Convergence of Broadband and Broadcast/Multicast in Maritime Information Networks

Jun Du, Jian Song*, Yong Ren, and Jintao Wang

Abstract: Recently, the fifth-generation (5G) of wireless networks mainly focuses on the terrestrial applications. However, the well-developed emerging technologies in 5G are hardly applied to the maritime communications, resulting from the lack of communication infrastructure deployed on the vast ocean, as well as different characteristics of wireless propagation environment over the sea and maritime user distribution. To satisfy the expected plethora of broadband communications and multimedia applications on the ocean, a brand-new maritime information network with a comprehensive coverage capacity in terms of all-hour, all-weather, and all-sea-area has been expected as a revolutionary paradigm to extend the terrestrial capacity of enhanced broadband, massive access, ultra-reliable, and low-latency to the vast ocean. Further considering the limited available resource of maritime communication infrastructure, the convergence of broadband and broadcast/multicast can be regarded as a possible yet practical solution for realizing an efficient and flexible resource configuration with high quality of services. Moreover, according to such multi-functionality and all-coverage maritime information network, the monitoring and sensing of vast ocean area relying on massive Ocean of Things and advanced radar techniques can be also supported. Concerning these issues above, this study proposes a Software Defined Networking (SDN) based Maritime Giant Cellular Network (MagicNet) architecture for broadband and multimedia services. Based on this network, the convergence techniques of broadband and broadcast/multicast, and their supporting for maritime monitoring and marine sensing are also introduced and surveyed.

Key words: Maritime Giant Cellular Network (MagicNet); integrated broadcast-multicast-unicast communications; maritime multimedia services; Ocean of Things (OoT); all-coverage

- Jun Du, Jian Song, Yong Ren, and Jintao Wang are with the Department of Electronic Engineering, Tsinghua University, Beijing 100084, China. E-mail: jundu@tsinghua.edu.cn; jsong@tsinghua.edu.cn; reny@tsinghua.edu.cn; wangjintao@tsinghua.edu.cn.
- Yong Ren is also with the Institute for Ocean Engineering, Tsinghua University, Beijing 100084, and Peng Cheng Laboratory, Shenzhen 518055, China.
- Jian Song and Jintao Wang are also with the Beijing National Research Center for Information Science and Technology, Tsinghua University, Beijing 100084, and the Key Laboratory of Digital TV System of Guangdong Province and Shenzhen City, Research Institute of Tsinghua University, Shenzhen 518057, China.
- *To whom correspondence should be addressed.
  Manuscript received: 2021-01-03; accepted: 2021-01-17

1 Introduction

Recently, the fifth-generation (5G) of wireless communications has been expected to realize fully intelligent network orchestration and management by integrating different radio access technologies through an efficient and cooperative way. As reported by the International Telecommunication Union (ITU), the three typical usage scenarios, i.e., enhanced Mobile BroadBand (eMBB), massive Machine-Type Communications (mMTC), and ultra-Reliable and Low-Latency Communications (uRLLC), are defined to support a great range of traditional and emerging applications and services, at anytime and anywhere[1, 2]. So far, the proposed 5G technologies, such as Terahertz communications, spectrum allocation, and 5G New

Radio (NR), are investigated specifically for terrestrial scenarios. Nevertheless, resulting from the difficulties and lack of deploying communication infrastructure on the ocean, the development of maritime communications and information service systems is far from the exceptional performances promised by 5G. With the increasing frequency of maritime activities and rapid development of marine economy, there is an urgent need for a new maritime information network to provide mobile broadband services, multimedia services, marine information sensing, etc., for maritime users.

1.1 Unique characteristics of maritime communications

There exist many challenges and difficulties to transplant the terrestrial communication protocols and standards immediately into the maritime applications, resulting from the particular characteristics of wireless propagation environment, user distribution, etc.

1.1.1 Different maritime channel characteristics

The wireless propagation environment over the sea is quite different from that of terrestrial communications, due to its special reflection from ocean surfaces, evaporation duct property, and atmospheric absorption loss[3]. In addition, the dynamic propagation environment and large transmission delay will further lead to limited and insufficient channel information acquisition.

1.1.2 Unique characteristics of maritime users

The terrestrial users are usually spatially distributed within the coverage of a cellular Base Station (BS) according to Homogeneous Poisson Point Processes (HPPPs) and move randomly[4, 5]. Differently, the vessel distributions on the vast ocean are sparse spatially and temporally. Meanwhile, users on these vessels may present a clustering feature, so do users on the island, offshore drilling platforms, and so on. Then maritime users are usually sparse spatially and temporally but clustering distributed on the sea.

1.1.3 Limited and vulnerable satellite communications

The high-throughput maritime satellites working at Ku/Ka-band have been regarded as an effective solution for maritime communications, especially for the coverage of high sea. However, since that the Ku/Ka-band communications are highly vulnerable to the rain and fog[6], satellites can hardly guarantee an all-

weather high-throughput link for maritime broadband communications.

1.2 Multi-functionality integrated maritime information networks

Confronting these challenges above, a new maritime information network architecture is required to support increasing mobile broadband services, multimedia services (including mobile video, mobile TV and so on), massive information sensing, gathering transmission and processing in Ocean of Things (OoT), information service and management for maritime transportation, etc., at all hours, under all weather conditions and in all sea area (all-coverage). As response, we propose a novel Maritime Giant Cellular Network (MagicNet) architecture, which relies on the so-called seaborne floating tower, to achieve all-coverage information services above[7]. In the MagicNet, these towers are equipped with broadcast antennas and/or cellular BS antennas, and communicate with each other over Line of Sight (LoS) wireless channels. In order to achieve a seamless and reliable coverage, the distance between two towers and the coverage area of each giant-cell, as well as carrier frequencies, need to be planned adequately considering the earth curvature, free space path loss, and Fresnel zone effect[3]. To be specific, the radius of Fresnel zone is proportionate to the square root of wavelength. Thus, low frequency bands are more susceptible to the Fresnel zone effect than high frequency bands, which limits their transmission distances of LoS, regardless of the transmission power. However, high frequencies will suffer severer signal attenuation resulting from the propagation loss than low frequencies over long distances. Furthermore, waves and meteorological conditions on the ocean also affect the quality of communication. On the vast ocean area, each floating tower is expected to encompass a radius of about 50–60 kilometers. Then the required antenna height might reach up to tens of meters or even around 100 meters, depending on the carrier frequency and transmission power selected.

Comparing to the terrestrial infrastructure, the cost of deploying such floating communication infrastructure might be much higher. In addition, the available space resources and energy supply on the floating tower are also limited. To take full advantage of resource limited floating towers, flexible networking of different traditional communication standards and efficient spectrum management play important roles

to support the increasing transmission requirements of broadband and multimedia traffic. Similar to the terrestrial multimedia services, only a small proportion of contents are requested frequently by a large number of users. Then these most popular contents delivered through the unicast transmission mode can be offloaded to broadcast networks to relieve heavy traffic load in the cellular networks, and the customized contents are still unicast to users. Such convergence or integration of unicast and broadcast transmission has been investigated in terrestrial communications for decades[8–10]. This orchestration of different networks can be considered a possible yet practical solution for maritime broadband and multimedia services. Additionally, the emerging technologies such Software Defined Networking (SDN) and Network Functions Virtualization (NFV) enable the flexible and on-demand network configuration for various communication services[11–13]. As response, this work will introduce a novel architecture of broadcast-multicast-unicast integrated MagicNets based on SDN. Moreover, different convergence structures for broadcast and cellular networks will be proposed for maritime communication applications. Furthermore, based on the proposed MagicNet, this work will also explore some feasible technologies for maritime monitoring and marine sensing on the high sea, by applying integrated unicast and broadcast communications.

1.3 Organization

The remainder of the paper is outlined as follows. An SDN-based architecture is established in Section 2 for realizing a flexible and on-demand integration of broadcast, multicast, and unicast in maritime information networks. Based on this architecture, the convergence technologies of broadcast/multicast and broadband for maritime communication services are discussed in Section 3. In Section 4, some typical applications for maritime monitoring and marine sensing based on the broadband and broadcast integrated networks are introduced, followed by a conclusion in Section 5.

2 Broadcast-Multicast-Unicast Integrated MagicNet

In this section, we will establish an SDN-based architecture for realizing a flexible and on-demand integration of broadcast, multicast, and unicast in maritime information networks, which can support broadband communications, multimedia services, and a

wide range of applications such as marine sensing and monitoring.

2.1 Architecture of broadcast-multicast-unicast integrated magicnet

As a multi-dimensional heterogenous network, the huge coverage of MagicNet is realized by deploying shore towers, insular towers, and seaborne floating towers equipped with cellular BSs or/and broadcast antennas, which can provide various or hybrid communication functionalities, models, and capacities. To satisfy different service requirements, these towers can provide on-demand unicast, broadcast, and multicast transmission modes intelligently and flexibly.

• **Unicast transmission** is a "one-to-one" transmission mode between the cellular BSs and users. In the MagicNet, the IP-based unicast data can be delivered by the floating or terrestrial cellular BS to the named offshore users through the switches and routers without copy. The main advantage of unicast is the rapid response and customized service providing for user requirements. However, unicast transmission of redundancy and repetition will result in a waste of maritime spectrum bandwidth and extra energy consumption. Specifically, if the same content is requested by N user terminals at the same time, this content will be transmitted to these N terminals separately by occupying different communication resources.

• **Broadcast transmission** provides a "one-to-all" transmission service by the floating or terrestrial broadcast towers through downlink channels. All users within the coverage of a broadcast tower can receive the broadcast data indiscriminately. Such mode can help to reduce the heavy traffic load suffered by the cellular BSs significantly, which makes broadcast become a possible candidate for common or correlated information distribution, such as popular multimedia, maritime public warning or services, and command and instruction information for network management. Especially for the high sea with limited communication resource and infrastructure, broadcast holds a great potential for high effectiveness of spectrum and energy. However, without the return channel, personalized services and feedbacks are not allowed by traditional broadcast.

• **Multicast transmission** can be considered as a special kind of broadcast, which realizes a "one-to-many" transmission provided by the floating or terrestrial broadcast towers. Different from broadcast

transmission, multicast serves users who are divided into groups according to the require contents or information. Considering that the vessel distributions on the vast ocean area are sparse spatially and temporally, meanwhile the users on these vessels usually exhibit some clustering properties. Therefore, it is a much more efficient mode of delivering different contents to grouped users through multicast transmission than unicast and broadcast. In addition, different from broadcast, contents can be delivered among various physical networks or network segments by multicast, which will benefit a flexible networking by integrated transmission resource such as floating towers and maritime satellites, especially for the high seas open sea communications.

To implement an intelligent management in the MagicNet, and to take its characteristics of heterogenous, time-varying, and resource-constrained into consideration as well as user distributions on the ocean, an SDN-based three-layered architecture characterized by lightweight, dynamic-adaptive, flexible, and reliable is constructed, as shown in Fig. 1. The architecture is composed by the MagicNet resource layer, distributed cooperative control layer, and service layer, respectively.

2.1.1 Heterogeneous resource layer

The heterogeneous resource layer is the basis for dealing with users' services, which consists of all network entities for communications, including unicast, multicast, and broadcast resources, as well as computing and caching resources in the MagicNet. These multi-dimensional and heterogeneous resources are provided by shore, insular, and seaborne floating platforms equipped with cellular BSs or/and broadcasting towers. In addition, floating broadcast towers can be operated as the carriers for ubiquitous communication, computing, and caching functions, considering their manufacturing cost, height, coverage, and available resources; while the shore and insular towers can also act as the resource managers, besides their inherent function of the resource providing. Although the vast in-network resources provide solid foundation for processing services in the network edge, the heterogeneity is an impediment, where different interfaces for configuration, scheduling, and control intensely lower the maneuverability and interpretability. Moreover, it is
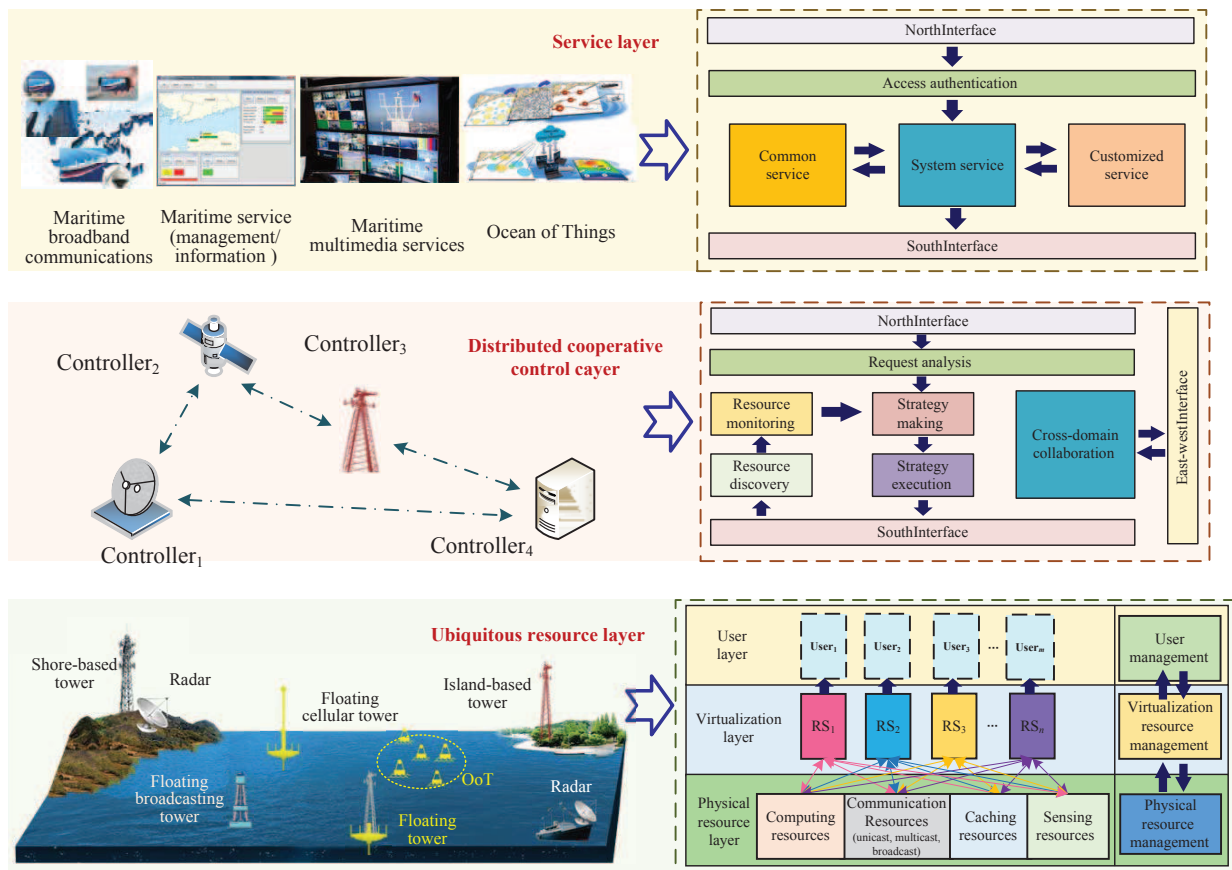

Fig. 1　SDN-based architecture of unicast, broadcast, and multicast transmission integrated MagicNet.

an inevitable tendency for the MagicNet to be further compatible with satellites, high altitude platforms, and other systems providing heterogenous communication, computing, and caching resources[14]. As a remedy, the lightweight container technologies focuses its attention on taking the advantages of fast-deployment and low-occupancy compared with traditional virtual machine technology. Hence, we are motivated by employing the container technology to mask the heterogeneity of different nodes. By virtualizing the physical different modes of communications, computing and caching resources into virtualized resources and further providing standardized operating interfaces, the maneuverability and interpretability can be intensely improved. Additionally, one can also employ multiple containers in one entity to realize resource slicing for serving multiple users simultaneously, and hence the MagicNet becomes homogeneous and easily-scheduled from the system-oriented perspective. Besides, due to the efficient isolation characteristics, different processing procedures in different resource slicing are non-interfering.

2.1.2 Distributed cooperative controller layer

The distributed cooperative controller layer can be considered as the bridge between the multi-functional resource layer and the service layer. Between the resource layer and the controller layer, the standardized *SouthInterface* is defined to shield the heterogeneity of underlying devices, which can realize the virtualization of resource. On the other hand, the flexible *NorthInterface* from the controller layer to the service layer is defined to realize resource allocation and network configuration on-demand. To orchestrate the massive and hybrid communication, computing, and caching resources of such a giant network, the shore and insular cellular and broadcast towers play the roles as controllers in managing the resources, which forms a distributed cooperative control layer with global control information interaction. Considering the dynamic of the in-network resources, as well as unpredictable weather and services requested on the ocean, these controllers keep resource discovered and monitored all along via SouthInterface. When the service requests arrive from NorthInterface, the controller makes an optimal strategy according to both the service requirements and the status of resources intra-domain. If the resources intra-domain cannot satisfy the service requirements or the potential cross-domain behaviors, the controller can collaborate with others to realize a multi-domain collaboration via East-WestInterface, which is designed for the interactions between distributed controllers of different SDN-based systems.

2.1.3 Service layer

The service layer is a logic layer, which can be located at access points or controllers in the light of specific situations and requirements. In this layer, users can employ standardized virtualized resources controlled by the distributed cooperative control layer for implementing services, instead of handling the physical hardware directly, which greatly simplifies the process of service construction. When a user initiates an access request, the identity authentication is required. Afterwards, users can employ the entire system according to their demands within the granted permissions. Considering the huge coverage and spare but clustering user distributions of MagicNet, the terrestrial monolithic service deployment methods, which are designed for increasing dense deployed BSs, are no longer suitable for the MagicNet. Micro-service is a kind of decentralized service deployment architecture, which decomposes the service into many fine-granularity and loose-coupling micro-service components. Such operation can greatly improve the resource utilization and portability. Specifically, this layer mainly includes three modules: the customized service, common service, and system service. The system service module is composed by service requirements abstract (e.g., latency, reliability, bandwidth, latency jitter, etc.), interface management, security policy, resource selection, etc., while the common service module provides common and basic services, such as collaborative computing, information dissemination. Moreover, the customized service module, which relies on common service module and system service module, serves for specifically applications, such as target-detection, remote sensing data processing, environment awareness, and so forth.

2.2 Advantages of broadcast-multicast-unicast integration in MagicNet

The advantages of the proposed multifunction-integrated for MagicNet can be summarized as follows.

● **Reducing spectrum and energy consumption:** Compared with "BS-channel-device" resource architecture, the proposed architecture can provide ubiquitous and flexible communication services, where different kinks of resources providing unicast, broadcast,

and multicast can be scheduled and configured according to a software defined approach, considering spectrum and energy efficiency and service requirements. Such resource management can significantly reduce the service processing latency.

- **Alleviating central burden:** Broadcast and multicast transmission can help to offload the common and similar content traffic requested by users on the ocean from the traditional single unicast transmission, which can intensely alleviate the burden imposed on the central region.

- **Increasing survivability:** The features of dispersibility, multi-functional integration, and flexibility can improve the survivability of the system significantly. With the giant service coverage of MagicNet, the sparse but clustering multimedia services requested from the vast ocean can be satisfied through an optimally on-demand transmission mode.

- **Enriching applications and scalability:** Benefiting from the pervasively deployed of the proposed floating towers on the ocean, compelling applications that cannot be supported before will be revived in the MagicNet, especially in the context of meteorological disasters and high-dynamic joint military operation, etc. Our proposed multi-functionality enabled architecture is capable of flexibly adjusting network topology for adapting to different scenarios and requirements, including communication, target detection and identification, and commanding information distribution.

- **Improving security:** In the proposed architecture, the transmission mode for the users within the coverage is selected distributed and intelligently at the related floating tower, and all intensely dispersed floating towers are operated independently, thereby greatly reducing the risk of local network attacks and centralized and massive information leakage.

2.3 Key techniques

Although the proposed architecture has some significant advantages summarized above, due to the inherent characteristics of the MagicNet, several key technical challenges still need to be further addressed. They are specified as follows:

- **Dynamic resource monitoring:** To achieve efficient scheduling of in-network resources, the monitoring of dynamic nodes is the foundation. Nevertheless, different from terrestrial networks, the wireless channel quality and transmission environment are much more complex and unpredictable, which makes the communication links among the floating towers and vessels/users unstable. Therefore, it is essential to explore Artificial Intelligence (AI) based monitoring methods, which can be optimized by learning the established trajectories, current environments, and historical observation data.

- **Collaboration among distributed controllers:** The aforementioned distributed cooperative control layer is responsible for the management of the whole system. Considering both of the performance and security, it is imperative to employ multiple controllers instead of a single central controller to manage the overall resources collaboratively. Therefore, the performance of the collaboration among distributed controllers has significant impact on the overall architecture. With the explosion of in-network resources and the system scale, the collaboration performance among distributed controllers may be a bottleneck to the subsequent expansion of our proposed architecture.

- **Differentiated Quality of Service (QoS)-oriented resource allocation:** As analyzed previously, the maritime users hold a special distribution property of sparsity and clustering, resulting from the shipping management. In addition, these users have a wide variety of QoS in terms of latency, reliability, bandwidth, throughput, latency jitter, etc. To satisfy the various QoS as well as to improve the utilization of resources, differentiated QoS-oriented resource allocation strategies are necessary. By analyzing different service requests and considering the status of resources intra-domain, the controller can make optimal spectrum and energy resource allocation decisions, and then schedule an appropriate network association via SouthInterface in terms of which parts of content requested by users should be unicast, broadcast, or multicast.

3 Convergence of Broadcast/Multicast and Broadband for Maritime Communication Services

Currently, some digital terrestrial television broadcast towers on shore and islands have been deployed to serve offshore users and island residents, respectively. Cooperating with these existing infrastructure, more broadcast towers and cellular BS towers floating on the ocean or fixed on islands and shores will be further deployed, which enables the MagicNet to improve the coverage and service capacities over the

sea gradually. Then according to the multi-functionality integrated architecture of MagicNet established in Section 2, unicast and broadcast/multicast transmission services can be achieved in a flexible and efficient way, depending on users' requirements and traffic or content characterization. Under such SDN architecture of resource management and service providing, how to achieve a cooperation between these broadcast and cellular BS networks plays an important role to realize a ubiquitous, efficient, and on-demand service for maritime users.

The convergence of broadcast and cellular networks has drawn the attention of researchers, especially for the terrestrial communications. Many hybrid systems consisted of cooperative broadcast, broadband, and cellular networks have been proposed and investigated in the past decades. Some classic and typical studies have been summarized as Table 1. However, the corresponding standards and protocols of maritime broadcast and broadband communications are still hardly studied. In this section, we will introduce some feasible network architectures of cooperative maritime unicast, broadcast, and multicast transmissions, considering the existing broadcast infrastructure deployment for maritime services, as well as emerging technologies that can be introduced to the future MagicNet establishment.

3.1 Converged architecture of maritime broadcast and cellular networks

In the past decades, maritime satellites have performed as a most well-known solution of broadband communications far from the coast. On the other hand, some digital TV or broadcast towers have been built to serve the island residents through the allocated broadcast channels and spectra. To promote the process of establishing MagicNet and broaden the service

coverage of existing communication infrastructure, additional floating cellular BS towers, i.e., 4G and 5G, as well as floating broadcast towers, will be deployed. Network convergence can be regarded as an opportunity of the renaissance of MagicNet. Taking advantage of the powerful broadcast capacity, the maritime broadcast networks can help to provide distributed bandwidth demanding multimedia services on the ocean. In addition, the traffic of common multimedia requirements and public information services in cellular networks can be also offloaded to the broadcast networks, which can greatly improve the overall system capacity and resource efficiency of channel and spectrum.

So far, several digital television broadcast standards have been adopted all over the world. For instance, DVB in Europe has become one of the most widely used digital television broadcast standards, and it has evolved into DVB-H (handheld), DVB-T/T2 (terrestrial), DVB-S/S2 (satellite), DVB-C (cable), and DVB-NGH (Next-Generation Digital Broadcasting). Integrated Service Digital Broadcasting (ISDB) was set by Digital Broadcasting Experts Group of Japan, which also has its different versions for terrestrial, satellite, and cable scenarios. Advanced Television Systems Committee (ATSC) adopted in America was first approved in 1995. Then in 2018, the next generation digital terrestrial broadcast system ATSC 3.0 was published, which promises a higher audio and video quality, improved compression efficiency and robust transmission on both fixed and mobile terminals. In China, Digital Television/Terrestrial Multimedia Broadcasting (DTMB) system was adopted as the national standard, and its advanced version (DTMB-A) was accepted by International Telecommunication Union in 2019[42, 43]. By introducing the state-of-art technologies in wireless digital communications, DTMB can achieve higher

Table 1   Convergence of digital terrestrial television standards and cellular broadband standards.

DTT standard	Cellular standard	Typical study	Key technology	Scenario
DVB-T/T2	GPRS	[15] (2001), [16] (2004), [17, 18] (2005)	- Architecture design	- Traditional TV broadcasting
	UMTS	[19, 20] (2002), [21] (2004), [22] (2011)	- Spectrum management	- Interactive video
	LTE, LTE-A	[23, 24] (2016), [25] (2018), [26] (2020)	- Power control	broadcasting
DVB-H	GPRS	[27] (2005), [28] (2007)	- Interference control	- Converged information
	UMTS	[28, 29] (2007), [30] (2008)	- Signaling protocols	broadcasting
	LTE, LTE-A	[31] (2013)	- Beamforming	- Mobile TV
DVB-NGH	LTE, LTE-A	[32] (2011)	- Content analysis	- Content delivery
ISDB	LTE, LTE-A	[33] (2015), [34] (2018)	- Video caching	- Emergency service
ATSC 3.0	LTE-A	[35] (2018), [36] (2019), [37, 38] (2020)	- Video coding	- Seamless connection of
DTMB	LTE, LTE-A	[9] (2008), [39] (2012), [40] (2014), [41] (2019)	- ⋯	various multimedia - ⋯

spectrum efficiency, stronger anti-multipath-interference, and better channel estimation.

All these broadcast network standards have the potential to converge with cellular networks from 2G to 5G, i.e., General Packet Radio Service (GPRS, 2G), Universal Mobile Telecommunications System (UMTS, 3G), Long Term Evolution (LTE, 3G), and LTE-Advanced (LTE-A, 4G). As summarized in Table 1, many hybrid or converged systems composed by Digital Terrestrial Television (DTT) standards and cellular broadband standards were proposed to enable interactive broadcast services. Such convergence architecture can be also introduced to the broadcast-and-cellular-networks-coexistent MagicNets. As shown in Fig. 2a, a typical converged maritime broadcast and cellular system can be realized by operated the SDN-based MagicNets formulated in Section 2. In this architecture, the floating cellular BS towers will provide interactive communication links between maritime users and the network through the unicast transmission mode, which will serve users with personalized contents. On the other hand, the broadcast towers, especially fixed on shores or islands with enough heights, are responsible for broadcasting or unicasting the popular or common multimedia contents, and the public service information such as the maritime weather forecast. In addition, the distributed cooperative and intelligent controllers will receive contents from different servers including multimedia servers, cloud or fog servers, etc. These contents will be analyzed at distributed controllers, and then separated into common and personalized parts,

depending on which the controllers will dispatch these contents to the corresponding users through broadcast and cellular networks, respectively.

3.2 Maritime 5G broadcast networks in MagicNet

Different from the terrestrial broadcast networks with much wider coverage than cellular networks, the coverage scale of floating broadcast towers is quite similar to that of cellular BS towers. In addition, considering the limited infrastructure resource and high deployment cost on the ocean, adding multicast and broadcasting support in cellular standards can be expected as an enhanced solution for maritime broadband services.

3.2.1 MBMS in WCDMA

Multimedia Broadcast Multicast Service (MBMS) launched in 2002 was proposed by the Third Generation Partnership Project (3GPP) 6 Release. To support MBMS, a Broadcast Multicast Service Center (BM-SC) was added in the traditional Wideband Code Division Multiple Access (WCDMA) and WCDMA2000 systems, the purposed of which is to support the special interface functions, channels, physical layer processing, and service such as subscription in MBMS. Moreover, three new logical channels, i.e., an MBMS Point-To-Multipoint (PTM) Control Channel (MCCH) for downlink control information, an MBMS PTM traffic channel (MTCH) carrying the actual application data, and an MBMS PTM Scheduling Channel (MSCH) for data scheduling on MTCH, and a physical channel, named MBMS notification Indicator Channel (MICH),
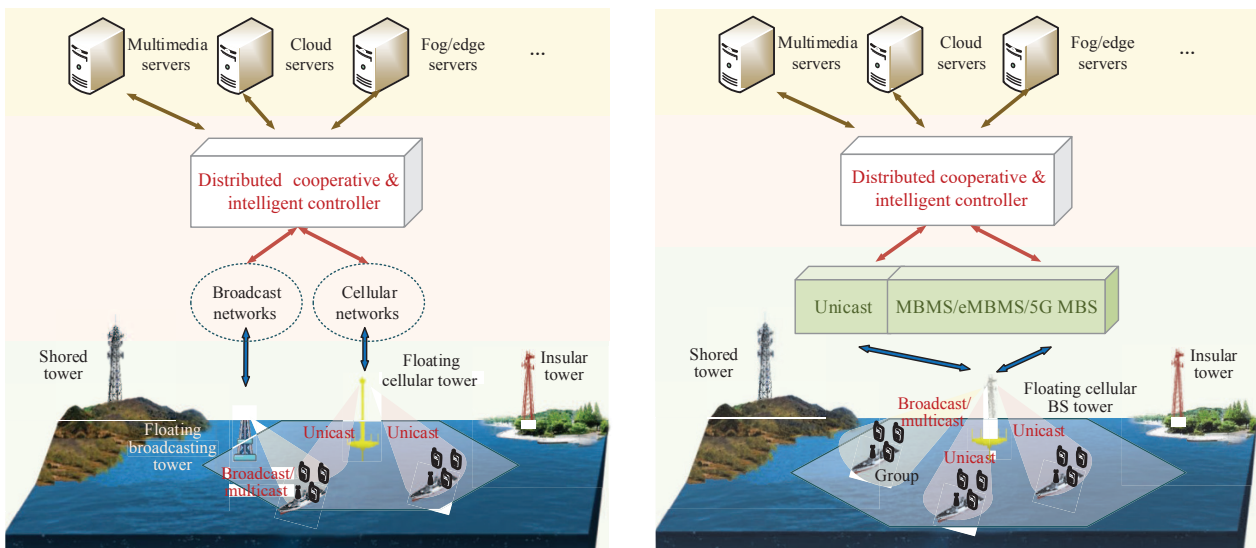
(a) Convergence of maritime broadcast and cellular networks.

(b) Maritime 5G broadcast networks in the MagicNet.

Fig. 2   Convergence of broadcast/multicast and broadband for maritime services.

were also implemented in WCDMA. According these implementations above in WCDMA, MBMS can be regarded as a function expansion of 3G systems.

3.2.2   eMBMS in LTE

To further support the increasing differentiated, customized, and rich services, the LTE-based enhanced-MBMS (eMBMS) was defined in 3GPP Release 14. By introducing a new Multicast Channel (MCH) besides the two reserved logical channels, i.e., MCCH and MTCH, the eMBMS can also realize a synchronous MBMS among different cells, in the content of a full broadcast coverage in each cell.

3.2.3   Multicast/broadcast services in 5G NR

In Release 15, 5G NR and the Next Generation Radio Access Network (RAN) were defined as new radio access technologies in the 5G network architecture[44, 45]. However, Release 15 and Release 16 only defined the Point-To-Point (PTP) unicast communications. To bring the advantages of broadcast/multicast and PTM transmission into full play, it is essential for Release 17 to specify the basic RAN functionalities for the support of broadcast and multicast transmission in NR[46]. Through the 5G NR Multicast/Broadcast Services (MBS), new interactive video broadcasting services can be received by all kinds of smart devices, no longer limited to TV, with a good signal coverage at anytime and anywhere.

Comparing to the convergence architecture introduced in Section 3.1, the 5G RAN architecture realizes a seamless integration of broadcast/multicasts functionalities into the cellular broadband network, which requires few updates to the network standards and protocols. In addition, based on the NR unicast, 5G MBS can be received by the regular 5G user equipment without any hardware alteration. Moreover, the eMBB, URLLC, and mMTC promised by the 5G network can satisfy the increasing maritime communications requirements. Therefore, it is significant to introduce the 5G RAN architecture for the MagicNet. Through the 5G NR enabled floating towers, as shown in Fig. 2b, a flexible switch among unicast, multicast, and broadcast can be achieved to serve various scenarios including hotspot and moving maritime 5G users.

3.3   Correlated maritime contents service

3.3.1   Fully correlated contents transmission

Investigate results of many studies show that only a relatively small percentage of content is requested frequently by a large number of users. Such phenomenon

in terrestrial communications also exists in the MagicNet, especially for the spare but clustering distributed users on the ocean. To be specific, many groups of users in different cruises or workers on distributed offshore drilling platforms might be watching the same live sport or famous variety program such as Spring Festival Gala on their smart mobile phones. Meanwhile, some different groups of users sharing the common interest may prefer to watch a popular webcast drama. For such scenario, the optimal service mode is to divide these users into different groups according to their interests or required contents and serve these user groups through broadcast and multicast transmission. Comparing with the unicast transmission, which deliver the same content separately to each user equipment through a dedicated channel, such broadcast/multicast mode can obtain an improved spectrum efficiency and system capacity. On the other hand, other users with special information requests or personalized information of feedbacks will be served through the unicast mode.

3.3.2   Partially correlated contents transmission

Different from the fully correlated contents transmission, some transmitted maritime information or service contents are partially correlated. For instance, the maritime public service information, such as the marine shipping information for passengers, including the speed, estimated time of sailing, position coordinates, and weather, can be displayed during playing on-line videos. Such services are quite similar to the flight information services experienced through airborne multimedia facilities on civil aircrafts. The maritime users might watch different multimedia contents they request, while receive the common public service information imbedded in these contents. For this kind of service, the common information should be broadcast, meanwhile the different multimedia contents for users are transmitted through the unicast mode.

Another case of partially correlated contents transmission is resulting from different types of uses' terminals. For example, the onboard multimedia facilities can provide a higher resolution of videos than mobile phones and tablets. Due to this facility diversity or users' personal preference, users might receive the same content with different qualities. For this situation, H.264 Scalable Video Coding (SVC) can be employed for video division: the basic-quality video can be broadcast, and the enhanced layer storing high-quality details will be unicast if requested[47].

3.4 Challenges and open issues

There are still many challenges in resource allocation, spectrum sharing and management, and physical layer convergence to realize a flexible and efficient switch or integration of unicast, multicast, and broadcast. In addition, it is still difficult to design a synchronization mechanism among potential broadcast receivers and then implement a configurable broadcasting transmission, since that the common contents might be requested from different users at any time. Moreover, considering the correlation of contents, content analysis, content-based transmission, and caching technologies also play important roles to achieve efficient and high-quality multimedia services on the ocean.

4 Integrated Broadband and Broadcast in Marine Sensing and Maritime Monitoring

In Section 3, we introduced the convergence architecture and techniques of broadcast/multicast and broadband for maritime communication services. Taking advantage of such integrated functionality transmission mode, an all-coverage maritime monitoring and marine sensing can be further realized, and the MagicNet will perform as an all-seeing eye on the high seas. Next, we will introduce some feasible applications and key technologies of digital television and broadcasting in OoT, Internet of Vessels (IoV), and maritime passive radars.

4.1 MBMS enabled ocean of things

Maritime Internet of Things, or called OoT[48], is deployed to enable a persistent marine and maritime situation awareness over extensive sea areas through millions of low-cost and intelligent floating or/and underwater sensors. These sensors are operated to collect the information of marine environment including the water temperature, salinity, density, suspended sand size, and some activity information about marine animals and other moving objects. With the rapid development of marine industry, the future OoT will not only require low-latency and low-payload Machine Type Communications (MTC), but is also expected to support the growing applications with multimedia data traffic. Additionally, to adapt to the typical use case of mMTC in the MagicNet, the PTM technology plays an important role in the massive OoT in the downlink direction. To be specific, PTM allows the simultaneous transmission to a infinite number of sensors in the OoT, which has

a significant meaning in the radio resource limited MagicNet.

4.1.1 Group based paging strategy and data delivery

As discussed in Section 3.2, eMBMS was original designed for DTT services. It is also regarded as an important enabler for OoT communications considering its PTM capacity. However, similar to the applications of MBMS in the Internet of Things (IoT)[49, 50], it also needs some simplifications when applied in the OoT. To be specific, not all OoT sensor nodes are expected to support the full MBMS protocol, especially for nodes with limited capacities of data processing, energy, and storage. In addition, to realize a low-power operation, sensor nodes perform Power Saving Mode (PSM) or Discontinuous Reception (DRX) to save power, and usually power down most of their circuitries when turn their idle mode on. As a result, the service announcement and sensor node notification over the MBMS should be modified. The authors of Ref. [51] proposed a paging strategy for MBMS service delivery specifically tailored to initially unplanned data delivery, which overcame this weakness of eMBMS when applied in the massive IoT. This modified strategy can be introduced to the MBMS enabled OoT to improve the efficiency of energy and latency. In the MBMS bearer and data delivery, the sensor nodes are paged by the floating cellular BSs according to *Standard Paging*, *Group Paging* and *Enhanced Group Paging*, which can ensure that only sensors in the list of OoT application service can receive the service information announcement. According to such paging mechanism, the reliability and stability of communications can be also improved[51].

4.1.2 Dedicated return channel utilization

The usage of Dedicated Return Channel (DRC), which has been defined in many existing DTT standards, introduces an opportunity for broadcast operators to conduct OoT applications and services independently, when uplink requests are far from frequent and extensive. For the downlink shown in Fig. 3, the broadcast service providers encode the multimedia data through the DTT gateway, and then send it to their maritime users. On the other hand, the OoT center sends the common signaling information including broadcast control information, DRC downlink Media Access Control Protocol Data Unit (MAC PDU) and uplink resource mapping information to the OoT sensor nodes through physical layer pipe in the gateway. For the
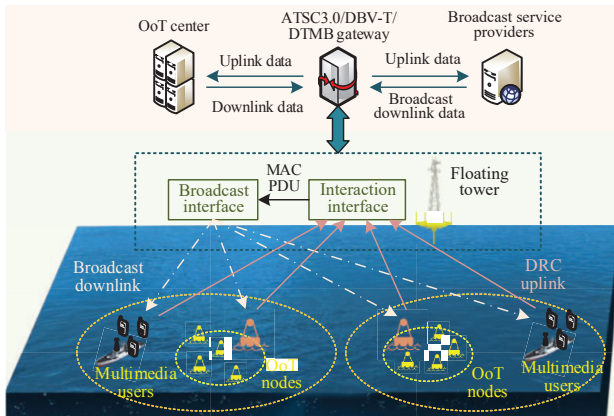
Fig. 3   Architecture of DRC-OoT in the MagicNet.

uplink, the data sent from OoT nodes and interactive data from DTT users will be delivered by the DRC, and then transmitted to the OoT center and broadcast service providers, respectively. However, the channel used to transmit the signaling information is usually limited with capacity. For instance, the spectrum resource in Physical Layer Pipe-R of ATSC 3.0 is insufficient for signaling information transmission[52]. Therefore, a DRC-OoT resource scheduling mechanism which considers the uplink and downlink jointly should be designed to avoid data congestion.

4.2   Broadband and broadcast services for internet of vessels

The Internet of Vessels (IoV) is a special industry application of OoT. This specificity is embodied in delicate and complex information exchange, multiparty cooperation, high requirement of low-latency, and safety issues[53]. Recently, various shipping service systems and standards have been proposed for IoV communications and management. A typical automated and intelligent vessel self-reporting system, known as the Automatic Identification System (AIS), was developed to enable intelligent vessel traffic services, including intelligent maritime navigation, collision avoidance, traffic monitoring, and identification[54]. With the rapid growing transmission requirements of maritime data, the AIS has to undertake a lot of ship-shore data exchange, which leads to severe traffic congestion and data jamming. Then the Very High Frequency (VHF) Data Exchange System (VDES), which can be considered the updating and enhanced version of AIS, was proposed to overcome the shortcomings of AIS by introducing additional spectrum and enabling a robust and efficient digital transmission at a much higher rate

than the AIS[55].

On the other hand, similar to the terrestrial Internet of vehicles[56], the IoV scenario involves communications among multi-party in the MagicNet, i.e., vessel-to-vessel, vessel-to-infrastructure, and vessel-to-network. It is necessary to deliver some special data packets transmitted in these communications, such as real-time videos collected by vessels, results of collision judgements, and traffic or routing information, to neighbor or relevant networks and vessels in the MagicNet. In allusion to this transport needs, maritime broadcast networks and broadcast-enabled cellular broadband networks become better candidates with more efficient transmission and higher quality of services than the PTP transmission[57].

4.3   Digital broadcasting based maritime passive radar

In the past decades, radars have been used to detect objects in the air or at sea, and the Over-The-Horizon (OTH) radar technologies have attracted a lot of research interest since its significant detection coverage. However, relying on high-power radar emitters, current radars detecting for sea are all deployed on shore or islands, which greatly discount the detection coverage for objects over the sea. Especially for the high sea, the target detection is mainly implemented by satellites, which can hardly achieve the all-hour, all-weather, and all-sea area monitoring. Such bottleneck can be well solved by the MagicNet, the floating towers in which can provide platforms and energy for radar emitters. Then the capacity and coverage of maritime monitoring can be largely expanded to all-sea area. Nevertheless, the limited space and energy supply on the floating towers still restrict the deployment of radar emitters. To address this problem and take full advantage of existing facilities on the floating towers, the digital broadcasting TV signals become alternative emitters for detection.

The introduction of digital broadcasting such as DVB-T, ATSC, and DTMB is not new to terrestrial passive radars[58–60]. Considering the form of Orthogonal Frequency Division Multiplexing (OFDM) used in DVB and DTMB systems, their transmitting signals are very close to random and wideband, which provides an excellent ambiguity function. In addition, resulting from the enough bandwidth and long coherent integration time, the Doppler resolution performance of digital broadcasting signals is also sufficient when it is operated for target detecting. Consequently, the floating broadcast

towers and broadcast-enabled floating cellular BS towers are very suitable to act as illuminators of opportunity in passive bistatic radar systems.

The main challenges and key technologies of digital broadcast based passive radars include waveform design, reference signal acquisition and reconstruction, multi-path clutter rejection, target detection, tracking and fusion, and real-time signal processing. Many researches have focused on these problems specifically in the terrestrial or shored passive radar systems, based on the existing DTT standards, as summarized in Table 2. Besides, due to the distributed deployment of floating towers over the sea, an optimal networking configuration can help to further extend the monitoring coverage and improve the detection precision. In addition, considering different propagation properties and coverage capacities, the comprehensive utilization of multiple bands holds a great potential for improving detectability. Furthermore, the channel characteristics over the high sea is rather different from that of terrestrial and short-sea areas. For instance, the environment characteristics of evaporation might have different effects on waveform design, interference rejection, etc., when introducing broadcast networks deployed over the high sea.

5 Conclusion

The broadband and multimedia data traffic is experiencing a dramatic increasing with the rapid development of maritime activities. Considering the huge coverage and spare but clustering user distributions on the vast ocean area, the convergence of broadcast/multicast and broadband is expected as a possible solution for supporting the growing maritime communication services and some other multimedia applications such as the OoT, IoV, and marine

monitoring in maritime information networks. Such multi-functionality and multi-service systems require a flexible and on-demand networking architecture and technologies. In this study, an SDN-based three-layered architecture of MagicNet has been proposed to realize a flexible switch and selection among unicast, broadcast, and multicast transmission modes for a large range of maritime information services and applications. Considering different communication infrastructure equipped on the shored, insular, and floating towers, as well as their variety of coverage and service capacities, different convergence schemes of broadcast networks and cellular networks were illustrated especially for maritime communication services. This study introduced some classic terrestrial integration technologies of DTT standards and cellular standards from 2G to 4G, and the 5G NR technology was also concerned at high-level without touching the physical transmission technologies, when designing the converged system for the MagicNet. Finally, we introduced some marine sensing and maritime monitoring applications which can take advantage of the proposed integrated functionality transmission mode, such as the OoT, IoV, and maritime passive radars systems especially deployed over the high sea.

This study focused on the emerging technologies and main challenges in the convergence of broadcast/multicast and broadband for MagicNets, as well as its networking solutions for efficient and on-demand maritime information services, including broadband communications and all-coverage monitoring. Furthermore, with the rapid development of maritime activities and industries, there are still many other challenges, such as the antenna design of maritime giant-cell BSs and broadcast tower, artificial intelligent and

Table 2 Digital broadcasting based passive radars in the literature.

DTT standard	Reference	Carrier frequency	Issue	Optimized performance
DVB-T	[58], 2020	UHF	Waveform design	Interference cancellation, target signature extraction
	[61], 2020	UHF	Radar image formation	Azimuth resolution, sidelobe reduction
	[62], 2018	VHF	Frequency/time offset estimation	Reductions of the Doppler sidelobes and interference
ATSC	[59], 2020	UHF	Optimal emitter maps, Cramer-Rao lower bound	Range and velocity measurement accuracy
	[63], 2018	UHF/VHF	Illuminator selection, networking configuration	Localization capability
	[64], 2015	UHF	Spatial cancelling of cochannel interference	Predicted coverage
DTMB	[60], 2020	UHF	Reference signal reconstruction, channel estimation	Target SNR improvement, reconstructed signal accuricy
	[65], 2020	VHF	Pseudorandom noise construction	Target SNR improvement
	[66], 2019	UHF	Interference elimination, multipath clutter rejection	Target SNR improvement, interfering peaks reduction

ubiquitous intelligent edge aided maritime information services, the further convergence with underwater swarm-intelligent networks, etc.

Acknowledgment

References

[1] Z. Q. Zhang, Y. Xiao, Z. Ma, M. Xiao, Z. G. Ding, X. F. Lei, G. K. Karagiannidis, and P. Z. Fan, 6G wireless networks: Vision, requirements, architecture, and key technologies, *IEEE Veh. Technol. Mag.*, vol. 14, no. 3, pp. 28–41, 2019.

[2] J. Du, C. X. Jiang, J. Wang, Y. Ren, and M. Debbah, Machine learning for 6G wireless networks: Carrying forward enhanced bandwidth, massive access, and ultrareliable/low-latency, *IEEE Veh. Technol. Mag.*, vol. 15, no. 4, pp. 123–134, 2020.

[3] F. B. Teixeira, T. Oliveira, M. Lopes, C. Leocádio, P. Salazar, J. Ruela, R. Campos, and M. Ricardo, Enabling broadband internet access offshore using tethered balloons: The BLUECOM+ experience, presented at OCEANS 2017-Aberdeen, Aberdeen, UK, 2017, pp. 1–7.

[4] T. T. Liu, J. Li, F. Shu, M. X. Tao, W. Chen, and Z. Han, Design of contract-based trading mechanism for a small-cell caching system, *IEEE Trans. Wirel. Commun.*, vol. 16, no. 10, pp. 6602–6617, 2017.

[5] J. Du, C. X. Jiang, E. Gelenbe, H. J. Zhang, Y. Ren, and T. Q. S. Quek, Double auction mechanism design for video caching in heterogeneous ultra-dense networks, *IEEE Trans. Wirel. Commun.*, vol. 18, no. 3, pp. 1669–1683, 2019.

[6] M. Abdollahvand, K. Forooraghi, J. A. Encinar, Z. Atlasbaf, and E. Martinez-de-Rioja, A 20/30 GHz reflectarray backed by FSS for shared aperture Ku/Ka-band satellite communication antennas, *IEEE Antennas Wirel. Propag. Lett.*, vol. 19, no. 4, pp. 566–570, 2020.

[7] R. Y. Duan, J. J. Wang, J. Du, Y. L. Wang, Y. Shen, and Y. Ren, New marine information network for realizing all-coverage over sea, (in Chinese), *J. Commun.*, doi: 10.11959/j.issn.1000-436x.2019051, 2019.

[8] K. Rapetswa and L. Cheng, Convergence of mobile broadband and broadcast services: A cognitive radio sensing and sharing perspective, *Intelligent and Converged Networks*, vol. 1, no. 1, pp. 99–114, 2020.

[9] Z. S. Niu, L. Long, J. Song, and C. Y. Pan, A new paradigm for mobile multimedia broadcasting based on integrated communication and broadcast networks, *IEEE Commun. Mag.*, vol. 46, no. 7, pp. 126–132, 2008.

[10] J. Song, J. Liu, Y. Zhang, S. Zhou, and C. Y. Pan, Energy efficient broadcast radius optimization in cellular networks, in *Proc. 2014 IEEE 11th Consumer Communications and Networking Conf.* (*CCNC*), Las Vegas, NV, USA, 2014, p. 14485212.

[11] M. A. Bouras, F. Farha, and H. S. Ning, Convergence of computing, communication, and caching in internet of things, *Intelligent and Converged Networks*, vol. 1, no. 1, pp. 18–36, 2020.

[12] Z. G. Shu and T. Taleb, A novel QoS framework for network slicing in 5G and beyond networks based on SDN and NFV, *IEEE Netw.*, vol. 34, no. 3, pp. 256–263, 2020.

[13] J. Du, E. Gelenbe, C. X. Jiang, H. J. Zhang, and Y. Ren, Contract design for traffic offloading and resource allocation in heterogeneous ultra-dense networks, *IEEE J. Sel. Areas Commun.*, vol. 35, no. 11, pp. 2457–2467, 2017.

[14] D. Zhou, S. Gao, R. Q. Liu, F. F. Gao, and M. Guizani, Overview of development and regulatory aspects of high altitude platform system, *Intelligent and Converged Networks*, vol. 1, no. 1, pp. 58–78, 2020.

[15] C. Rauch, W. Kellerer, and P. Sties, Hybrid mobile interactive services combining DVB-T and GPRS, in *Proc. EPMCC 2001, 4th European Personal Mobile Communications Conf.*, Vienna, Austria, 2001.

[16] G. Gardikis, A. Kourtis, and P. Constantinou, Modelling TCP performance in mobile DVB-T receivers, *WSEAS Trans. Commun.*, vol. 3, no. 2, pp. 632–635, 2004.

[17] D. Kouis, D. Loukatos, K. Kontovasilis, G. Kormentzas, and C. Skianis, On the effectiveness of DVB-T for the support of IP-based services in heterogeneous wireless networks, *Comput. Netw.*, vol. 48, no. 1, pp. 57–73, 2005.

[18] G. Gardikis, G. Kormentzas, G. Xilouris, H. Koumaras, and A. Kourtis, Broadband data access over hybrid DVB-T networks, in *Proc. Conf. Heterogeneous Networks* (*HETNETs*), Ilkley, UK, 2005.

[19] J. Cosmas, T. Itagaki, L. Cruickshank, L. Zheng, K. Krishnapillai, A. Lucas, and L. Elgohari, System concept of a novel converging DVB-T and UMTS mobile system, in *Proc. London Communications Symp.*, London, UK, 2002.

[20] C. Hamacher, Required guard bands for co-operation of DVB-T and UMTS, in *Proc. 13th IEEE Int. Symp. Personal, Indoor and Mobile Radio Communications*, Pavilhao Altantico, Portugal, 2002, pp. 1550–1554.

[21] B. Heidkamp, A. Pohl, U. Schiek, F. Klinkenberg, J. Hynynen, A. Sieber, P. Christ, T. Owens, J. Cosmas, T. Itagaki, et al., Demonstrating the feasibility of standardised application programme interfaces that will allow mobile/portable terminals to receive services combining UMTS and DVB-T, *Int. J. Services Standards*, vol. 1, no. 2, pp. 228–242, 2004.

[22] C. Y. Ho, W. S. Chan, Y. Y. Lin, and T. H. Lin, A quadrature bandpass continuous-time delta-sigma modulator for a tri-mode GSM-EDGE/UMTS/DVB-T receiver, *IEEE J. Solid-State Circuits*, vol. 46, no. 11, pp. 2571–2582, 2011.

[23] L. Polak, O. Kaller, L. Klozar, M. Slanina, J. Sebesta, and T. Kratochvil, Coexistence between DVB-T/T2 and LTE standards in common frequency bands, *Wirel. Pers. Commun.*, vol. 88, no. 3, pp. 669–684, 2016.

[24] M. Denkovska, P. Latkoski, and L. Gavrilovska, Optimization of spectrum usage and coexistence analysis of DVB-T and LTE-800 systems, *Wirel. Pers. Commun.*, vol. 87, no. 3, pp. 713–730, 2016.

[25] L. Polak, D. Kresta, J. Milos, T. Kratochvil, and R. Marsalek, Coexistence of DVB-T2 and LTE in the 800 MHz band: analysis of DVB-T2 system configurations, in *Proc. 2018 IEEE Int. Symp. Broadband Multimedia Systems and Broadcasting (BMSB)*, Valencia, Spain, 2018, pp. 1–5.

[26] G. Ancans, E. Stankevicius, V. Bobrovs, and G. Ivanovs, Estimation of electromagnetic compatibility between DVB-T/DVB-T2 and 4G/5G in the 700 MHz band for co-channel case, *Latvian J. Physics Tech. Sci.*, vol. 57, no. 5, pp. 30–38, 2020.

[27] J. Yao, W. F. Huang, and M. S. Chen, IP datacasting and channel error handling with DVB-H, in *Proc. Conf. Emerging Information Technology 2005*, Taipei, China, 2005.

[28] P. Leroux, V. Verstraete, F. De Turck, and P. Demeester, Synchronized interactive services for mobile devices over IPDC/DVB-H and UMTS, in *Proc. 2007 2nd IEEE/IFIP Int. Workshop on Broadband Convergence Networks*, Munich, Germany, 2007, pp. 1–12.

[29] N. Vulic, S. H. de Groot, and I. G. M. M. Niemegeers, DVB-H-UMTS integration at radio access level, in *Proc. 2007 IEEE 65th Vehicular Technology Conf.-VTC2007-Spring*, Dublin, Ireland, 2007, pp. 1250–1254.

[30] X. D. Yang and T. J. Owens, Intersystem soft handover for converged DVB-H and UMTS networks, *IEEE Trans. Veh. Technol.*, vol. 57, no. 3, pp. 1887–1898, 2008.

[31] A. A. Razzac, S. E. Elayoubi, T. Chahed, and B. El Hassan, Planning of mobile TV service in standalone and cooperative DVB-NGH and LTE networks, in *Proc. 2013 11th Int. Symp. and Workshops on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt)*, Tsukuba Science City, Japan, 2013.

[32] F. Foroughi, J. Lofgren, and O. Edfors, Channel estimation for a mobile terminal in a multi-standard environment (LTE and DVB-H), in *Proc. 2009 3rd Int. Conf. on Signal Processing and Communication Systems*, Omaha, NE, USA, 2011, p. 39.

[33] D. M. Okamoto, L. A. R. da Silva Mello, and M. P. C. de Almeida, Analysis of the interference from LTE system in ISDB-TB digital TV system at 700 MHz, in *Proc. 2015 SBMO/IEEE MTT-S Int. Microwave and Optoelectronics Conf. (IMOC)*, Porto de Galinhas, Brazil, 2015.

[34] C. A. Makluf, J. León, and Y. Iano, Digital TV (ISDB-TB) broadcasting over LTE broadcast: A feasibility study, in *Proc. 3rd Brazilian Technology Symp.*, Campinas, Brazil, 2018, pp. 145–155.

[35] M. Fuentes, D. Mi, H. Z. Chen, E. Garro, J. L. Carcel, D. Vargas, B. Mouhouche, and D. Gomez-Barquero, Physical layer performance evaluation of LTE-advanced pro broadcast and ATSC 3.0 systems, *IEEE Trans. Broadcast.*, vol. 65, no. 3, pp. 477–488, 2019.

[36] J. Y. Lee, S. I. Park, H. J. Yim, B. M. Lim, S. Kwon, S. Ahn, N. Hur, and H. M. Kim, ATSC 3.0 and LTE cooperation for LDM and SHVC based mobile broadcasting, in *Proc.*

[37] *2019 IEEE Int. Symp. on Broadband Multimedia Systems and Broadcasting (BMSB)*, Jeju, South Korea, 2019. J. Y. Lee, S. I. Park, H. J. Yim, B. M. Lim, S. Kwon, S. Ahn, and N. Hur, IP-based cooperative services using ATSC 3.0 broadcast and broadband, *IEEE Trans. Broadcast.*, vol. 66, no. 2, pp. 440–448, 2020.

[38] J. Montalban, G. M. Muntean, and P. Angueira, A utility-based framework for performance and energy-aware convergence in 5G heterogeneous network environments, *IEEE Trans. Broadcast.*, vol. 66, no. 2, pp. 589–599, 2020.

[39] X. Y. Xu, D. X. Meng, Y. M. Chen, and J. W. He, Compatability study on broadcasting system interfering with LTE system, in *Proc. 2012 IEEE 2nd Int. Conf. Cloud Computing and Intelligence Systems*, Hangzhou, China, 2012, pp. 908–912.

[40] L. F. Huang, X. L. Yang, Z. Y. Shi, T. Yuliang, X. Su, and J. Zeng, Analysis of coexistence between the DTMB system and TD-LTE system, in *Proc. 2014 Tenth Int. Conf. on Intelligent Information Hiding and Multimedia Signal Processing*, Kitakyushu, Japan, 2014, pp. 932–937.

[41] J. Chen and M. Li, Coexistence analysis between eMTC and LTER/broadcasting service system in 450MHz-470MHz band, in *Int. Conf. Inform. Commun. Signal Process. (ICICSP)*, Weihai, China, 2019, pp. 15–19.

[42] J. Song, Z. X. Yang, L. Yang, K. Gong, C. Y. Pan, J. Wang, and Y. S. Wu, Technical review on Chinese digital terrestrial television broadcasting standard and measurements on some working modes, *IEEE Trans. Broadcast.*, vol. 53, no. 1, pp. 1–7, 2007.

[43] J. Song, C. Zhang, K. W. Peng, J. T. Wang, C. Y. Pan, F. Yang, J. Wang, H. Yang, Y. L. Xue, Y. Zhang, et al., Key technologies and measurements for DTMB-A system, *IEEE Trans. Broadcast.*, vol. 65, no. 1, pp. 53–64, 2019.

[44] J. J. Gimenez, J. L. Carcel, M. Fuentes, E. Garro, S. Elliott, D. Vargas, C. Menzel, and D. Gomez-Barquero, 5G new radio for terrestrial broadcast: A forward-looking approach for NR-MBMS, *IEEE Trans. Broadcast.*, vol. 65, no. 2, pp. 356–368, 2019.

[45] M. Säily, C. B. Estevan, J. J. Gimenez, F. Tesema, W. Guo, D. Gomez-Barquero, and D. Mi, 5G radio access network architecture for terrestrial broadcast services, *IEEE Trans. Broadcast.*, vol. 66, no. 2, pp. 404–415, 2020.

[46] *Study on Architectural Enhancements for 5G Multicast-Broadcast Services (Release 17)*, v0.3.0, 3GPP, Rep. TR 23. 757, 2020.

[47] Q. T. Zhang, J. Y. Chen, and H. B. Zhu, Network convergence: Theory, architectures, and applications, *IEEE Wirel. Commun.*, vol. 21, no. 6, pp. 48–53, 2014.

[48] J. Waterston, J. Rhea, S. Peterson, L. Bolick, J. Ayers, and J. Ellen, Ocean of things: Affordable maritime sensors with scalable analysis, in *Proc. OCEANS 2019-Marseille*, Marseille, France, 2019.

[49] *MBMS for Internet of Things (IoT)*, 3GPP TR 26.850, 2018.

[50] X. R. Fan, H. Ding, Y. Y. Zhang, W. Trappe, Z. Han, and R. Howard, Distributed beamforming based wireless power transfer: analysis and realization, *Tsinghua Science and Technology*, vol. 25, no. 6, pp. 758–775, 2020.

[51] O. Vikhrova, S. Pizzi, A. Iera, A. Molinaro, K. Samuylov,

and G. Araniti, Performance analysis of paging strategies and data delivery approaches for supporting group-oriented IoT traffic in 5G networks, in *Proc. 2019 IEEE Int. Symp. Broadband Multimedia Systems and Broadcasting* (*BMSB*), Jeju, South Korea, 2019, pp. 1–5.

[52] K. K. Wang, D. Z. He, Y. Xu, R. B. Cai, W, J. Zhang, and Y. Jian, IoT resource scheduling based on dedicated return channel in ATSC 3.0, in *Proc. 2019 IEEE Int. Symp. Broadband Multimedia Systems and Broadcasting* (*BMSB*), Jeju, South Korea, 2019.

[53] S. Aslam, M. P. Michaelides, and H. Herodotou, Internet of ships: A survey on architectures, emerging applications, and challenges, *IEEE Internet Things J.*, vol. 7, no. 10, pp. 9714–9727, 2020.

[54] R. W. Liu, J. T. Nie, S. Garg, Z. H. Xiong, Y. Zhang, and M. S. Hossain, Data-driven trajectory quality improvement for promoting intelligent vessel traffic services in 6G-enabled maritime IoT systems, *IEEE Internet Things J.*, doi: 10.1109/JIOT.2020.3028743, 2020.

[55] I. Gómez, F. Valdés, B. Ares, J. Taibo, J. M. Ei Malek, and N. Alagha, Field trials of the VHF data exchange system (VDES) satellite downlink component, in *Proc. Int. Communications Satellite Systems Conf.* (*ICSSC*), Niagara Falls, Canada, 2018, pp. 1–8.

[56] M. K. Shi, Y. Zhang, D. Y. Yao, and C. Lu, Application-oriented performance comparison of 802.11p and LTE-V in a V2V communication system, *Tsinghua Science and Technology*, vol. 24, no. 2, pp. 123–133, 2019.

[57] L. Zhang, Y. Y. Wu, W. Li, K. Salehian, S. Lafleche, X. B. Wang, S. I. Park, H. M. Kim, J. Y. Lee, N. Hur, et al., Layered-division multiplexing: An enabling technology for multicast/broadcast service delivery in 5G, *IEEE Commun. Mag.*, vol. 56, no. 3, pp. 82–90, 2018.

[58] F. Colone, DVB-T based passive forward scatter radar: inherent limitations and enabling solutions, *IEEE Trans. Aerosp. Electron. Syst.*, doi: 10.1109/TAES.2020.3035435, 2020.

[59] M. Alslaimy, R. J. Burkholder, and G. E. Smith, SINR modeling for evaluating the CRLB for ATSC signal based passive radar systems, in *Proc. 2020 IEEE Int. Radar Conf.* (*RADAR*), Washington, DC, USA, 2020, p. 19688656.

[60] X. Zhang, J. X. Yi, X. R. Wan, and Y. Q. Liu, Reference signal reconstruction under oversampling for DTMB-based passive radar, *IEEE Access*, vol. 8, pp. 74024–74038, 2020.

[61] Y. Fang, G. Atkinson, A. Sayin, J. Chen, P. B. Wang, M. Antoniou, and M. Cherniakov, Improved passive SAR imaging with DVB-T transmissions, *IEEE Trans. Geosci. Remote Sens.*, vol. 58, no. 7, pp. 5066–5076, 2020.

[62] G. Bournaka, M. Ummenhofer, D. Cristallini, J. Palmer, and A. Summers, Experimental study for transmitter imperfections in DVB-T based passive radar, *IEEE Trans. Aerosp. Electron. Syst.*, vol. 54, no. 3, pp. 1341–1354, 2018.

[63] K. M. Scott, W. C. Barott, and B. Himed, Illuminator selection statistics using ATSC passive radar with a mobile receiver, in *Proc. 2018 IEEE Radar Conf.* (*RadarConf18*), Oklahoma City, OK, USA, 2018, p. 17842583.

[64] W. C. Barott and B. Himed, Cochannel interference in ATSC passive radar, in *Proc. 2015 IEEE Radar Conf.* (*RadarCon*), Arlington, VA, USA, 2015, p. 15240141.

[65] G. Fang, J. X. Yi, Y. P. Dan, X. R. Wan, and H. Y. Ke, PN signal as a new illuminator of opportunity for passive radar applications, *IEEE Geosci. Remote Sens. Lett.*, vol. 17, no. 1, pp. 67–71, 2020.

[66] M. Lü, J. X. Yi, X. R. Wan, and W. J. Zhan, Cochannel interference in DTMB-based passive radar, *IEEE Trans. Aerosp. Electron. Syst.*, vol. 55, no. 5, pp. 2138–2149, 2019.

Jian Song received the bachelor, and PhD degrees in electrical engineering from Tsinghua University, Beijing, China in 1990 and 1995, respectively. He was with the Chinese University of Hong Kong and the University of Waterloo, in 1996 and 1997, respectively. He worked for industry in the US for seven years. He joined the faculty team with Tsinghua University as a professor in 2005, where he is currently the director of the Tsinghua's DTV Technology Research and Development Center. His research interests include digital television terrestrial broadcasting, wireless communication, power line communication, and visible light communication. He has published over 290 peer-reviewed journal and conference papers in the above areas and one book in DTV area by Wiley, holds two US and over 70 Chinese patents. He was a recipient of the IEEE Scott Helt Memorial Award in 2015. He is the founding editor-in-chief of two academic journals of ITU, one is *ICT Discoveries* and the other is *Intelligent and Converged Networks*. He also serves as an editor of *IEEE Transactions on Broadcasting*. He is an the fellow of IET CIE, and CIC.

Jun Du received the BS degree in information and communication engineering from Beijing Institute of Technology, in 2009, and the MS and PhD degrees in information and communication engineering from Tsinghua University, in 2014 and 2018, respectively. From Oct. 2016 to Sep. 2017, she was a sponsored researcher, and she visited Imperial College London. Currently, she holds a postdoctoral position at the Department of Electrical Engineering, Tsinghua University. She has published more than 60 journal and conference papers. Her research interests are mainly in resource allocation and system security of heterogeneous networks and space-based information networks. She is the recipient of the Best Student Paper Award from IEEE GlobalSIP in 2015, the Best Paper Award from IEEE ICC 2019, and the Best Paper Award from IWCMC in 2020.

Yong Ren received the BS, MS, and PhD degrees in electronic engineering from Harbin Institute of Technology, China, in 1984, 1987, and 1994, respectively. He worked as a post doctor at the Department of Electronics Engineering, Tsinghua University, China from 1995 to 1997. Now he is a professor at the Department of Electronics Engineering, and the director of the Complexity Engineered Systems Lab (CESL) in Tsinghua University, and also the professor of Peng Cheng Laboratory, Shenzhen. He holds 60 patents, and has authored or co-authored more than 300 technical papers in the behavior of computer network, P2P network, and cognitive networks. He has serves as a reviewer of *IEICE Transactions on Communications*, *Digital Signal Processing*, *Chinese Physics Letters*, *Chinese Journal of Electronics*, *Chinese Journal of Computer Science & Technology*, *Chinese Journal of Aeronautics*, and so on. His current research interests include complex systems theory and its applications to the optimization and information sharing of the Internet, Internet of Things and ubiquitous network, cognitive networks, and cyber-physical systems.

Jintao Wang received the BEng and PhD degrees in electronic engineering from Tsinghua University, Beijing, China in 2001 and 2006, respectively. Since 2006, he has worked at the Department of Electronic Engineering, Tsinghua University. Now he is a full professor and PhD supervisor. He is the fellow of Chinese Institute of Electronics. He has published more than 150 journal and conference papers and holds more than 50 national invention patents. His current research interests include digital multimedia broadcasting, wireless broadband communication, visible light communication, and AI enhanced communication systems.