MagicNet: The Maritime Giant Cellular Network

Sanghai Guan, Jingjing Wang, Chunxiao Jiang, Ruiyang Duan, Yong Ren, and Tony Q. S. Quek

Abstract

Recently, the development of marine industries has increasingly attracted attention from all over the world. A wide-area and seamless maritime communication network has become a critical supporting approach. In this article, we propose a novel architecture named the maritime giant cellular network (MagicNet) relying on seaborne floating towers deployed in a honeycomb topology. The tower-borne giant-cell base stations are capable of providing wide-area seamless coverage for maritime users and can construct multihop line-of-sight (LoS) links connecting to terrestrial networks. Then the MagicNet-aided maritime network architecture is expounded in terms of five dimensions (i.e., space, air, shore, surface, and underwater), which is compatible with existing systems including maritime satellite networks and maritime Internet of Things, and supports a range of compelling industrial applications. Moreover, we introduce a joint multicast beamforming and relay system for the sake of supporting high-speed and low-cost information services for near-shore areas, as well as a three-tier space-air-surface hybrid network in order to provide reliable wide-area communications for deep offshore areas. Finally, we discuss the open issues and future works on MagicNet.

Introduction

With the exploration and development of oceans, the "blue industry" has raised considerable concern in recent years. It turns out that seamless and wide-area broadband maritime information coverage has become the fundamental pillar for the huge potential of marine industries [1]. For the sake of the promotion of so-called smart ocean construction, the next-generation maritime information network should further meet the following challenges:

- Provide high-rate and low-cost information services for marine users, and be compatible with the existing maritime sensing and communication systems.
- Support efficient seamless network information coverage with the lack of infrastsructure.
- Design advanced network technologies to beneficially coordinate limited system resources and sparse user distribution in the context of complex maritime scenarios.

At present, maritime communications mainly rely on maritime MF/HF/VHF-band communications, satellite communications, and shore-based mobile communications [2]. To elaborate, the navigational telex (NAVTEX) system is a typical MF-band information system that broadcasts navigation warning, weather, and other emergency information for vessels from shore-based transmitters. Moreover, the automatic identification system (AIS) is a widely used automatic broadcast system operating on VHF-band. Shipborne, shore-based, and buoy-borne AIS transceivers automatically exchange navigation information for electronic nautical charts, traffic management, and maritime rescue. Additionally, the International Telecommunication Union (ITU) describes the MF/HF/VHF-band maritime wireless communications blueprint in ITU Recommendations. The latest international maritime satellite communication system (INMARSAT) [3] consists of four geosynchronous Earth orbit (GEO) satellites and operates on Ka-band to provide global high-speed information services. Moreover, relying on a large number of 3G/4G/5G base stations (BSs) built at coastal regions, mobile communications can be provided for near-shore vessel users [4]. Meanwhile, some widely used terrestrial communication systems are extended to maritime scenarios such as the worldwide interoperability for microwave access (WiMAX) [5] and Internet of Things (IoT) [6, 7]. Table 1 summarizes typical maritime information projects for maritime big data sensing, communications, and networking.

However, the data rate of MF/HF/VHF-band communication systems is relatively low due to the limited bandwidth (e.g., 100 b/s of NAVTEX and 9.6 kb/s of AIS), which cannot support broadband information services. Although substantial progress has been achieved in maritime satellite communications aimed at providing high data rate access (i.e., 50 Mb/s downlink and 5 Mb/s uplink of INMARSAT-5), users have to compromise with its expensive cost and high latency. Furthermore, the popular Ka-band satellite communications may be vulnerable to unfavorable weather and difficult to set up all-the-time seamless communication links. In contrast, the shore-based mobile communication system can provide a feasible way for low-cost and convenient information services, while its coverage is limited within the near-shore area, which may only be suitable for ports and docks. Moreover, the aforementioned communication systems are incompatible and incorporative in terms of the physical reality.

Hence, in this article, we propose a novel marine information network, namely the maritime giant cellular network (MagicNet), where the original contribution can be summarized as follows:

The authors propose a novel architecture named the maritime giant cellular network (MagicNet) relying on seaborne floating towers deployed in a honeycomb topology. The tower-borne giant-cell base stations are capable of providing wide-area seamless coverage for maritime users and can construct multihop line-of-sight (LoS) links connecting to the terrestrial networks.

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Digital Object Identifier: 10.1109/MCOM.001.2000831

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Project	Year	Brief descriptions
Maritime information sensing oriented projects		
ARGO	2000–	ARGO (Array for Real-time Geostrophic Oceanography) is a global program that deploys thousands of satellite-tracked drifting buoys over the global oceans to measure the temperature and salinity.
IOOS	2002–	IOOS (U.S. Integrated Ocean Observing System) collects coastal and marine data, including ocean temperature, currents, waves, water level, and winds by satellites, buoys, tide gauges, radars, and UAVs.
ESONET	2004–	ESONET (European Seafloor Observatory Network) monitors the ocean margin environment around Europe through various underwater sensors and cameras.
DONET	2006–	DONET (Dense Oceanfloor Network System for Earthquakes and Tsunamis) constructs a submarine cable-based seafloor observatory network around Japan.
GO-SHIP	2007–	GO-SHIP (Global Ocean Ship-based Hydrographic Investigations Program) collects ship-based hydrographic data and develops a globally coordinated hydrographic network.
Maritime communications and networking oriented projects		
SEAWEB	1996–2008	SEAWEB is a military maritime networking architecture proposed by the U.S. Navy including Iridium satellite, ships, buoys, underwater acoustic nodes, and underwater vehicles.
MARPOS	2011–	MARPOS (EU Maritime Policy Support) project aims at various maritime transport research. In MARPOS FP7 ABSOLUTE and SUNNY subprojects, unmanned aerial vehicles and customized helium balloon kite with airborne base stations are adopted to collect and transmit information for maritime surveillance scenarios.
TRITON	2013–	TRITON (Tri-Media Telematic Oceanographic Network) constructs a WiMAX-based offshore multihop ad hoc vessel network in coastal areas of Singapore.
BLUECOM+	2013–	BLUECOM+ project proposed a tethered balloon base-station-based architecture to realize wide-area offshore communication coverage and multihop backhaul for Portugese coastal areas.
LTE-Maritime	2017–	LTE-Maritime project realize offshore communication coverage by high altitude shore LTE base stations to support various e-Navigation services in Korean waters.

TABLE 1. Maritime information sensing and communication networking projects.

- To the best of our knowledge, it is the first time that both the concept and the architecture of MagicNet are proposed. It is characterized by the collaboration of all dimensions from space to underwater, which supports various compelling maritime industrial applications.
- In order to construct the basic backbone of our proposed MagicNet, seaborne floating towers are introduced. Equipped with sorts of communication and detection payloads, they are capable of realizing wide-area information coverage and interconnecting with maritime users and other nodes through these tower-borne BSs.
- For providing high-rate and low-cost information services for near-shore areas, a joint multicast beamforming and relay system is investigated, while as for supporting the reliable and wide-area offshore information coverage, an unmanned aerial vehicle (UAV)-aided space-air-surface hybrid network is discussed.

The remainder of the article is outlined as follows. The architecture, key technologies, and industrial applications of MagicNet are introduced. A pair of MagicNet-aided maritime communication and networking paradigms are discussed, followed by our conclusions and future work.

The Maritime Giant Cellular Network

Architecture

Considering the lack of maritime information infrastructures, we introduce a new kind of maritime BS relying on the so-called seaborne floating towers, which is a semi-submersible steel reinforced concrete platform. The floating towers can be dragged by ship to the deployed position and anchored on the seafloor, and have been widely used in offshore engineering such as oil exploitation. These towers are able to resist sway in serious sea states and have a long service life of about 20 years. Given their outstanding stability, reliability, and deployment flexibility, they become an ideal choice for use as the infrastructure of maritime BSs.

Inspired by the terrestrial cellular networks, our proposed MagicNet arranges the floating-tower BSs in terms of a honeycomb topology. Considering the open environment with few obstacles and the sparse distribution of users, the distance between the BSs and the coverage of a single cell are far greater than in terrestrial networks, and hence we name the coverage area "giantcell." As a result, it improves the coverage efficiency and reduces the construction cost per unit area of the maritime network. The maritime BS covers the surrounding large sea area with the antenna on top of the floating tower, and carries various communication equipment on deck to support satellite communications, AIS, 3G/4G/5G, WiMAX, and so on. Benefitting from it, users are able to access broadband information service without installing expensive communication equipment such as satellite communication modems, which reduces the equipment cost for maritime communications. Moreover, the bottom of the platform is installed with the acoustic communication modem, which provides information access for the underwater users or devices. These BSs are connected by line-of-sight (LoS) wireless links so that the MagicNet is capable of connecting to the terrestrial core networks through

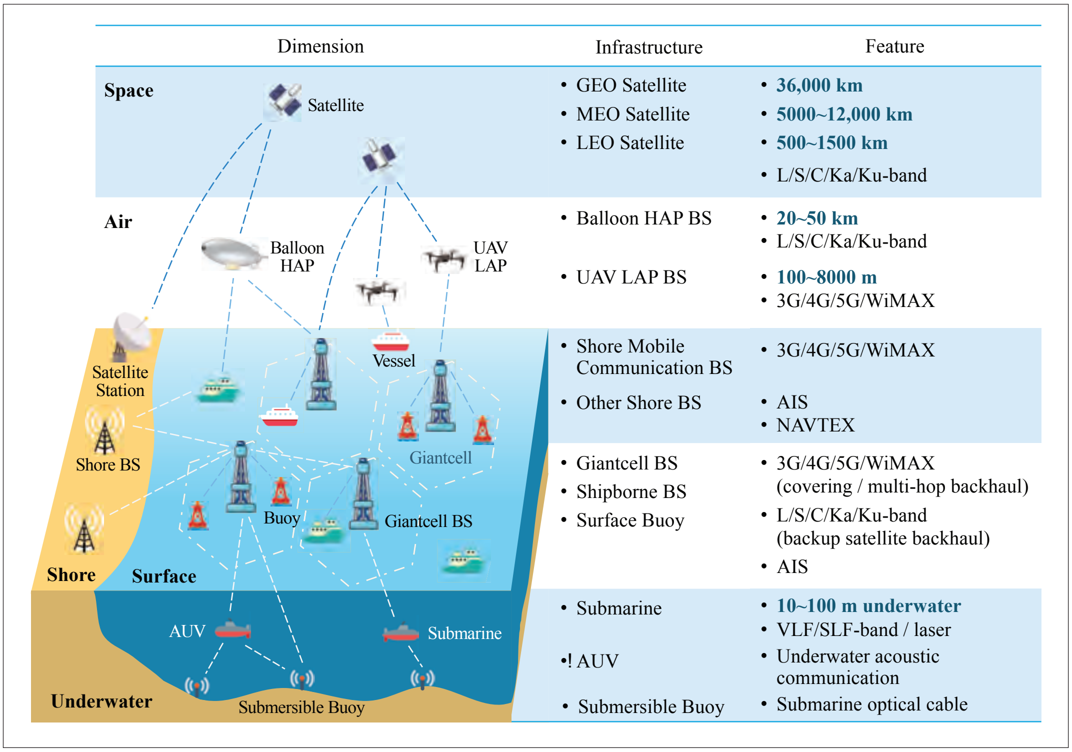

FIGURE 1. The architecture of the MagicNet-aided maritime networks.

The floating towers can be dragged by ship to the deployed position and anchored on seafloor, and have been widely used in offshore engineering such as oil exploitation. These towers are able to resist sway in serious sea states and have a long service life of about 20 years. Given their outstanding stability, reliability, and deployment flexibility, they become an ideal choice for use as the infrastructure of maritime BSs.

multihop links, while satellites are taken as the backup in case of the failure of multihop links. The MagicNet interconnecting with terrestrial networks, satellite networks and various nodes in this architecture relies on standardized inter- and intranetwork protocols, and provides different kinds of services by standardized user interfaces. The architecture of all of the maritime networks is shown in Fig. 1, where the infrastructure is divided into five dimensions.

Space Dimension: The space dimension includes the various maritime communication satellites, such as INMARSAT GEO systems, which provide the largest range of information coverage for maritime users, and also operate as the backup relay nodes between the MagicNet and terrestrial networks. Moreover, the rapidly developed commercial low Earth orbit (LEO) satellite constellation represented by the Starlink system has acknowledged enormous potential in maritime services in the future for its low latency.

Air Dimension: In order to enhance the service ability of the MagicNet, high altitude platforms (HAPs) deployed at altitudes of 20–50 km (e.g., balloons), as well as low altitude platforms (LAPs) deployed at the altitude below 10 km (e.g., UAVs), constitute airborne BSs, which operate as on-demand aerial access points. Balloon HAP communication systems such as Google Loon and BLUECOM+ [8] provide wide-coverage and long-endurance information services, while the economic UAV LAPs can be flexibly deployed for low-cost information services.

Shore Dimension: Shore infrastructures include NAVTEX broadcasting stations, shore AIS stations, and terrestrial mobile communication BSs. The terrestrial BSs can enlarge the coverage and connect to giantcell BSs through multihop relaying.

Surface Dimension: Giantcell BSs are the core infrastructures of the MagicNet. Moreover, the surface infrastructures also include a large number of buoys, such as AIS navigation buoys and environmental observation buoys, constructing the maritime IoT.

Underwater Dimension: Traditional submarine communication systems operate in VLF/SLF-band with long dragging antennas. With the rapid development and compelling applications of autonomous underwater vehicles (AUVs) and underwater buoys for underwater/seabed monitoring [9], acoustic communications become the primary choice for underwater communications. Considering the short communication distance and long delay of underwater acoustic propagation, the submersible buoys can forward data to giantcell BSs via AUVs. Furthermore, infrastructures requiring high time sensitivity, reliability, and stability can be directly connected to the land through submarine optical cables.

Key Technologies

Wide-Area Seamless Coverage: In the MagicNet, the giantcell BSs are connected with LoS wireless links. Hence, the primary problem is to determine the distance between the floating towers and the coverage area of the giantcell. Considering the curvature of the Earth, the uneven atmospheric density, and waves on the oceans, based on the Fresnel zone mode [10], Fig. 2 shows the reliable communication distance of BS-to-BS and BS-to-vessel LoS links vs. the required height of the BS antennas at some common adopted frequencies, while corresponding free space path loss is also provided. It is assumed that the height of sea wave is 1.5 m and the height of shipborne antennas is 10 m. It can be found that high frequency band can reduce the required

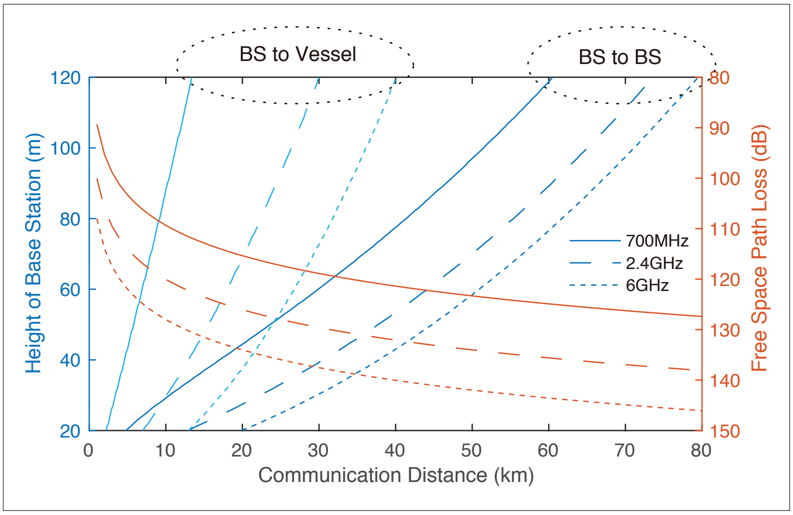

FIGURE 2. The required BS antenna height based on Fresnel zone model and free space path loss vs. communication distance.

antenna height and improve the communication distance and coverage, but also suffers higher loss at the same time. Hence, there is a trade-off between antenna height and transmission power. Furthermore, considering the decline of directional transmission caused by the sway of waves and the variable sea states, antenna parameters such as beamwidth should be flexibly configured to make a balance between reliability and communication distance. In addition, for more accurate fading and path loss estimation, several empirical, two-ray-, and three-ray-based maritime channel models [11] can be utilized according to the realistic oceanic environment. Finally, over-the-horizon communications represented by evaporation duct is also a potential method that cannot be ignored.

Maritime Internet of Things: Tens of thousands of sensor nodes are distributed on/under the sea, which are deployed for various areas of ocean exploration. Most of these sensor nodes are organized as small-scale ad hoc networks, which has challenges in the data backhaul, network expansion, and maintenance. In the MagicNet, the giantcell BS can support access and information collection for thousands of sensor nodes and construct a large-scale maritime IoT network. Among widely used IoT protocols, narrowband IoT (NB-IoT) is suitable for deployment on maritime IoT networks given its low power consumption and wide range coverage. The key technologies of maritime IoT networks include ultra-long network life, green energy supply, anti-swing and anti-corrosion, transparent conversion between underwater acoustic protocols and wireless electromagnetic wave protocols, and more.

Heterogeneous Resource Allocation: Since the maritime network is characterized by heterogeneity, time-varying topology, and multimedia, considering its limited and asymmetrical resource distribution, the cooperation optimization of different network resources becomes particularly important, for example, how to multiplex the electromagnetic wave and underwater acoustic channel, and how to strike a trade-off by utilizing the computing and caching resource edge nodes and the cloud. More intelligent and fine-grained resource allocation methods should be integrated and developed to inspire more advanced applications. More specifically, a centralized resource management architecture, such as cloud computing and software defined networking, may be beneficial for integrating these heterogeneous resources, while distributed machine learning and artificial intelligence algorithms may be operable and low-cost and adapt to the dynamic environments.

Maritime Industrial Applications

As shown in Fig. 3, based on the three-layer software-defined architecture, a range of compelling maritime applications can be realized and enhanced relying on the MagicNet, which are summarized as follows.

Maritime Mobile Communications: MagicNet provides sailors and passengers with convenient, high-rate, and low-cost mobile communication services including voice calls, Internet surfing, email, and even multimedia services.

Environment Monitoring and Resource Exploration: MagicNet constitutes a wide range of ocean monitoring networks, which promotes scientific research such as ocean hydrology and weather prediction, as well as marine industries such as offshore oil exploration.

Marine Transportation Management: On the basis of the AIS system, MagicNet can further realize the real-time vessel positioning and tracking as well as video monitoring and transportation scheduling.

Aquaculture and Fishing: As for the fishing industry, the permanent nodes including floating towers and buoys continuously monitor the trend of fish shoals and report to fishing boats. With regard to offshore aquaculture, hydrological information and cage monitoring video can be sent back to the shore remote control center.

Maritime Patrol, Search, and Rescue: MagicNet is able to detect and collect evidence in a large ocean area and strengthen the ability of ocean law enforcement, while improving the success rate and reducing the cost of maritime accident search and rescue.

MagicNet-Aided Maritime Communications and Networking Paradigms

With the support of the aforementioned architecture and infrastructure of the MagicNet, in the following we introduce two beneficial maritime communications and network systems for both near-shore high-rate communications and offshore wide-area information coverage, respectively, as the guidance for system design and optimization.

Near-Shore Multicast Relaying Communication System

In fact, most of the vessels sail within about 50 km from the coast, while the shore-based mobile communication BSs cannot provide seamless wideband coverage for these coastal regions because of shore obstacles, interference, and spectrum scarcity, which launches the urgent need for low-cost broadband coastal information service. Considering the long communication distance, transmit-site beamforming can provide an effective way to compensate the high path loss. Moreover, since maritime users are much sparser than those on the ground and characterized by being clustered by ships distributed on scheduled routes, multicast techniques has been recognized as a remedy to extend the coverage and support high-rate services to users with common interests [12]. Hence, in this section we construct a maritime multicast beamforming-aided relaying communication system utilizing giantcell BSs as relay nodes (RNs) for the sake of providing high-speed multimedia services for near-shore vessel users.

As shown in Fig. 4, we design a maritime multicast relaying system including a single shore BS, a certain number of RNs, and vessel users, and investigate its downlink optimization problem. The vessel users are equipped with a single transmit antenna, while the shore BS and the RNs have multiple transmit antennas. The vessel users are divided into different user groups according to their quality of service (QoS) requirements and positions. Specifically, the near-shore groups are served by the shore BS directly, while the other offshore groups are served by the associated RNs. Considering the severe power limit of such maritime communication systems, the objective is to minimize the total transmit power while ensuring vessel users' QoS. The QoS of users can be described by signal-to-interference-plus-noise ratio (SINR). Moreover, the total transmit power consumption mainly includes two parts. One is the transmit power of the shore BS described by its beamforming vectors, and the other is the transmit power of the RNs described by RNs' processing matrices. Therefore, the problem can be formulated as minimizing the total transmit power by optimizing the shore BS's beamforming vectors and RNs' processing matrices, with respect to the received SINR constraints for each group.

Considering the structure and non-convex nature of the problem, relying on the feasible point pursuit successive convex approximation (FPP-SCA) approach [13], we can transform the non-convex constraints into convex ones. Then we divide the primal optimization problem into a pair of subproblems, and alternately optimize the shore BS's beamforming vectors and RNs' processing matrices until the downlink scheduling scheme converges.

In the simulation, we consider a scenario with one shore BS with 16 antennas and 4 RNs with 8 antennas for each, and the transmit antenna gains of the shore BS and RNs are assumed as 40 dBi and 35 dBi, respectively. It is also assumed that there are four shore BS-assisted groups and four RN-aided groups. Each RN serves one RN-aided group containing two single-antenna users. The communication distance of each hop is 10 km, and the channel models of two hops are assumed as the empirical loss Rician fading model and the two-ray reflection model with Rayleigh fading, respectively. The carrier frequency is set as 1.9 GHz. In the simulation results, our proposed algorithm convergences in less than 20 iterations. Compared to a greedy algorithm without alternate optimization, the total transmit power of the system is reduced by about 5 dBW under the QoS requirements of 10 dB SINR for all the users. It is characterized by good convergence, and strengthens the desired signals and reduces the interference at the same time with appealingly low power consumption.

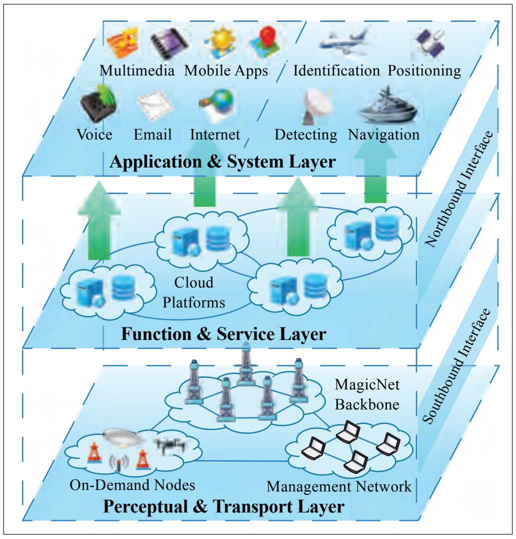

FIGURE 3. The three-layer software-defined architecture of the MagicNet.

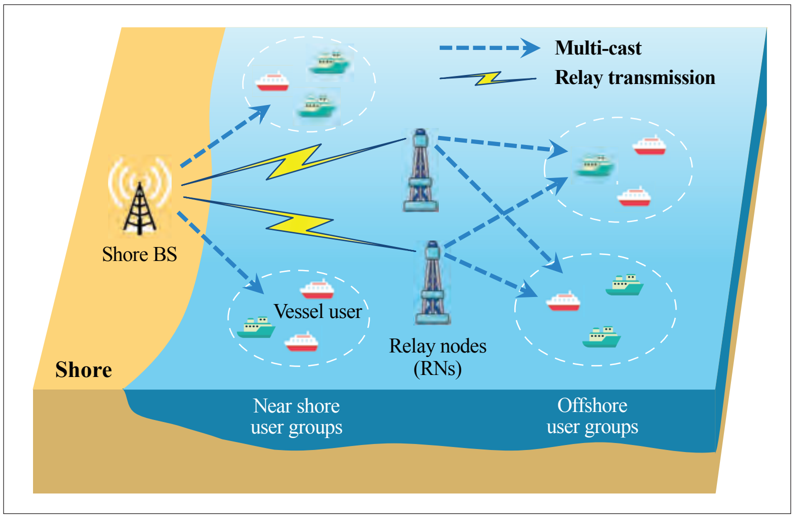

FIGURE 4. The structure of the near-shore multicast relaying system.

UAV-Aided Offshore Space-Air-Surface Hybrid Network

In distant offshore areas, the maritime satellite is capable of providing global coverage, while the giantcell BSs of the MagicNet realize economical broadband information services. Furthermore, considering the cases of overload or contingency, in order to offload the giantcell BSs or construct emergency communication links, deploying drones as on-demand aerial access points and constituting temporary enhanced UAV networks become a substantially feasible choice [14]. As a result, the satellite network, giantcell network, as well as UAV networks construct a space-air-surface three-tier heterogeneous network for the sake of both realizing seamless coverage, and improving the connectivity, capacity, and flexibility for maritime mobile communication as well as maritime IoT.

As shown in Fig. 5, we conceive a hybrid network including a GEO satellite network, a giantcell network with a BS, and several UAV networks within the coverage of the giantcell. This hybrid network shares the same channel, where the subchannels can be allocated to the users in each UAV network. For this system, we focus on

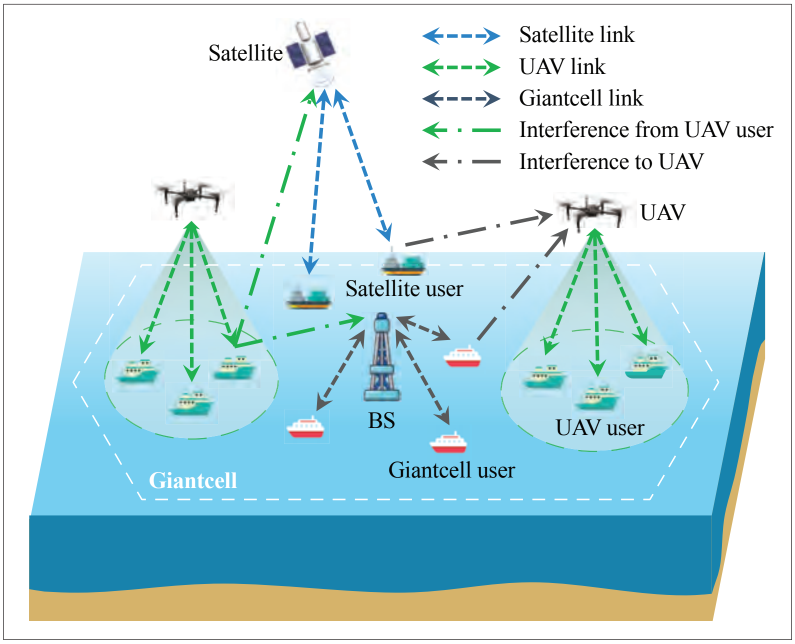

FIGURE 5. The structure of satellite-UAV-giantcell three-tier hybrid network.

the uplink transmission of the UAV networks. For each UAV user, the uplink capacity is described as the capacity of its allocated subchannel. Each UAV user also has different required capacity as the minimum QoS. A user's uplink capacity can be raised by increasing its transmission power, but each UAV network has a maximum total transmission power. Our objective is to maximize the total capacity of all UAV users. Because the giantcell and satellite networks share the frequency resources with UAV networks, in order to avoid cross-tier interference, the interference from UAV networks on each subchannel must be lower than the threshold for the giantcell network and the satellite network, respectively. Moreover, for flight safety, UAVs must be deployed at different hovering altitudes within the specified altitude ranges. As a result, how to deploy the UAVs safely and achieve the maximum transmission efficiency with minimum energy consumption and interference becomes a tough challenge. Therefore, we can formulate the resource allocation problem as maximizing the total capacity by optimizing the subchannel allocation scheme, UAV user power, and UAVs' hovering altitude, while the constraints include subchannel monopoly, maximum transmission power, UAV safety flight and hovering altitude, users' QoS, as well as the interference to giantcell and satellite networks.

For this complicated optimization problem including non-convex and integer constraint, we put forward a low-computational-complexity two-stage algorithm. In the first stage, we fix the UAV's hovering altitude and search the optimal power control and subchannel allocation scheme through the Lagrangian dual decomposition method. In the second stage, we achieve the optimum UAV hovering altitude with the aid of a concave-convex procedure method [15]. Through the iterative optimization and mutual converge process, the near optimal resource allocation scheme is obtained.

In the simulation, we assume that there are 10 giantcell users and 10 satellite users. The carrier frequency is set as 2.4 GHz, and the channel with bandwidth 1.92 MHz is divided into 128 subchannels. The channel models are assumed as Rayleigh fading between users and the BS, as well as Rician fading between users and the satellite and UAVs, respectively. The altitude range of UAVs spans from 200 m to 400 m. The maximum interference limit of both the BS and the satellite is 0 dBm, and the maximum total transmission power of UAV users is 1000 mW. Here we assume two cases with four UAVs and nine UAVs, where each UAV serves four UAV users. The QoS-sensitive and QoS-tolerant UAV users with the minimum capacity requirement of 30 kb/s and 0 kp/s randomly appear in simulation. Compared to the average resource allocation scheme, our proposed scheme improves the spectral efficiency of the UAV networks by on average 190 b/s/Hz and 270 b/s/Hz, respectively. In both cases, the probability of satisfying capacity requirement stays at 100 percent.

Conclusions and Future Works

In a nutshell, in this article, we firsty investigate the pros and cons of existing maritime communication systems. Then we introduce the architecture, key technologies, and industrial applications of the MagicNet. We also concentrate on two paradigm systems with the aid of the MagicNet; the near-shore multicast relaying system and the offshore space-air-surface hybrid network. The remaining open issues and future research trends of the MagicNet include the design of maritime giantcell BSs and devices, data-driven and artificial-intelligence-aided maritime communication services, underwater intelligent communications and networking, and so on. We hope that the maritime giant cellular network will inspire related research and bring progress to marine industries.

Acknowledgments

This work was partly supported by the National Natural Science Foundation of China (Grant No. 62071268) and partly supported by the China Postdoctoral Science Foundation (Grant No. 2020T130357).

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