoul, South Korea, Sep. 2017, pp. 7–12.

[173] O. S. Oubbati, N. Chaib, A. Lakas, P. Lorenz, and A. Rachedi, "UAV-assisted supporting services connectivity in urban VANETs," *IEEE Trans. Veh. Tech.*, vol. 68, no. 4, pp. 3944–3951, 2019.

[174] Y. Chen, W. Feng, and G. Zheng, "Optimum placement of UAV as relays," *IEEE Commun. Lett.*, vol. 22, no. 2, pp. 248–251, Feb. 2018.

[175] W. Feng, J. Wang, Y. Chen, X. Wang, N. Ge, and J. Lu, "UAV-aided MIMO communications for 5G Internet of Things," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 1731–1740, Apr. 2019.

[176] M. Stasolla, J. J. Mallorqui, G. Margarit, C. Santamaria, and N. Walker, "A comparative study of operational vessel detectors for maritime surveillance using satellite-borne synthetic aperture radar," *IEEE J. Sel. Topics Applied Earth Observations & Remote Sensing*, vol. 9, no. 6, pp. 2687–2701, Jun. 2016.

[177] A. Baroni, A. Michel, M. Pannozzo, D. Zamberlan, M. Andrenacci, and F. Silvestri, "Performance assessment of the Smart mAritime saTellite terminal for mUltimedia seRvices and conteNts (SATURN) system," in *Proc. Advanced Satellite Multimedia Systems Conf. & Signal Process. Space Commun. Workshop*, Livorno, Italy, Sep. 2014, pp. 136–143.

[178] M. Pannozzo, A. F. Cominotto, M. Andrenacci, S. Titomanlio, S. Granelli, and D. Zamberlan, "SATURN: Smart mAritime saTellite

terminal for mUltimedia seRvices and conteNts," in *Proc. IEEE AESS European Conf. Satellite Telecommun.*, Rome, Italy, Oct. 2012, pp. 1–5.

[179] T. Aoyagi, K. Suzaki, Y. Suzuki, T. Hirose, and T. Sugiyama, "Modeling of interferences on other satellites in maritime satellite communications," in *Proc. IEEE Intern. RF & Microwave Conf.*, Penang, Malaysia, Dec. 2013, pp. 247–252.

[180] M. Koletta, V. Milas, and P. Constantinou, "Analysis and simulation of the interference produced to the fixed service receivers by the mobile satellite service in a maritime environment in the Ku band," in *Proc. Asia-Pacific Conf. on Commun.*, Beijing, China, Sep. 2004, pp. 209–213.

[181] M. Geissler, F. Woetzel, M. Bottcher, S. Korthoff, A. Lauer, M. Eube, and R. Gieron, "Innovative phased array antenna for maritime satellite communications," in *Proc. European Conf. Antennas & Propagation*, Berlin, Germany, Mar. 2009, pp. 735–739.

[182] M. Geissler, F. Woetzel, M. Buttcher, S. Korthoff, A. Lauer, M. Eube, and M. Wleklinski, "L-band phased array for maritime satcom," in *Proc. IEEE Intern. Symp. Phased Array Systems & Tech.*, Waltham, MA, USA, Oct. 2010, pp. 518–523.

[183] K. Feng, J. Xu, and N. Li, "A phased array antenna system for INMARSAT mobile ground terminal," in *Proc. IEEE Intern. Symp. Microwave, Antenna, Propagation & EMC Tech. Wireless Commun.*, Beijing, China, Oct. 2009, pp. 415–418.

[184] W. Feng, N. Ge, and J. Lu, "Coordinated satellite-terrestrial networks: a robust spectrum sharing perspective," in *Proc. Wireless & Optical Commun. Conf.*, Newark, USA, Apr. 2017, pp. 1–5.

[185] R. Boreli, Y. Ge, T. Iyer, C. Dwertmann, and J. S. Pathmasuntharam, "Intelligent middleware for high speed maritime mesh networks with satellite communications," in *Proc. Intern. Conf. Intell. Transport Systems Telecommun.*, Lille, France, Oct. 2009, pp. 370–375.

[186] A. Kessab, L. Mroueh, P. Martins, and I. Bucaille, "Optimizing end-to-end propagation delays in hybrid satellite-maritime mobile ad hoc networks," in *Proc. Intern. Conf. Software, Telecommun. & Computer Networks*, Split, Croatia, Sep. 2016, pp. 1–5.

[187] J. P. Dhivvya, S. N. Rao, and S. Simi, "Analysis of optimal backhaul link selection in a novel maritime communication network," in *Proc. Intern. Conf. Wireless Commun., Signal Process. & Networking*, Chennai, India, Mar. 2017, pp. 101–106.

[188] M. Shaat and A. I. Perez-Neira, "Joint flow control and link scheduling in hybrid terrestrial-satellite wireless backhauling network," in *Proc. IEEE Intern. Conf. Commun. Workshops*, Paris, France, May 2017, pp. 870–875.

[189] Y. Li, Q. Zhang, P. Yuan, and Z. Yang, "A back-tracing partition based on-path caching distribution strategy over integrated LEO satellite and terrestrial networks," in *Proc. IEEE Intern. Conf. Wireless Commun. & Signal Process.*, Hangzhou, China, Oct. 2018, pp. 1–6.

[190] G. Zhong, J. Yan, and L. Kuang, "QoE-driven social aware caching placement for terrestrial-satellite networks," *China Commun.*, vol. 15, no. 10, pp. 60–72, Oct. 2018.

[191] S. P. Romano and C. Roseti, "Secure hybrid in-network caching in a hybrid satellite-terrestrial environment: the SHINE project," in *Proc. IEEE Intern. Symp. Broadband Multimedia Systems & Broadcasting*, Valencia, Spain, Jun. 2018, pp. 1–6.

[192] SpaceX: SpaceX designs, manufactures and launches advanced rockets and spacecraft, 2019. [Online]. Available: https://www.spacex.com/. [Accessed: July. 4, 2019].

[193] OneWeb: Revolutionizing the economics of space, 2019. [Online]. Available: https://onewebsatellites.com/. [Accessed: July. 4, 2019].

[194] TeleSat: World's First 5G Backhaul Demo over LEO Satellite, 2019. [Online]. Available: https://www.telesat.com/news-events/worlds-first-5g-backhaul-demo-over-leo-satellite. [Accessed: July. 4, 2019].

[195] GeekWire: Amazon to offer broadband access from orbit with 3,236-satellite Project Kuiper constellation, 2019. [Online]. Available: https://www.geekwire.com/2019/amazon-project-kuiper-broadband-satellite/. [Accessed: July. 4, 2019].

[196] F. Capozzi, G. Piro, L. A. Grieco, et al., "Downlink packet scheduling in LTE cellular networks: Key design issues and a survey," *IEEE Commun. Surveys & Tuts.*, vol. 15, no. 2, pp. 678–700, 2013.

[197] C. Wengerter, J. Ohlhorst, and A. E. Elbwart, "Fairness and throughput analysis for generalized proportional fair frequency scheduling in OFDMA," in *Proc. Veh. Tech. Conf.*, Stockholm, Sweden, May 2005, pp. 1903–1907.

[198] R. Kwan, C. Leung, and J. Zhang, "Proportional fair multiuser scheduling in LTE," *IEEE Signal Process. Lett.*, vol. 16, no. 6, pp. 461–464, Jun. 2009.

[199] R. Kwan, C. Leung, and J. Zhang, "Multiuser scheduling on the downlink of an LTE cellular system," *Research Lett. Commun.*, vol. 2008, no. 3, Jan. 2008.

[200] I. Ahmad and K. Chang, "Analysis on MIMO transmit diversity and multiplexing techniques for ship ad-hoc networks under a maritime channel model in coastline areas," in *Proc. Intern. Conf. Info. Commun. Tech. Convergence*, Jeju, South Korea, Oct. 2017, pp. 945–947.

[201] Y. Li, L. Su, T. Wei, Z. Zhou, and N. Ge, "Location-aware dynamic beam scheduling for maritime communication systems," in *Proc. Intern. Conf. Commun., Circuits & Systems*, Chengdu, China, Dec. 2018, pp. 1–5.

[202] I. B. Mabrouk, J. C. Reyes-Guerrero, and M. Nedil, "Radio-channel characterization of an over-sea communication," in *Proc. European Conf. Antennas & Propagation*, Lisbon, Portugal, Apr. 2015, pp. 1–4.

[203] A. Tingsuwatit and P. Janpugdee, "An analysis of maritime communications between a ship at sea and a shore station by a ray-based Monte Carlo method," in *Proc. Progress Electromagnetics Research Symposium*, St. Petersburg, Russia, May 2017, pp. 3462–3466.

[204] P. Kabacik, A. Byndas, W. Fraczek, D. Sysak, M. Hofman, and F. Bekkadal, "Over-the-horizon broadbad maritime communications utilizing novel lightweight antennas," in *Proc. Oceans*, Aberdeen, UK, Jun. 2017, pp. 1–5.

[205] R. M. Schmalenberger and M. G. Edrich, "Channel modelling for wideband data communication in a maritime mobile environment," in *Proc. IEEE/AFCEA Eurocomm.*, Munich, Germany, May 2000, pp. 150–154.

[206] S. Jiang, "Fostering marine Internet with advanced maritime radio system using spectrums of cellular networks," in *Proc. IEEE Intern. Conf. Commun. Systems*, Shenzhen, China, Dec. 2016, pp. 1–6.

[207] K. S. Zaidi, V. Jeoti, and A. Awang, "Wireless backhaul for broadband communication over Sea," in *Proc. IEEE Malaysia Intern. Conf. Commun.*, Kuala Lumpur, Malaysia, Nov. 2013, pp. 298–303.

[208] A. Adejo, J. Hussein, and S. Boussakta, "Optimal transmit power configuration for soft frequency reuse in irregular cellular networks," in *Proc. Intern. Conf. Ubiquitous & Future Networks*, Milan, Italy, Jul. 2017, pp. 711–713.

[209] J. Park, N. Lee, and R. W. Heath, "Base station cluster patterns for semi-static multi-cell cooperation in irregular network topologies," in *Proc. European Signal Process. Conf.*, Nice, France, Aug. 2015, pp. 2441–2445.

[210] L. Kayili and E. Sousa, "Cell outage compensation for irregular cellular networks," in *Proc. IEEE Wireless Commun. & Networking Conf.*, Istanbul, Turkey, Apr. 2014, pp. 1850–1855.

[211] Y. Kim, Y. Song, and S. H. Lim, "Hierarchical maritime radio networks for Internet of maritime things," *IEEE Access*, vol. 7, pp. 54218–54227, 2019.

[212] H. K. Son and Y. J. Chong, "Analysis of the interference effects from maritime earth station in motion to 5G mobile service," in *Proc. Intern. Conf. Info. & Commun. Tech. Convergence*, Jeju, South Korea, Oct. 2017, pp. 1225–1228.

[213] H. Kim, Y. Cho, E. Edwin, H.-S. Jo, "Adjacent channel interference from maritime earth station in motion to 5G mobile service," in *Proc. Intern. Conf. Info. & Commun. Tech. Convergence*, Jeju, South Korea, Oct. 2018, pp. 1164–1169.

[214] L. Xu, S. Wu, J. Xu, Y. Wang, and Q. Zhang, "Fairness-aware interference coordination by combined SFR and CoMP for heterogeneous networks," in *Proc. IEEE Veh. Tech. Conf.*, Toronto, Canada, Sep. 2017, pp. 1–6.

[215] C. Liu, W. Feng, T. Wei, and N. Ge, "Fairness-oriented hybrid precoding for massive MIMO maritime downlink systems with large-scale CSIT," *China Communications*, vol. 15, no. 1, pp. 52–61, Jan. 2018.

[216] T. Wei, W. Feng, N. Ge, and J. Lu, "Optimized time-shifted pilots for maritime massive MIMO communication systems," in *Proc. Wireless & Optical Commun. Conf.*, Newark, USA, Apr. 2017, pp. 1–5.

[217] M. Zhou, H. Harada, P. Kong, and J. S. Pathmasuntharama, "Interference range analysis and scheduling among three-hop neighborhood in maritime WiMAX mesh networks," in *Proc. IEEE Wireless Commun. & Networking Conf.*, Sydney, Australia, Apr. 2010, pp. 1–6.

[218] A. Kachroo, M. K. Ozdemir, and H. T. Mogulkoc, "Optimization of LTE radio resource block allocation for maritime channels," in *Proc. IEEE Sarnoff Symp.*, Newark, USA, Sep. 2016, pp. 88–93.

[219] Y. Xu, "Quality of service provisions for maritime communications based on cellular networks," *IEEE Access*, vol. 5, pp. 23881–23890, Oct. 2017.

[220] N. Takatsu, T. Kimoto, H. Mikasa, K. Harada, S. Watanabe, M. Uematsu, and S. Tsunogai, "Development of offshore monitoring platform 'SOLAReS' for SOLAS," in *Proc. Oceans*, San Diego, USA, Sep. 2003, pp. 850–856.

[221] ITU-R M.2202, "Maritime broadband wireless mesh networks," Geneva, Switzerland, Rep. ITU-R M.2202, Dec. 2011.

[222] A. A. Allal, K. Mansouri, M. Youssfi, and M. Qbadou, "Toward a new maritime communication system in Detroit of Gibraltar where conventional and autonomous ships will co-exist," in *Proc. Intern. Conf. Wireless Networks & Mobile Commun.*, Rabat, Morocco, Nov. 2017, pp. 1–8.

[223] G. Giorgi, P. J. G. Teunissen, and T. P. Gourlay, "Instantaneous global navigation satellite system (GNSS)-based attitude determination for maritime applications," *IEEE J. Oceanic Engineering*, vol. 37, no. 3, pp. 348–362, Jul. 2012.

[224] St. D. Ilcev, "Satellite CNS for maritime transportation augmentation system (MTAS)," in *Proc. Intern. Crimean Conf. Microwave & Telecommun. Tech.*, Sep. 2009, pp. 3–8.

[225] L. Bracciale, P. Loreti, M. Luglio, C. Roseti, and F. Zampognaro, "SMARTSOS: Systems for maritime advanced rescue through satellite and optimized sensor networks," in *Proc. Intern. Conf. Info. & Commun. Tech. Disaster Management*, Vienna, Austria, Dec. 2016, pp. 1–5.

[226] A. Weinberg, Y. Kaminsky, and F. Keblawi, "A novel concept for a satellite-based maritime search and rescue system," *IEEE Trans. Veh. Tech.*, vol. 26, no. 3, pp. 258–269, Aug. 1977.

[227] R. M. LaRosa, "Maritime satellite requirements and utilization," *IEEE Trans. Veh. Tech.*, vol. 26, no. 3, pp. 251–257, Jul. 1977.

[228] A. G. Stove, M. S. Gashinova, S. Hristov, and M. Cherniakov, "Passive maritime surveillance using satellite communication signals," *IEEE Trans. Aerospace & Electronic Systems*, vol. 53, no. 6, pp. 2987–2997, Dec. 2017.

[229] S. Holsten, "Global maritime surveillance with satellite-based AIS," in *Proc. Oceans*, Bremen, Germany, May 2009, pp. 1–4.

[230] S. Jayasimha, J. Paladugula, A. V. Gadiraju, and M. K. Medam, "Satellite-based AIS receiver for dense maritime zones," in *Proc. Intern. Conf. Commun. Systems & Networks*, Bangalore, India, Jan. 2017, pp. 15–22.

[231] U.S. Coast Guard Navigation Center. *Long Range Identification and Tracking (LRIT) Overview.* Accessed: Nov. 30, 2020. [Online]. Available: https://www.navcen.uscg.gov/?pageName=lritMain

[232] Z. Xiao, X. Fu, L. Zhang, and R. S. M. Goh, "Traffic pattern mining and forecasting technologies in maritime traffic service networks: A comprehensive survey," *IEEE Trans. Intell. Transp. Syst.*, vol. 21, no. 5, pp. 1796–1825, May 2020.

[233] P. Braca, S. Maresca, R. Grasso, K. Bryan, and J. Horstmann, "Maritime surveillance with multiple over-the-horizon HFSW radars: An overview of recent experimentation," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 30, no. 12, pp. 4–18, Dec. 2015.

[234] S. Grosdidier, A. Baussard, and A. Khenchaf, "HFSW radar model: Simulation and measurement," *IEEE Trans. Geosci. Remote Sens.*, vol. 48, no. 9, pp. 3539–3549, Sep. 2010.

[235] J. Urbanski, W. Morgas, and C. Specht, "Perfecting the maritime navigation information services of the European Union," in *Proc. Intern. Conf. Info. Tech.*, Gdansk, Poland, May 2008, pp. 1–4.

[236] J. Zhao, T. Yang, H. Feng, and J. Li, "Study on wide-band communication at sea under E-navigation framework," in *Proc. Intern. Conf. Info., Cybernetics & Computational Social Systems*, Dalian, China, Jul. 2017, pp. 48–52.

[237] M. S. Choi, M. A. Jeong, S. M. Jeon, J. H. Kim, C. H. Kim, H. J. Lee, H. M. Park, J. Y. Choo, and S. R. Lee, in "Ship to shore maritime communication for e-Navigation using IEEE 802.16e," in *Proc. Intern. Conf. Info. Commun. Tech. Convergence*, Jeju, South Korea, Oct. 2013, pp. 759–762.

[238] O. J. Rodseth, "A maritime ITS architecture for e-Navigation and e-Maritime: Supporting environment friendly ship transport," in *Proc. Intern. Conf. Intell. Transportation Systems*, Washington, USA, Oct. 2011, pp. 1156–1161.

[239] L. Ye and Y. Wang, "Marine navigation services based on COMPASS (Beidou) and GPS," in *Proc. Ubiquitous Positioning, Indoor Navigation & Location Based Service*, Helsinki, Finland, Oct. 2012, pp. 1–7.

[240] J. Tagg and B. Stafford, "Future maritime radar: Requirements and solutions," in *Proc. Intern. Conf. Radar Systems*, Belfast, UK, Oct. 2017, pp. 1–4.

[241] M. Zhou, H. Harada, and J. S. Pathmasuntharam, "An analysis model of DoA in maritime environment for ship-to-ship/shore wireless communications," in *Proc. Intern. Conf. Intell. Transport Systems Telecommun.*, Lille, France, Oct. 2009, pp. 376–380.

[242] D. Yoo, H. Kim, J. Choi, B. Jang, and S. Ro, "A novel antenna tracking technique for maritime broadband communication (MariComm) system," in *Proc. Intern. Conf. Advanced Commun. Tech.*, Seoul, South Korea, Jul. 2015, pp. 225–229.

[243] J. Tiemann, O. Feldmeier, and C. Wietfeld, "Supporting maritime search and rescue missions through UAS-based wireless localization," in *Proc. IEEE Globecom Workshops*, Abu Dhabi, United Arab Emirates, Dec. 2018, pp. 1–6.

[244] G. G. Cruz, L. M. Guzman, M. F. D. Guzman, and S. M. Cheng, "Compensation of antenna misalignment using selection diversity for maritime communications," *Proc. IEEE Region 10 Conf.*, Jeju, South Korea, Oct. 2018, pp. 350–355.

[245] B. Sun, "Marine environmental information service system based on visualization technology," in *Proc. Intern. Symp. Knowledge Acquisition & Modeling*, Wuhan, China, Dec. 2009, pp. 315–318.

[246] T. Yang, H. Liang, N. Cheng, and X. Shen, "Towards video packets store-carry-and-forward scheduling in maritime wideband communication," in *Proc. IEEE Global Commun. Conf.*, Atlanta, GA, USA, Dec. 2013, pp. 4032–4037.

[247] M. Bouaziz and A. Rachedi, "A survey on mobility management protocols in Wireless Sensor Networks based on 6LoWPAN technology," *Computer Commun.*, vol. 74, pp. 3–15, 2016.

[248] Mekki, Kais, et al., "A comparative study of LPWAN technologies for large-scale IoT deployment," *ICT Express*, vol. 5, no. 1, pp. 1–7, 2019.

[249] A. Hoeller, J. Sant'Ana, J. Markkula, K. Mikhaylov, R. Souza and H. Alves, "Beyond 5G low-power wide-area networks: A LoRaWAN suitability study," *2020 2nd 6G Wireless Summit (6G SUMMIT)*, Levi, Finland, 2020, pp. 1–5, doi: 10.1109/6GSUMMIT49458.2020.9083800.

[250] Shakkottai, Sanjay, Theodore S. Rappaport, and Peter C. Karlsson, "Cross-layer design for wireless networks," *IEEE Commun. Magazine*, vol. 41, no. 10, pp. 74–80, 2003.

[251] Setton, Eric, et al., "Cross-layer design of Ad-hoc networks for real-time video streaming," *IEEE Wireless Commun.*, vol. 12, no. 4, pp. 59–65, 2005.

[252] Madan, Ritesh, et al., "Cross-layer design for lifetime maximization in interference-limited wireless sensor networks," in *Proc. Annual Joint Conference IEEE Computer & Commun. Societies*, vol. 3, 2005.

[253] Hasan, Mohammed Zaki, Fadi Al-Turjman, and Hussain Al-Rizzo, "Analysis of cross-layer design of quality-of-service forward geographic wireless sensor network routing strategies in green internet of things," *IEEE Access*, vol. 6, pp. 20371–20389, 2018.

[254] D. Parlanti, F. Paganelli, and D. Giuli, "A service-oriented approach for network-centric data integration and its application to maritime surveillance," *IEEE Systems J.*, vol. 5, no. 2, pp. 164–175, Jun. 2011.

[255] B. Yang, Y. Hao, J. Wang, and Z. Hu, "Flexible service architecture for maritime business promotion based on mobile technology," in *Proc. Intern. Conf. Networks Security, Wireless Commun. & Trusted Computing*, Wuhan, China, Apr. 2010, pp. 490–493.

[256] D. Bendouda, A. Rachedi, and H. Haffaf, "Programmable architecture based on software defined network for Internet of Things: Connected dominated sets approach," *Future Generation Computer Systems*, vol. 80, pp. 188–197, 2018.

[257] T. Yang, R. Wang, Z. Cui, J. Dong, and M. Xia, "Multi-attribute selection of maritime heterogenous networks based on SDN and fog computing architecture," in *Proc. Intern. Symp. Modeling & Optimization Mobile, Ad Hoc & Wireless Networks*, Shanghai, China, May 2018, pp. 1–6.

[258] H. Chu, P. Li, X. Zhu, H. Hong, and Y. Guo, "Bandwidth improvement of center-fed series antenna array targeting for base stations in offshore 5G communications," *IEEE Access*, vol. 7, pp. 33537–33543, Mar. 2019.

[259] M. Gheisarnejad, M.-H. Khooban, and T. Dragicevic, "The future 5G network aased secondary load frequency control in maritime microgrids," *IEEE J. Emerging & Sel. Topics Power Electronics*, to appear, 2019. DOI: 10.1109/JESTPE.2019.2898854.

[260] P. Kokkinakos, A. Michalitsi-Psarrou, S. Mouzakitis, I. Alvertis, D. Askounis, and S. Koussouris, "Big data exploitation for maritime applications a multi-segment platform to enable maritime big data scenarios," in *Proc. Intern. Conf. Engineering, Tech. & Innovation*, Funchal, Portugal, Jun. 2017, pp. 1131–1136.

[261] T. Yang, H. Feng, C. Yang, Y. Wang, J. Dong, and M. Xia, "Multi-vessel computation offloading in maritime mobile edge computing network," *IEEE Internet Things J.*, vol. 6, no. 3, pp. 4063–4073, Jun. 2019.

[262] T. Yang, Y. Zhang, and J. Dong, "Collaborative optimization scheduling of maritime communication for mobile edge architecture," in *Proc.*

IEEE Intern. Conf. RFID Tech. & Application, Macau, China, Sep. 2018, pp. 1–5.

[263] K. Wang, P. Xu, C.-M. Chen, S. Kumari, M. Shojafar and M. Alazab, "Neural architecture search for robust networks in 6G-enabled massive IoT domain," *IEEE IoT. J.*, doi: 10.1109/JIOT.2020.3040281.

[264] Y. Liu, X. Yuan, Z. Xiong, J. Kang, X. Wang, and D. Niyato, "Federated learning for 6G communications: Challenges, methods, and future directions," *China Communications*, vol. 17, no. 9, pp. 105–118, Sep. 2020.

[265] T. Wei, W. Feng, J. Wang, N. Ge, and J. Lu, "Exploiting the shipping lane information for energy-efficient maritime communications", *IEEE Trans. Veh. Tech.*, vol. 68, no. 7, pp. 7204–7208, Jul. 2019.

[266] G. Wikstrom et al., "Challenges and technologies for 6G," *2020 2nd 6G Wireless Summit (6G SUMMIT)*, Levi, Finland, 2020, pp. 1–5, doi: 10.1109/6GSUMMIT49458.2020.9083880.

[267] X. Li, W. Feng, Y. Chen, C. Wang, and N. Ge, "Maritime coverage enhancement using UAVs coordinated with hybrid satellite-terrestrial networks," *IEEE Trans. Commun.*, vol. 68, no. 4, pp. 2355–2369, Apr. 2020.

[268] X. Li, W. Feng, J. Wang, Y. Chen, N. Ge, and C.-X. Wang, "Enabling 5G on the ocean: a hybrid satellite-UAV-terrestrial network solution," *IEEE Wireless Commun.*, vol. 27, no. 6, pp. 116–121, Dec. 2020.

[269] N. H. Mahmood, H. Alves, O. A. Lopez, M. Shehab, D. P. M. Osorio, and M. Latva-Aho, "Six key features of machine type communication in 6G," *2020 2nd 6G Wireless Summit (6G SUMMIT)*, Levi, Finland, 2020, pp. 1–5, doi: 10.1109/6GSUMMIT49458.2020.9083794.

[270] T. Yang et al., "Two-stage offloading optimization for energy-latency tradeoff with mobile edge computing in maritime Internet of Things," *IEEE IoT. J.*, vol. 7, no. 7, pp. 5954–5963, Jul. 2020.

[271] H. Wei, W. Feng, C. Zhang, Y. Chen, Y. Fang, and N. Ge, "Creating efficient blockchains for the Internet of Things by coordinated satellite-terrestrial networks," *IEEE Wireless Commun.*, vol. 27, no. 3, pp. 104–110, Jun. 2020.

[272] T. Nguyen, N. Tran, L. Loven, J. Partala, M. Kechadi, and S. Pirttikangas, "Privacy-aware blockchain innovation for 6G: Challenges and opportunities," *2020 2nd 6G Wireless Summit (6G SUMMIT)*, Levi, Finland, 2020, pp. 1–5, doi: 10.1109/6GSUMMIT49458.2020.9083832.

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