Maritime Internet of Things: Challenges and Solutions

Tingting Xia, Michael Mao Wang, Jingjing Zhang, and Lei Wang

Abstract

The concept of maritime IoT was originally developed by the United Nations' International Maritime Organization under the name e-Navigation for the harmonization and digitization of marine navigation information and operation, and supporting a broad variety of maritime services. As with any other IoT application, communication, in particular the MTC, is the key to the materialization of this concept. However, maritime MTC faces many practical challenges rooted in maritime environments, service requirements, and the radio spectrum. This article addresses these requirements and challenges as well as the solutions with a focus on the network architecture, air interface, and radio spectrum of such a unique communication system.

Introduction

The oceans cover more than 70 percent of the surface of the Earth, and maritime shipping accounts for more than 90 percent of world trade. In an effort to modernize the maritime information and communication infrastructure, the United Nations' International Maritime Organization put forward a maritime Internet of Things (IoT) concept, under the name e-Navigation [1]. As with any other IoT application, machine-type communication (MTC) is the key to maritime IoT due to the need for establishing the communication between vessels and shore as well as among vessels to support various types of maritime IoT services. Without it, maritime IoT will remain a mirage. As such, the International Association of Marine Aids to Navigation and Lighthouse Authorities has been leading the effort to establish a VHF Data Exchange System (VDES) to enable e-Navigation [2]. Nevertheless, maritime communication technologies have been severely lagging behind their land counterparts, and struggling to meet the challenging maritime MTC requirements. This article intends to fill this gap by pointing out the key challenges, and presenting a *conceptual* design of a maritime MTC system for VDES, focusing on network architecture, air interface, and radio spectrum.

Maritime IoT Services

MTC is a form of data communication that involves one or more entities that do not necessarily need human interaction or intervention; and maritime MTC is simply a type of MTC with a specific application in maritime IoT in which most of the use cases or services require little or no intervention of humans and to work even in the absence of human operators.

Examples of such maritime IoT services include search and rescue (SAR) in which an MTC device installed on SAR equipment enables communication between the equipment and the maritime rescue coordination center or the ships in the vicinity, providing precise location, weather conditions, and other information that helps the SAR operation. MTC also allows the rescue coordination center to poll ships in the vicinity to ask for their SAR capabilities in an automated manner. Evidently, this type of device should require minimum human intervention due to either a lack of knowledge or physical incapacitation.

An aids-to-navigation device (e.g., a buoy or lighthouse) may use a maritime MTC device to provide precision piloting to passing ships in areas such as dangerous coastlines and channels, and hazardous shoals and reefs. Similarly, via the maritime MTC network, maritime safety information services provide vessels with navigational warnings, meteorological forecasts, and hydrographic services, among other safety-related information.

In ship reporting, a ship periodically broadcasts its static and voyage related information such as the ship's identification, draught, vessel type, its intended destination, and estimated time of arrival, or dynamic information such as position, speed over ground, course over ground, and navigational status. This allows tracking and monitoring of vessels and maritime devices worldwide.

Container tracking allows for geo-locating a specific container aboard a cargo vessel, and even remotely monitoring the internal conditions. Real-time cargo tracking and tracing relying on maritime MTC have thus become vital for today's maritime service operators.

Autonomous shipping may be the ultimate way forward; route exchange, however, is the coveted and viable solution to vessel collision, in which ships in close proximity coordinate and optimize their routes autonomously so that close quarter situations can be predicted and avoided at an early stage.

Finally, maritime IoT is expected to play an essential role in meteorological and oceanographic information collection via maritime sensor networks for monitoring, studying, and protecting the marine environment.

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Requirements and Challenges

The fundamental role of maritime MTC is the provision of connectivity to various types of maritime IoT applications and services. This section summarizes the key requirements and challenges that such a maritime MTC system faces.

Ubiquitous Connectivity and Service Continuity

First and foremost, a maritime MTC system is required to provide ubiquitous connectivity between vessels and shore on a global scale, especially over open oceans including the most remote areas of the world like the Polar Regions, to ensure unbroken and consistent existence of maritime services. Currently, the presence of services in offshore settings is limited by lack of information and communication infrastructures. Moreover, the services have always been in a campus-style deployment; *cross-region* continuity of maritime service remains inconsistent and even absent. Ultimately, a global cooperative maritime IoT network is essential for the undisrupted services across organizational, regional, and national boundaries especially in times of crisis.

Traffic Nonuniformity

Despite its global nature, maritime traffic is highly unevenly distributed. Heavy traffic concentration is typical in ports, near-shore, and waterways. For instance, coastal shipping accounts for more than 50 percent of the total ship transport to and from the ports of the coastal countries, where the cargo vessels primarily follow the routes that are set close to the shore wherever possible. By contrast, traffic on the high seas is mainly from intercontinental transportation or deep sea shipping, and is relatively sparse in density. The maritime MTC network thus must have an efficient solution to cope with this type of traffic characteristics.

Service-Centricity

Differently from traditional mobile networks where services are built around the network architecture, the maritime MTC system must support the efficient provisioning, discovery and execution of various types of maritime application and service components distributed over the network in order to reap the full benefits of moving to maritime IoT.

As aforementioned, maritime IoT applications and services vary from simple periodic reporting to route exchange and remote control (e.g., autonomous shipping). As such, a maritime MTC system is not confined to a one-time design and deployment; it is expected to offer amorphous services that adapt to a wide variety of maritime IoT specific needs, and match changing demands. Hence, both network configuration and communication resources must be made flexible and adaptive to the specific service offered. Evidently, traditional maritime communication systems and designs that lack the architecture and protocols for dealing with diverse maritime applications and interworking with other networks (e.g., the Internet) is no longer up to the task or adequate for this requirement.

Device Heterogeneity

To serve a broad variety of maritime IoT applications, maritime MTC is required to support various types of MTC devices from the lower-end category with reduced functionality (e.g., cost and power-limited mass deployments like sensors and buoys) to the higher-end category with full functionality (e.g., large ships that encompasses a premises network with a plural of application clients/hosts). Therefore, this high degree of heterogeneity in communication capability, including hardware, power supplies, interoperability, and protocols, calls for an efficient system with the capability of absorbing the heterogeneity under a single unified framework.

Simplicity and Reliability

In contrast to most terrestrial systems, simplicity has been traditionally the overall system design criterion for maritime communication systems. It has to be taken into consideration as we strive to meet these goals and requirements since a simpler system is cheaper to manufacture and maintain, and typically more robust and reliable under complex marine environments. Indeed, reliability is of paramount importance to maritime systems, whereas low-cost is also an important factor that cannot be overlooked. To improve the safety of navigation, the maritime MTC system like VDES will ultimately be mandated on all ships. Therefore, low cost and free loyalty are essential to the selection/development of the MTC technology.

Capacity and Scalability

It is a misconception that simplicity means low efficiency. In fact, simplicity should never be the excuse for inefficiency. The demand to handle the ever-growing maritime traffic places great stress on the MTC system and drives the need for greater capacity; constrained by the extremely scarce communication resources, efficiency is the only vital means to maximize the system capacity. Physical and higher layers of the MTC system must be optimized to enable more spectrally-efficient communications. At the same time, the system must be scalable with future growth when resources are added in response to growing demand for capacity and increasing bandwidth needs.

Interoperability

It is essential for a vessel or maritime device in a maritime MTC system to receive services from other systems or networks, considering the fact that most service providers reside on the Internet. The maritime MTC is thus expected to offer the ability for different information systems and applications to access, exchange, integrate and cooperatively use data in a coordinated manner, within and across network boundaries, and to provide timely and seamless portability of information efficiently and securely across the complete spectrum of maritime IoT services, regardless of its developer or origin.

Radio Spectrum Internationality

Another essential element for a maritime MTC system is the radio spectrum which is without doubt the most critical component for any wireless communication system, and even more so for maritime MTC because of its global coverage nature. To successfully deploy the system globally and to function properly, it is imperative that an international frequency band is available and

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To successfully deploy the system globally and to function properly, it is imperative that an international frequency band is available and established with appropriate standards and regulations. To meet this goal, technical and regulatory challenges must be addressed by the international standards and regulatory bodies, as well as by the world's maritime community.

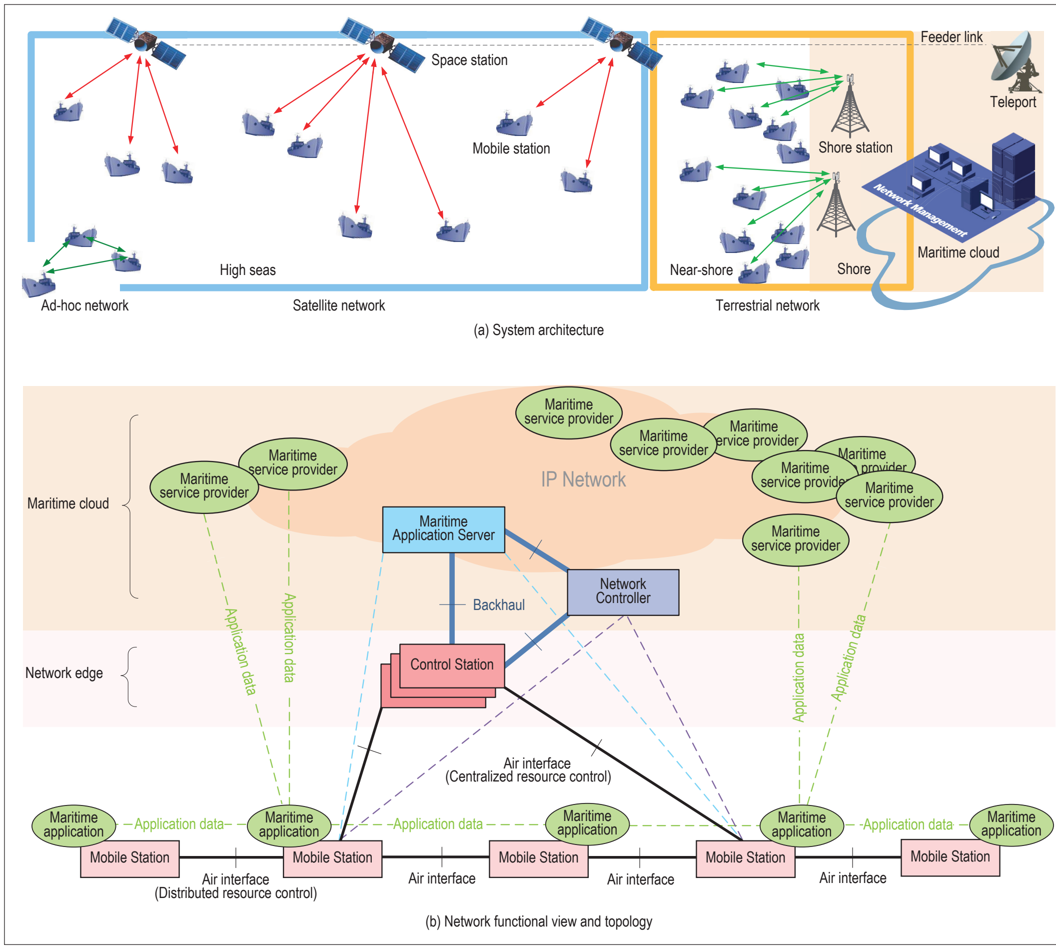

FIGURE 1. a) Space-earth integrated maritime MTC system that consists of a satellite-terrestrial integrated network infrastructure as well as self-organized ad-hoc networks; b) Functional view and topology of the service-centric maritime MTC network architecture, where solid lines denote physical interfaces, and dashed lines logical interfaces. A control station can be either a space station or a shore station. The "maritime cloud" is a trusted platform for providing network management and diverse ubiquitous maritime services and applications with the highest computational and storage capacity in the maritime IoT framework.

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The Solution

This section provides an overall design of a maritime MTC system to address the maritime MTC requirements, and to serve as a conceptual model for VDES. The system architecture is graphically illustrated in Fig. 1a. To materialize this concept, we need a service-centric network, an air interface, and internationally-authorized radio spectrum.

Network Architecture

First, we propose a maritime MTC network architecture that consists of three functional entities, *Network Controller*, *Maritime Application Server*, and *Control Station*, as depicted in Fig. 1b, where a Mobile Station is a mobile transceiver that is capable of mobile communication with the network via a control station. Under this structure, a mobile station provides interworking between the maritime MTC network and a maritime device or a premises network; it is also capable of engaging in a direct communication with other mobile stations to form an ad-hoc local network for maritime proximity services. A mobile station is uniquely identified and addressed by a 9-digit Maritime Mobile Service Identity (MMSI) [3] at the data link layer (Fig. 2) within the network.

The Network Controller is a logically centralized entity responsible for providing network-related control functionalities for communications from a global perspective. It exploits both satellite and terrestrial domains of the infrastructure to provide the network capabilities for mobile stations to access a broad variety of maritime applications and services. The Controller properly configures all the resources and infrastructure components necessary for a specific maritime service via a Network Resource Control module (NRC, Fig. 2a) responsible for configuration, provisioning, optimization, remediation, lower layer control of the stations, and terrestrial and satellite system integration, among many other things. It also maintains a *federated* Maritime Identity Registry (MIR) responsible for identification and authentication of mobile stations, as well as a Maritime Messaging Service (MMS) that supports store-

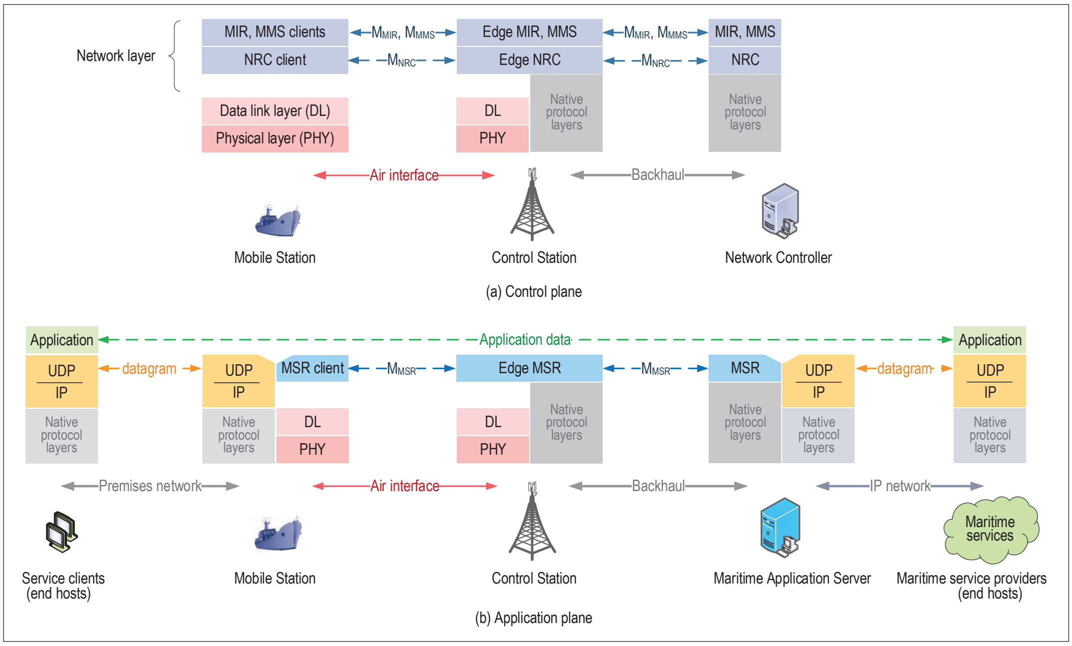

FIGURE 2. Maritime MTC layer structure: a) control plane; b) application plane, where "M_X" denotes the interface between the network layer components Xs, standardized for interoperability. It can be seen that the application layer is not part of the maritime MTC protocol stack.

and-forward functionality for reliable delivery and geo-casting of messages, through which messages can be exchanged between a mobile station and a maritime service provider in a target area using unicast or broadcast, and maps geographic location related information to appropriate target areas for the broadcast.

The Maritime Application Server automates the end-to-end provisioning of the maritime services and applications. In particular, it provides: service identification and authentication, service abstraction and presentation (to the Network Controller), and inter-network adaptation and operability between the maritime MTC network and the IP network where the maritime service providers reside. The adaptation function hides the topology and complexity of the IP network from the maritime MTC network so that a mobile station can interact with the service providers without being overburdened by the resource and power-hungry wired protocols that drive the IP network, which is of particular importance to the simplicity and efficiency of maritime IoT that are characterized by short bursty traffic.

A Control Station, either a satellite space station or a shore station, resides at the "edge" of the network. In addition to serving as a wireless access point to the network for mobile stations, it also maintains an "edge deployment" of part of the centralized functionality. The Controller and Application Server execute the functionalities via two separate virtual planes, known as the *control plane* (Fig. 2a) and the *application plane* (Fig. 2b), through a distributed architecture that involves the control stations, allowing software-defined service-centric networking without limiting scalability.

Specifically, the Application Server encompasses a *federated* Maritime Service Registry (MSR) that maintains a list of authenticated maritime service providers, each of which is identified by a Maritime Service ID (e.g., 16 bits). For outbound traffic, the MSR client at the mobile station receives the IP datagram from the service client destined to the service provider addressed by the provider's public IP address. The MSR translates the destination IP to the corresponding Service ID, and the service client's private IP to the Client ID (e.g., 8 bits), and then hands it down to the lower layers, encapsulated in an MSR message (M_{MSR}), for transmission over the air interface to the control station. At the MSR of the control station, the Service ID is converted back to the public IP of the service provider as the destination IP, and the Client ID under the mobile station's MMSI is mapped to a port number associated with the Application Server's public IP as the source address. A new IP datagram is then constructed, and routed to the destination over the public IP network.

For inbound traffic (i.e., when the service provider responds to the service client), the Application Server takes the incoming IP datagram destined to it that carries the service data from the service provider, maps the destination port of the datagram back to the Client ID and MMSI associated with the mobile station, and dispatches the service data encapsulated in an MSR message to the station (addressed by MMSI) over the VDES network (with the help of MMS for location information if necessary). Once received, the MSR client at the mobile station looks up the private IP address of the service client by the Client ID, and forwards the service data over the premises network to the end host or service client.

This network function simply ensures that the *over-the-air* overhead incurred by IP is kept to a minimum during the message exchange between a mobile station and a service provider. This not only helps improve the system spectral efficiency but also helps reduce the power consumption for those power-limited maritime devices. More importantly, this secures that only the authenticat-

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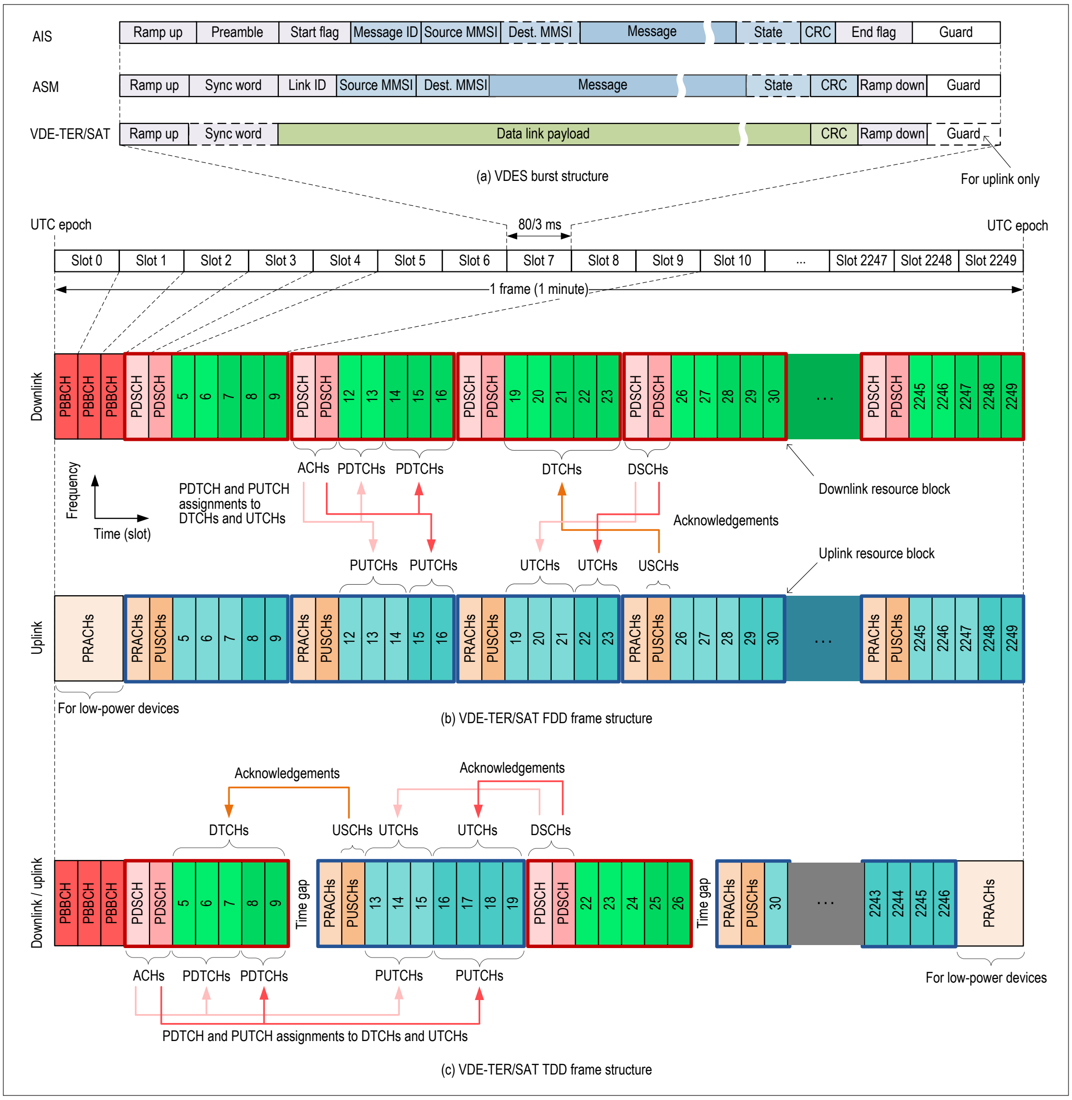

FIGURE 3. a) VDES burst structure, where the "sync word" is a preamble for time and frequency synchronization as well as channel estimation at a receiver, and is control station-specific in VDE-TER and SAT; the "state" denotes the "communication state," "CRC" the "cyclic redundancy check," and "Guard" the "guard period"; b) VDE-TER/SAT FDD frame structure; and c) VDE-TER/SAT TDD frame structure (time-partitioned in favor of uplink traffic), where the "time gap" is explained in Fig. 4. Note that the length of a burst can be an integer multiple of a slot depending on the channel condition as well as the mobile station category.

ed services are "visible" to the mobile station, and vice versa.

Air Interface

In this subsection, we propose an air interface design that includes four types of air interfaces, employing single-carrier waveforms for power efficiency and simplicity, and sharing the same transmission time structure that is organized into frames. As shown in Fig. 3, each frame consists of 2250 slots indexed from 0 to 2249, spanning 60 seconds or 1 minute that is aligned with the Coordinated Universal Time (UTC). When UTC is unavailable, synchronization is provided by other stations.

AIS and ASM Air Interfaces: The legacy Automatic Identification System (AIS) [4] is inherited as one of the four air interfaces. It is for direct communication between mobile stations in an ad hoc network structure, originally designed to provide a simple and low-cost means for maritime communication with minimum functionality. It can only be used for transmitting up to 64 *pre-defined* maritime messages, and yet no channel coding is employed. As depicted in Fig. 3a, the burst employs the Gaussian-filtered minimum shift keying (GMSK) waveform for best power efficiency. A "guard period" at the end of the burst is for guarding against overlapping of successive transmission bursts from different stations due to different propagation delays. There are two types of AIS interfaces, the short range AIS and the long-range AIS. The latter is designed for satellite reception with an extended guard period for absorbing the larger arrival time difference of the AIS signals from different stations on Earth. The "communication state" field in an AIS link layer frame is useful for distributed resource allocation for collision avoidance among AIS devices.

The Application Specific Messages (ASM) air interface is intended for delivering more versatile application-specific contents with higher spectral efficiency via channel coding and rate adaptation, indicated by the "Link (Configuration) ID", to boost system capacity. The medium access control (MAC) of ASM employs the distributed resource allocation scheme similar to AIS to support self-organized ad-hoc networking for maritime proximity services like route exchange.

VDE-TER Air Interface: Both AIS and ASM operate in a distributed resource allocation fashion. The advantage is the great flexibility that enables direct communication without the presence of a control station; nevertheless, the disadvantage is also the lack of supervision of control stations which gives rise to frequent collisions among transmitting stations in the *clustered high traffic area*, such as ports and waterways. Collisions cause not only poor overall system efficiency that limits the system capacity, but also the instability of the system. VDE-TER is thus intended to alleviate this problem with centralized resource management that relies on a managed infrastructure consisting of control stations (e.g., shore stations) connected to the maritime cloud network (Fig. 1). All communications are through the shore stations in a "star network" topology. The shore station provides a common connection point for mobile stations. The network-originated message is communicated from a shore station over the *downlink* to the mobile station(s), and the mobile-originated message is over the uplink to the shore station.

Centralized resource allocation is characterized by the principle that any communication taking place has to go through the network via control stations, and is handled by the MAC at the data link layer, where the downlink and uplink traffic are represented by the logical traffic channels (TCHs). The MAC in the control station includes a dynamic resource scheduler that assigns physical resources (slots) to both downlink TCH (DTCH) and uplink TCH (UTCH), and signals to its peers at the mobile stations over the downlink logical control channel, that is, the Assignment Channel (ACH). A mobile station requests transmission resources for UTCH through the logical Random Access Channel (RACH). In addition, the logical Signalling Channel (SCH) is for delivering information from a receiver to the transmitter regarding the state of a specific TCH, for example, Acknowledgment to the reception of a message over the TCH, among other things.

The physical realizations of these logical channels for airborne are through the physical channels defined at the physical layer. Specifically, the DTCH is carried by the Physical DTCH (PDTCH), and the UTCH by the Physical UTCH (PUTCH), whose sizes (slots) are configurable by ACH. The downlink SCHs (DSCHs) and ACH are jointly carried by the Physical DSCH (PDSCH), whereas the uplink SCH (USCH) and RACH are carried by the Physical USCH (PUSCH) and the Physical RACH (PRACH), respectively.

A bulletin board (BB) message from NRC of the network layer (Fig. 2) contains information on the network configuration necessary for accessing the network. It is broadcast by the control station through the Physical Bulletin Board Channel or PBBCH.

A unified channelization framework of the physical channels for both VDE-TER and VDE-SAT is constructed based on the concept of a "transmission resource block". A unified framework not only reduces the complexity and cost of a VDES transceiver, but more importantly, facilitates both frequency-division duplexing (FDD) and time-division duplexing (TDD) transmission modes with ease. As depicted in Fig. 3b, a resource block that consists of a group of sequential time slots is partitioned into a *signaling zone* and a *traffic zone*. The downlink signaling zone contains two PDSCHs, and the traffic zone includes multiple PDTCHs. The uplink resource block contains a plural of PRACHs and PUSCHs in the signaling zone shared among multiple mobile stations in a code-division-multiplexing fashion, as well as multiple PUTCHs in the traffic zone in a time-division-multiplexing fashion. For ease of centralized resource management and transmission error control, a downlink resource block and an uplink resource block are "paired" such that the logical association between these channels involved in a transmission can be clearly defined, as exemplified in Fig. 3b and Fig. 3c for FDD and TDD, respectively. The actual frame structure and configuration depend on the radio spectrum and traffic characteristics, and are indicated in BB; nonetheless, it is seen that TDD is more flexible in accommodating asymmetric traffic.

Similar adaptive modulation and coding schemes to ASM are employed by VDE-TER with a default uplink guard period of 0.83 ms (supporting up to a 120-NM coverage radius).

VDE-SAT Air Interface: Apparently, vessels on the high seas or in the arctic region are not covered by shore stations. VDE-SAT is thus intended for addressing the ubiquitous network access requirement via low earth orbit (LEO) satellite space stations to extend the network coverage to the regions that are not reachable by the shore stations.

Since a satellite space station has a larger field of view than a mobile station on Earth, mobile stations within the field of view are likely beyond the radio horizon of each other. Distributed resource allocation is hence ineffective in preventing collisions at the satellite receiver; rather, centralized resource control is more efficient, and provides better system capacity.

The VDE-SAT air interface is thus similar to TER under the unified framework except that an extra 4 kHz for each guard band is necessary to cope with the maximum Doppler shift at VHF induced by 8-km/sec speed of the LEO satellite. Moreover, a much larger uplink guard period (i.e., Δ_{GP} = 8 ms) is also needed, owing to larger differences in uplink propagation delay between mobile stations. This increases not only the overhead but also the timing ambiguity that degrades the uplink timing detection performance at the satellite receiver. However, adaptive timing advance can be used at the mobile station to reduce the difference as depicted in Fig. 4, in which the propagation delay is estimated from the downlink signals and used to advance the uplink transmission timing to compensate for the delay.

Radio Spectrum

Radio spectrum is undoubtedly the most critical component for any wireless communication system, especially for a maritime MTC system like

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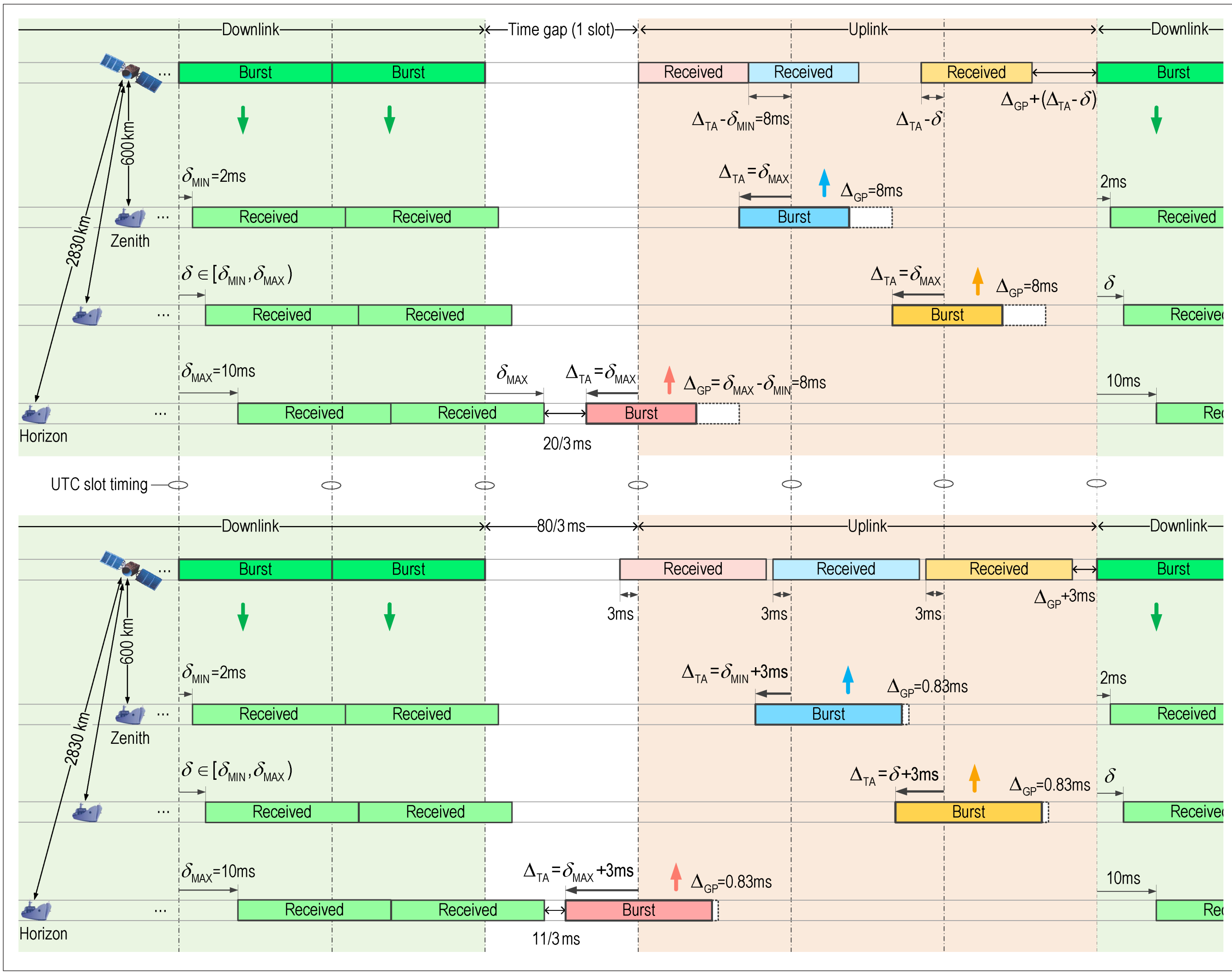

FIGURE 4. Illustration of TDD transmission timing parameterized under VDE-SAT as example, where downlink transmissions by the control station are time-aligned with the UTC slot timing, and a one-slot (80/3 ms) time gap is reserved at the downlink to uplink transition for consolidating the uplink and downlink propagation delays and RF switching time. Top: *fixed* uplink timing advance ($\Delta_{TA} = \delta_{MAX}$ =10 ms) that necessitates an *uplink* guard period of $\Delta_{GP} = \delta_{MAX} - \delta_{MIN}$ = 8 ms, whereas for VDE-TER, $\Delta_{TA} = \delta_{MAX}$ =0.83 ms ($\sim$ 120 NM) and $\Delta_{GP} = \delta_{MAX} - \delta_{MIN}$ =0.83 ms. Bottom: adaptive timing advance. In this example, the uplink guard period (for absorbing the timing advance errors) is configured to be the same as VDE-TER, that is, Δ_{GP} = 0.83 ms, for unification. Apparently, no guard period for downlink is needed.

VDES whose worldwide existence depends on the "internationality" of the radio spectrum. This is the VHF maritime mobile band allocated by the International Telecommunication Union (ITU), depicted in Fig. 5.

AIS and ASM Spectrum: Channels 75 and 76 as well as 2087 and 2088 have been allocated to AIS, of which the lower two are dedicated to long range (satellite) reception. Next to the upper two are Channels 2027 and 2028 recently allotted to ASM.

VDE-TER Spectrum: As depicted in Fig. 5a, traditional paired FDD bands have been allocated for VDE-TER; the lower leg includes Channels 1024, 1084, 1025, and 1085 for uplink, and the upper leg includes Channels 2024, 2084, 2025, and 2085 for downlink [5]. The transmitter and receiver operate on different frequency channels, allowing for constant and simultaneous transmission and reception. This also means that the receiver of a station is constantly exposed to the out-of-band emissions of its own transmission, that is, the FDD cross-link interference.

To prevent the leakage of the transmitter from getting into the receive band, the required isolation between the transmitter and the receiver is at least 150 dB for a 1 W transmitter, and 160 dB for a 12.5 W transmitter. With the frequency separation of 4.5 MHz, the FDD transceiver of a shore station typically relies on a VHF band-pass filter combined with a spatially-separated transmit and receive antenna system to bring down the interference to the noise level, for example, –125 dBm (per 25kHz).

However, what is of particular concern is the leakage of the downlink emissions into the adjacent AIS and ASM channels less than 75 kHz apart. Although such isolation in principle is achievable using higher-end VHF filter systems, there still could be deployments where such a degree of isolation between the VDE-TER and AIS transceivers *co-located* at a shore station is too costly, considering that a typical VDE-TER band-pass filter provides at most 75 dBc attenuation within a 75 kHz stop band. Therefore, ITU has

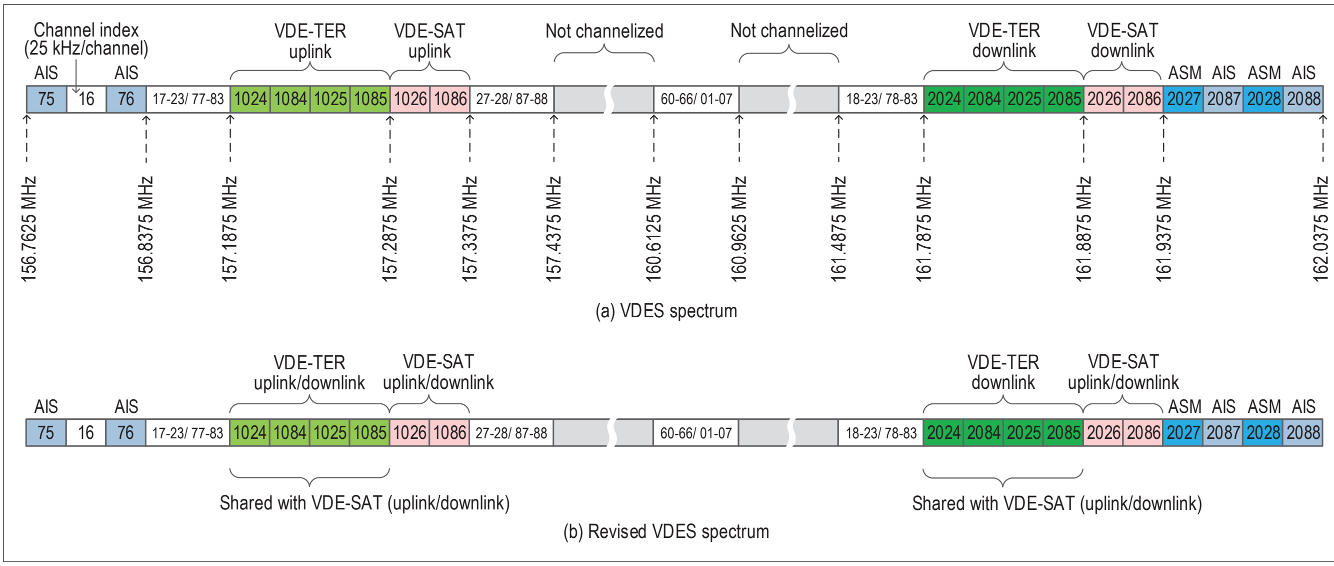

FIGURE 5. VDES frequency spectrum allocation: a) the original VDES spectrum; b) the revised VDES spectrum. The VDE-TER spectrum can be shared with VDE-SAT wherever VDE-TER is absent (e.g., offshore).

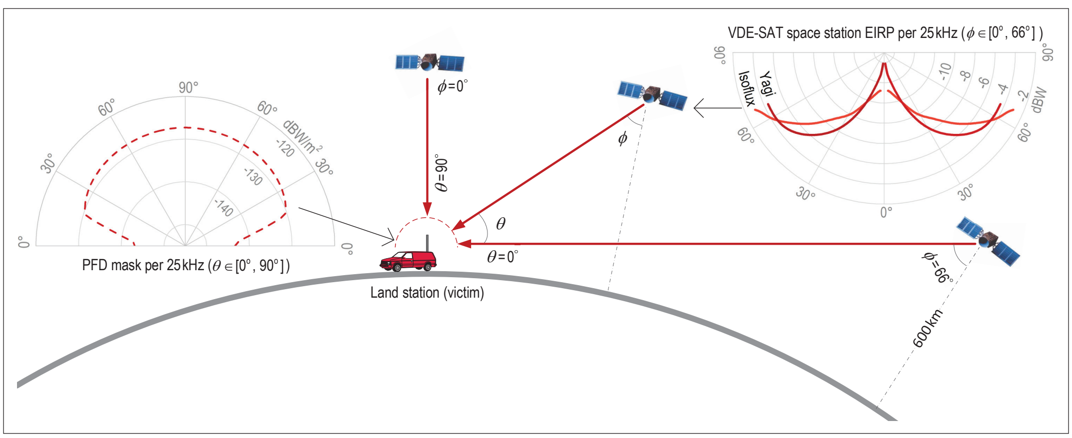

FIGURE 6. Illustration of the interference (measured by the power flux density or PFD) from a VDE-SAT space station into a victim land station receiver, where the equivalent isotropically radiated power (EIRP) of the space station is constrained by the PFD mask.

most recently revised the VDE-TER spectrum to allow both uplink and downlink transmissions on the lower leg (see Fig. 5b) [6]. A shore station now at least has an option to use the lower leg for both uplink and downlink transmissions in a TDD fashion to avoid the downlink transmission on the upper leg. The larger frequency separation (4.675 MHz) greatly eases the isolation, for instance, a regular VDE-TER filter coupled with an antenna system with, for example, 10-m vertical separation. The TDD frame structure and timing are illustrated in Fig. 3c and Fig. 4, respectively.

VDE-SAT Spectrum: Spectrum allocation for VDE-SAT is more complicated than that for VDE-TER, mainly due to its unique interference issues, that is, the satellite downlink interference to the incumbent land systems, as well as to its own uplink.

Like VDE-TER as depicted in Fig. 5a, traditional paired FDD channels are allocated for VDE-SAT, with the lower leg including Channels 1026 and 1086 for uplink, and the upper leg including 2026 and 2086 for downlink.

However, *on land*, this band, in most countries, is allocated to various communication services. This raises a unique interference issue related to the *global* broadcasting nature of a satellite system. The solution is to employ an electromagnetic *power flux density mask* as described in detail in [7], which serves as a "protection mask" for land systems such that the actual interference from the space station that the victim land system sees is no worse than that from any other land system permitted by the regulations. This concept is graphically illustrated in Fig. 6.

Another issue related to the downlink transmission is its out-of-band emissions. Here, the interference to the AIS and ASM reception (as seen in VDE-TER) is no longer an issue since they are not meant for satellite reception. Nonetheless, the FDD cross-link interference presents a serious challenge for VDE-SAT.

From Fig. 6, the downlink transmit power spectral density of the space station is up to 18 dBm/25 kHz (Yagi antenna); nearly 150 dB of isolation is thus needed to bring the interference down to the noise floor (–129 dBm/25 kHz). Since a regular VHF filter provides no more than 100 dB of rejection within 4.6 MHz of frequency separation, the remaining deficit has to come

Like most of today's communication systems, the maritime IoT network like VDES will likely continue to evolve as a collection of non-communicating private networks until such time as there is an assurance of security from a trusted internationally-federated maritime service platform under which information can be collected from and safely shared among private networks.

from high-performance VHF band-pass filter systems and/or *spatial* separation of antennas, neither of which is practical for both payload-limited and dimension-limited LEO space stations. So realistically, only half-duplex FDD can be supported, in which the space station and mobile station take turns to transmit on the downlink and uplink frequencies, respectively. Although the leakage from the transmitter to the receiver is avoided via time separation, the duty cycle per channel is halved, and the spectral efficiency is in effect cut down to half, which is detrimental to VDE-SAT whose bandwidth is already thin. A viable solution to circumvent the cross-link interference without sacrificing the spectral efficiency is the TDD transmission technique, in which both downlink and uplink transmissions are duplexed onto the same frequency band but in *different* time slots with the help of a simple RF switch, providing the same time separation effect as in half-duplex FDD but retaining full channel utilization. This approach maximizes the spectral efficiency and hence system capacity, and yet allows reuse or "time-share" of the radio resources, such as the antennas, filters, mixers, frequency sources and synthesizers, a significant advantage for battery-constrained and cost-constrained maritime deployments.

This point is captured in [7], and has convinced ITU to overturn the original allocation plan (Fig. 5a) to allow both uplink and downlink transmissions on both the lower and upper legs (Fig. 5b) for optional TDD operation. Its frame structure and timing are illustrated in Fig. 3c and Fig. 4, respectively. Nonetheless, half-duplex FDD is likely to be the default transmission mode for VDE-SAT due to its simplicity. The timing structure for half-duplex FDD is straightforward from Fig. 4.

Conclusions

Although 5G is all about enabling revolutionary use cases, maritime IoT has not yet received the sufficient attention that it deserves in the 5G community. Therefore, it can be foreseen that maritime MTC will emerge as an imperative component in the evolving landscape of communication technology beyond 5G. The challenge is to meet the diverse requirements imposed by maritime IoT and the radio spectrum constraints. This article describes the typical use cases of maritime IoT, addresses their requirements and challenges, and presents a practical solution under a *unified* network architecture and air interface framework. Finally, it is worth pointing out that while the ubiquitous connectivity and service centricity as promised by the proposed network architecture might hold true at the national level, service continuity remains in question as soon as a mobile station moves out of its national network's footprint. Indeed, control ownership and data privacy are among the leading concerns challenging the centralized controllability of the network architecture, ergo the service centricity and continuity, ultimately plaguing the globalization of maritime IoT. Therefore, like most of today's communication systems, the maritime IoT network like VDES will likely continue to evolve as a collection of non-communicating private networks until such time as there is an assurance of security from a trusted internationally-federated maritime service platform under which information can be collected from and safely shared among private networks.

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