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Non-Satellite Broadband Maritime Communications for e-Navigation Services

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ABSTRACT The development of broadband network access technologies available to users on land has triggered a rapid expansion of a diverse range of services provided by terrestrial networks. However, due to limitations of digital communication technologies in the off-shore area, the maritime ICT systems evolution so far has not followed that trend. Despite the e-navigation initiative defining the set of Maritime Services, the progress in the maritime ICT systems evolution has been slow. Only a few systems, including the VHF Data Exchange System (VDES), or the TRI-Media Telematic Oceanographic Network (TRITON) have been proposed to extend the basic set of services offered by classical radio-communication solutions. However, all those systems have significant limitations. The purpose of this paper is to introduce the netBaltic system designed as a fully heterogeneous system for modern maritime communications. Its unique feature is the capability to transparently use different communication technologies to efficiently support maritime ICT services, as well as openness for the incorporation of future communication technologies. The paper presents an overview of VDES, TRITON and netBaltic systems and analysis showing their expected strengths and weaknesses. The systems are then compared in simulated environments, illustrating real-world usage scenarios based on real maritime traffic information and performance measurements obtained during off-shore measurement campaigns. Results indicate that netBaltic seems to be the most versatile one and is capable of offering access to all services defined by International Maritime Organization, due to its ability to use different communication technologies simultaneously and functionality offered by its Delay Tolerant Networking component.

INDEX TERMS Communication systems, computer networks, data communication, mobile communication, marine technology, network topology, wireless communication, wireless mesh networks.

I. INTRODUCTION

The popularization of Information and Communication Technologies (ICT) in a diverse range of human activities is considered to be one of the most significant developments in recent decades, influencing our everyday life [1]. The observed evolution towards the Information Society [2] has been possible due to the rapid development and spread of inexpensive communication devices. However, further progress depends significantly on their ability to process and quickly transfer growing volumes of information – which has so far been possible due to the evolution of both computational capabilities and communication technologies. While wired solutions are expected to offer a reliable, high-bandwidth communication infrastructure for critical computing centres and stationary users, wireless technologies are aimed to enable the ubiquitous access to the global internetwork and its resources for mobile users. Opportunities enabled by the evolving technological capabilities (the so-called ''technology push'') have resulted so far in the emergence of many IT services offered by commercial and non-commercial entities. The rapidly growing number of users interested in ICT solutions has, in turn, been stimulating the business sector to expand the set of services to reach an even higher number of customers (the so-called ''business pull'') [3].

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Apart from the variety of services intended for individual users, generating a considerable income due to numerous customers, there is also a significant group of general and business-specific services for commercial entities such as those provided by Intelligent Transportation Systems (ITSs) [4]. ITS services are meant to facilitate diverse tasks related to cargo and passenger transport, especially concerning transport planning, monitoring and management. Such a functionality, combined with automation of many work-intensive document exchange tasks, is expected to improve reliability and efficiency of transport operations [5], [6]. An important aspect of deployment of ITS services refers to the maritime environment, as about 80% of the world trade is transported by sea [7], [8].

Modern maritime activities include a wide variety of tasks, such as cargo transport in high quantities, passenger transport, tourism and recreation, oil and gas mining, fishing and scientific research [9]. Characteristics of the environment and vessels utilized in maritime activities make the advance operational planning and access to information a necessity (for example, to take into account the weather-related warnings, port accessibility information, etc.). The correctness of such plans and their timely modification to accommodate changing conditions is even more important in maritime environment than in case of similar land-based tasks. Therefore, as indicated in [10], [11], the application of maritime-oriented IT services can certainly help mitigate many difficulties of sea operations [12].

However, despite the advantages mentioned above, we have been observing a slow deployment of digital electronic systems in the maritime environment, designed to handle specific tasks (mainly related to safety, security and the most crucial navigational needs) [13]–[15]. It is important to note that until now, the general model describing IT service evolution in the on-shore environment does not seem to work in case if the maritime environment. When taking a closer look, two fundamental reasons for the relatively slow deployment of modern IT systems in the marine context become evident. The first one is that in the case of the majority of maritime IT services (especially safety or navigation-related), reliability is much more critical than in most of the on-shore deployments. In particular, it is not acceptable for maritime navigation or safety signalling systems to show intermittent, momentary failures (relatively frequent and tentatively accepted in popular, on-shore consumer systems) [16].

The second reason is a lack of high-throughput digital, maritime communication solutions (as opposed to the numerous network access options available in the on-shore industrialized areas). Currently operating maritime communication systems officially supported by maritime organizations, in particular by International Maritime Organization (IMO) and International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), concentrate on offering their users a closed set of critical functionalities. A group of the most important functionalities and services has been defined by the specification of the Global Maritime Distress and Safety System (GMDSS) [13], [14], [17].

Such systems, as they are designed to solve particular problems, cannot be used as a general purpose communication solution. Thus there is still room for propositions of new approaches to the communications problem. Considering the characteristics that should be possessed by an universal and efficient maritime communication system, it should be noted that in the Maritime Radio Communications Plan [18], IALA defined three types of maritime services: commercial, operational and safety-related. Each of them is characterized by a different priorities regarding the following, general requirements like: bandwidth, transmission range, frequency usage, cell capacity, scalability, interoperability or openness to new wireless technologies.

Clear limitations of the currently employed maritime communication solutions and the availability of many broadband technologies successfully deployed on-shore have created much interest in their possible adaptation for the off-shore use [19], [20]. Several research initiatives such as [21]–[23] have been undertaken to find a way to utilize various Wireless Local Area Network (WLAN) and Wireless Metropolitan Area Network (WMAN) technologies in maritime conditions.

The main goal on which we concentrate in the paper is the presentation of characteristics (based on real-world measurement campaigns which provided information necessary to conduct the presented simulations) of a heterogeneous wireless network designed to take advantage of multiple wireless technologies and provide communication for maritime ICT services without the need to use the satellite links. For this purpose, a number of other original elements are also presented, including:

- Overview of limitations and advantages of each of the analyzed systems and above-mentioned design approaches on which they are based.
- Comparison of the systems in specific context of their ability to support ICT services which are expected to be useful to the maritime community (IMO-defined Maritime Services).
- Presentation of simulation results illustrating example deployment scenarios of ICT services, based on real-world ship locations and over-the-sea communication ranges of WLAN and WMAN technologies obtained by measurement campaigns.
- Illustration of high usefulness of delay tolerant networking (and support mechanisms such as soft handover) in deployment of IMO-defined Maritime Services.

As indicated above, in this paper, we concentrate on solutions which we find representative for three following, main development trends of maritime communication systems evolution:

- VHF Data Exchange System (VDES) [24] – **a narrowband, long-range solution** introduced by International Maritime Organization, intended for critical, safety-related e-navigation services.

- TRI-media Telematic Oceanographic Network (TRITON) project [25] – **a homogeneous broadband system** optimized for maritime conditions, based on modification and extension of a standardized IEEE 802.16 (WiMAX) [26] technology.
- netBaltic project [27] – **an universal integration platform** for multiple communication solutions, creating a versatile heterogeneous network capable of utilizing many different communication infrastructures.

The paper structure and the respective content of further sections is as follows. Section II presents IMO-defined maritime services, providing an overview of currently recognized fields where introduction of ICT technology is expected to benefit the maritime community. Section III provides description and analysis of the selected maritime communication systems, namely: the long-range VDES; the broadband, homogeneous TRITON solution and the broadband, heterogeneous netBaltic system. Section IV presents the assessment of strengths and weaknesses of the communication systems (and different approaches to maritime communications they represent) when employed in support of IMO-defined maritime services. The analysis is illustrated by results of simulation scenarios based on parameters obtained from experiments made in the real marine environment. Section V concludes the paper.

II. IMO MARITIME SERVICES

Maritime communication solutions in widespread use today are strictly tied to particular services which are known to be feasible in maritime environment (for example, distress signalling [15]) and whose specifications include the approved technical means for their implementation. However, the development of e-navigation initiative promotes a different approach: instead of creating a critical set of clearly feasible, necessary services, e-navigation aims to define a comprehensive set of maritime-related services which are seen as advantageous by the maritime community and only then search for technical means of their implementation [28], [29]. Such an approach promotes separation between technical means used to implement a service (for example a communication system used for access) and a service itself, leading to an ecosystem similar to the one we are currently experiencing on-shore. From the e-navigation perspective, the ideal ICT system would offer both a highly reliable communication solution for critical services, as well as allow a wide variety of non-critical services to be deployed [30]. Based on lessons learned from the on-shore IT evolution, e-navigation also aims to facilitate the integration between various critical and non-critical systems without decreasing their reliability and ability to operate independently [31].

As an essential step in the popularization of e-navigation approach, IMO provided a description of Maritime Services (MSs) [32] – currently recognized groups of IT services are expected to be of high utility for the maritime community. It is important to note that a definition of a given MS in [10] does not indicate that it is currently available or even potentially ready for implementation. Concerning the majority of MSs, a significant research, implementation and deployment effort still needs to be put due to lack of technical solutions available to support them in an efficient way [18].

In this section, we briefly characterize each MS and discuss their requirements concerning underlying communication technologies.

Vessel Traffic Service Information Service (MS1) aims to provide essential information for on-board navigational decision making. It requires timely message dissemination both at intervals and on-demand. Exchanged messages contain diverse information on vessel navigation safety, including vessel MSSI, intention and destination, maneuverability limitations as well as hydrological and meteorological conditions. The main goal of this MS is an overall improvement of safety and efficiency of vessel traffic.

Navigational Assistance Service (MS2) is defined as a means of assistance to the crew in unusual circumstances like the unexpected equipment failure or incapacity of a key member of the bridge team to allow them to continue making safe navigational decisions.

Traffic Organization Service (MS3) is intended to prevent the development of dangerous situations related to maritime traffic. It is to be provided by National Competent Vessel Traffic Service (VTS) Authority coordinating day-by-day vessel traffic to avoid disruptions caused by exceptional cases like special transports, nautical activities or marine work in progress.

Port Support Service (MS4) is one of the most dynamically evolving services defined by IMO. It is to be provided by Local Port or Harbor Operator and encompass a wide range of functionalities beneficial for safety, ease and efficiency of interaction between maritime vessels, harbour infrastructure and administration. Business-related functionalities can also be deployed as a part of this service. The MS4 do not need to fulfil a requirement of the global interoperability. It can be implemented using a diverse range of technologies and deployed in a manner most beneficial in a given local environment. Such an approach allows a broad range of services to be made available while conserving communication resources used by globally interoperable MSs. It is also a place where modern, broadband communication technologies can be efficiently utilized.

Maritime Safety Information Service (MS5) aims to allow a global exchange of Maritime Safety Information defined in Safety of Life at Sea (SOLAS) convention for the Global Maritime Distress and Safety System [15]. This MS is considered to be of high importance, as it includes safety and disaster response related functionality currently seen as critical for the safety of maritime activities.

Pilotage Service (MS6) is intended to provide support for the bridge personnel, ensuring that vessels in a specific operating area can safely reach their destinations, observing specific local conditions. For this purpose, highly

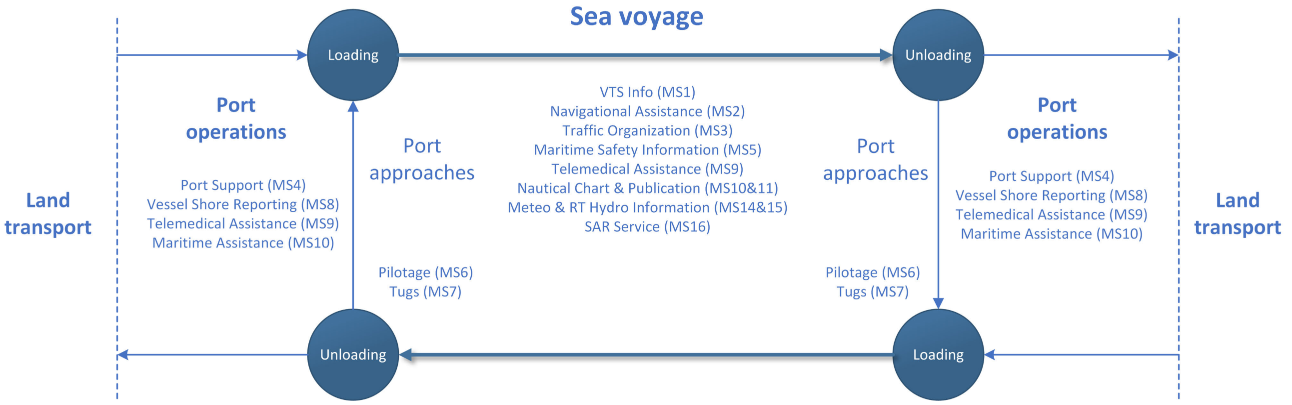

FIGURE 1. The flowchart of IMO Maritime Services applicability in maritime transport operations.

experienced pilots with knowledge about a particular area and efficient communications between the pilot, the master and the bridge team are needed. While Pilot Portable Units (PPUs) supporting the pilot have been frequently employed already, the manner of navigational data exchange and presentation has not been standardized yet.

Tugs Service (MS7) is to improve the safety and efficiency of various local tug services (from personnel transportation, mooring assistance and towing operations to the emergency response). It is to be provided by port authorities or dedicated tug organizations. Similar to **Vessel Shore Reporting (MS8)** aiming to facilitate the preparation of reports required to be submitted to authorities by maritime vessels, it is expected to benefit from reliable, high-throughput communications within groups of vessels and between vessels and local shore-based authorities.

Telemedical Assistance Service (MS9) is to be provided by dedicated or national health organizations. It aims to assure the medical care for vessel crews continuously and uninterruptedly. Although the specific functionalities of this MS were defined for delivery using the existing communication systems (especially HF and VHF radios), there is an enormous room for improvement in both quality and diversity of services. With broadband connectivity or delay-tolerant delivery of sizeable data packages, increasing the maturity of the already deployed e-health services and relatively new medical Internet of Things (IoT) solutions would change the role of this service from emergency reaction to proactive prevention.

Maritime Assistance Service (MS10) – is a service providing general-purpose communications between actors in the maritime community (e.g., coastal authority, port authority, ship officers, fleet owners or brokers, etc.). Providers are responsible only for forwarding messages and situation monitoring, serving as a contact point between all parties.

Nautical Chart Service (MS11) is to provide distribution of information describing navigational dangers, a state of coastal areas, water depth, tides, etc. This MS is also to include functions allowing the efficient distribution and licensing of nautical charts. It is to be provided together with **Nautical Publication Service (MS12)** ensuring the availability of up-to-date waterways description. On the other hand, meteorological information such as the weather forecasts, wind speed and direction, etc., also essential for maritime safety, is to be provided by **Meteorological Information Service (MS14)**. Taking into account the rapidly changing conditions of ice-infested water areas, **Ice Navigation Service (MS13)** is proposed as a dedicated solution for ice-covered regions. All services mentioned above are also to be extended by periodical updates by **Real-time Hydrographic and Environmental Information Service (MS15)** to enhance navigational information with additional data such as, e.g., maritime habitat and bathymetry, detailed description of sea areas, or lists and descriptions of lighthouses and lightbouys.

The last currently defined group: **Search and Rescue Service (MS16)** aims to improve the efficiency of search and rescue operations. Although various solutions addressing this need have been deployed, the use of new communication systems can bring substantial benefits, e.g., by the ability to constrain the search areas based on results of modelling and computation performed by an on-shore infrastructure.

In Fig. 1 we present the IMO-defined MSs in a flowchart of maritime transport operations [33]. As indicated by the descriptions above, some of them directly address administrative and logistical port operations, while another group is dedicated to support a sea voyage itself. A majority of the latter group will be utilized all through the voyage, but some (such as pilotage and tug services) are intended to support maritime operations on port approaches. A special case of Telemedical Assistance (MS9) can belong to both administrative and general groups, as it is currently employed to support medical procedures required by port authorities, but there is a significant interest to make it possible to monitor and protect the crew health while the vessel is operating at sea.

III. MODERN MARITIME COMMUNICATION SOLUTIONS AND PROJECTS

As already discussed in this paper, deployment of services using different communication technologies was the result of two factors (a) the need for services related to safety, disaster response and navigation to be available over the marine area as broadly as possible and (b) the lack of a universally viable communication solution capable of supporting their requirements [34]. The need to operate over large areas and the possibility to provide their basic functionality without exchanging a large amount of data influenced the selection of these technologies in favour of HF/VHF and satellite communication solutions. The resulting multitude of employed communication methods significantly reduces the efficiency of maritime HF/VHF radio bands usage.

With e-navigation initiatives aiming to introduce many new services and to raise the integration level of various existing maritime systems, it became clear that a more comprehensive approach to VHF communications is necessary. VHF Data Exchange System [35] defines a list of communication scenarios, regulates access of existing services to terrestrial and satellite frequency bands currently used for maritime communications and defines communication channels open for use by newly-defined services. As an IMO-supported, natural evolution of traditional, long-range / low-bandwidth maritime communication systems and their associated services, VDES is an essential example of digital maritime communication solutions.

A development of on-shore broadband communication systems and popularization of a diverse range of Internet Protocol-based ICT services triggered an interest in their deployment in the maritime environment (i.e., outside the coverage of the land-based network access infrastructure). However, with a clear preference of the maritime community towards well-established and well-tested services and due to a lack of cost-effective, broadband communication systems, there is a significant absence of both business-pull and technology-push elements of the previously mentioned IT-evolution model. As a result, with some exceptions of costly proprietary solutions (such as, for example [36]), most of proposals come from academic research projects such as [22] or [37]. From this group, we have selected the TRI-Media Telematic Oceanographic Network (TRITON) [38] and netBaltic [39] projects as representative examples. Each of them offers a functional, broadband maritime communication system, successfully tested in the intended operational environment, while taking a different approach to addressing the problem. In particular, TRITON uses a single transmission technology and modifies it to suit better the maritime conditions (thus creating a homogeneous communication system). netBaltic, in turn, aims to create a heterogeneous communication system by allowing practically any transmission technology capable of carrying Internet Protocol traffic to be used as a part of the self-organizing communication network. These approaches and assessment of their ability to support the Maritime Services defined by IMO are described in detail in the remaining part of this paper. We also include a short description of a number of other maritime communication initiatives which we find interesting despite somewhat limited information available regarding specifics of their operation and deployments. However, our primary focus remains on VDES (an IMO-proposed technology), TRITON (a functional homogeneous solution) and netBaltic (a comprehensive heterogeneous system).

A. VHF DATA EXCHANGE SYSTEM

VHF Data Exchange System has been developed by e-NAV Committee of the International Association of Marine Aids to Navigation and Lighthouse Authorities with active support of other relevant organizations, such as Radio Committee ITU (ITU-R) and IMO. It is expected to facilitate many different applications for safety and security of navigation, protection of the marine environment, the efficiency of shipping and others [34], [35], [40].

The Automatic Identification System (AIS) [14] in use today is a globally recognized solution, utilized for both its primary purpose of collision avoidance by supplementing information obtained from marine radar, and for exchange of digital information used for other marine services. It is required for SOLAS Class-A vessels, but in practice it can be found in other applications such as Aids to Navigation (AtoN), Search and Rescue Transmitters (SART), Man Over-Board units (MOB) and Emergency Position-Indicating Radio Beacon (EPIRB) [41]. Such widespread use of the system caused the load it imposes on VHF Data Link (VDL) [42] to become an ongoing concern for both IMO and ITU [34], [40].

In this situation and with increasing demand for radio resources to support other applications (such as mobile phones and data), it has been necessary to develop a more efficient method of utilizing the available radio spectrum in VHF band. Such technique has been described in ITU-R M.1842-1 [43] and became a basis of the VHF Data Exchange System. It is capable of providing up to 32 times higher data rates compared to AIS and optimized to offer a high probability of successful reception of digital data packets in maritime conditions.

Following the well-established IMO practice, VDES system is intended to support the unambiguous identification and location of its terminals as a default service creating a unique location map. For identification, the Maritime Mobile Service Identity (MMSI) is used as defined in Recommendation ITU-R M.585 [44]. The concept of VDES comprises the functions of the existing AIS, additional communication links for the exchange of Application Specific Messages (ASM) to be used by various services and for enabling higher capacity VHF digital data exchange (VDE). However, the top priority is still assigned to AIS position reporting and the dissemination of safety-related information.

The overall architecture of the system includes both terrestrial and satellite radio communication links in the VHF maritime mobile bands [24]. As presented in Fig. 2, possible VDES communication options and services mainly include:

- one-hop shore-to-ship (and vice versa) VHF terrestrial communications for AIS, VDE and ASM services;

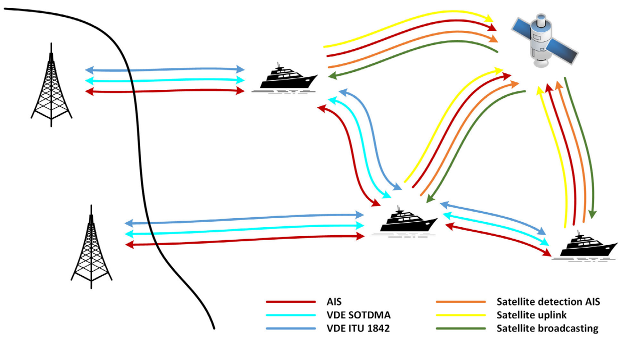

FIGURE 2. **VDES architecture.**

- one-hop ship-to-ship VHF terrestrial communications for AIS, VDE and ASM services;
- shore-to-ship (and vice versa) VHF satellite aided AIS services;
- satellite broadcasting services, e.g., for VDE messages of general interest.

Currently, IMO is still developing an e-navigation implementation strategy and conducting a review and modernization of GMDSS – a system of critical importance for the safety of maritime operations and disaster response at sea.

VDES can provide a globally-interoperable data exchange using popular maritime communication frequency bands and offer transmission speeds exceeding those for AIS or other currently utilized, service-specific communication technologies, such as Digital Selective Calling (DSC) [45]. Therefore, it is likely to become one of the core elements of basic e-navigation services and modernization of GMDSS. VDES standardization documents describe a set of narrowband communication solutions, which are capable of supporting a critical subset of currently utilized maritime services, and regulate the use of radio-frequency bands required for their deployment.

The VHF Data Exchange Terrestrial (VDE-TER) [24] enables seamless two-way data exchange between ships and between ships and shore in the coastal coverage areas exceeding the capabilities of ASM. The communication range of VDE-TER is by default 20-50 NM, and the supported throughput is up to 300 kbps (32 times higher than by AIS). Furthermore, its framework allows data exchange not bounded to the message structure of ASM, enabling the deployment of a range of new applications requiring data exchange of higher volume. Data transmission is done using one of five TDMA methods in the VHF maritime mobile band with the separate frequency bands allocated for the uplink (ship-to-shore) and the downlink (shore-to-ship and ship-to-ship) transmission.

In addition to VDE-TER, the VHF Data Exchange by satellite (VDE-SAT) [24] is defined to provide data exchange between ships and shore via a satellite. VDE-SAT complements VDES-TER outside the coverage area of coastal stations, enabling a global coverage of the VDE system. Low Earth Orbit (LEO) satellites [46], at 600 km altitude, are currently considered for a typical VDE satellite solution. It should be noted that other orbital selections are also possible according to the overall system design considerations. As VDE-SAT and VDE-TER both share some of their assigned frequency channels (Fig. 2), interference can occur due to a vast area covered by the satellite beam and the associated difficulties in obtaining a spatial separation of these services. The technical characteristics of ship-to-satellite-to-shore and shore-to-satellite-to-ship communications are not yet comprehensively defined, and the full satellite capability of VDES is still under development.

All VDES subsystems are legitimated to transmit data in the VHF maritime mobile bands defined during the World Radio Conference in 2015 [47]. The radio spectrum can be used in 25 kHz, 50 kHz or 100 kHz channels.

One of the most significant drawbacks of VDES is a lack of node authentication mechanism [40]. Thus all messages can be easily spoofed by an attacker causing them to be treated as information packets sent by a legitimate user.

The described VDES data transmission capabilities indicate that while it is a significant improvement over the currently standardized methods (such as sending Application Specific Messages over AIS), it is still a narrowband communication technology. Moreover, its long-range transmission capability makes it relatively easy for an application to overload the system by sending an excessive number of messages. To establish a set of guidelines regarding an acceptable usage of the system, ITU proposed the following timing criteria for the most common information types [48]:

- dissemination of static information – once every 6 minutes or when data has been amended (on request);
- dissemination of dynamic information – dependent on speed and course alteration can vary from 2 s (i.e., for ship speed higher than 14 knots and changing) to 3 min (for ships at anchor or moored and not moving faster than 3 knots);
- voyage-related information – every 6 minutes or when data has been amended (on request);
- safety-related messages – as required.

Having in mind a relatively long transmission range of VDES, it should be expected that with a significant number of vessels in mutual communication range, random access algorithms used for transmission on-demand can reduce the system capacity.

To further improve the efficiency of medium access and thus conserve the limited radio resources, the system utilizes signalling channels created over dedicated time slots or frequency bands. Specifically, in the case of VDE-TER, a shore station is in charge of transmission coordination through the Terrestrial Bulletin Board (TBB) channel and Announcement of Signalling Channels (ASC) [24]. The satellite component of the system (VDE-SAT) employs Satellite Bulletin Board (SBB) in place of TBB and has its own dedicated ASC channel. Due to the necessity of coordination of satellite transmission of VDE-SAT and terrestrial communications of VDE-TER, coordination information is transmitted in VDE-TER using TBB/ASC. At the same time, satellites of the system receive and respect all requirements of VDE-TER controlling stations they detect in their own (changing and usually large) coverage area.

As far as interoperability is concerned, services designed for maritime VDES-based environment are severely limited in their scope and functions compared to on-shore ICT services. Moreover, there is no possibility of employing VDES for direct access to ICT services currently popular on-shore in any general fashion. According to [46], support for IP-based transport protocols such as Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) is necessary for this purpose. Additionally, a number of application protocols (e.g., Simple Network Management Protocol (SNMP), Secure File Transfer Protocol (SFTP), or Simple Mail Transfer Protocol (SMTP)) should be also supported. However, in case of VDES, no direct IP communication with destinations in external networks is available, and IP terrestrial networks are terminated at the terrestrial network gateway – a dedicated network element required to allow VDES users to access specific selected services.

Despite the development of the IMO-proposed VDES, the maritime environment remains an area where the lack of technical capabilities is a factor limiting the design and implementation of new user applications. It is a radically different situation from the one, which can be observed on-shore for the last decade. Indeed, ''technology push'' (availability of technical means) is one of the main driving factors leading to a rapid evolution of ICT systems in the on-shore environment and maintaining the continued user interest in new services. In contrast, in the case of the maritime environment, the interest in new services seems limited, as potential users prefer to utilize already verified solutions instead of deploying new ones, which can still be facing unknown technical difficulties.

B. TRI-MEDIA TELEMATIC OCEANOGRAPHIC NETWORK (TRITON)

IMO standardization focused on narrowband VDES as a reliable communication solution for a well-recognized set of critical functionalities and had no specific plans of deploying a globally recognized, broadband, maritime communication system allowing the deployment of radically new services. Therefore, other independent research teams concentrated their efforts on preparing propositions of such solutions. A few proprietary, costly, broadband communication technologies specifically designed for maritime use and already available for some time [36] have not influenced the general IT deployment speed remarkably. Having a significant number of relatively inexpensive, high-performance communication technologies utilized in the on-shore environment, it seemed natural to try to use them in the off-shore conditions by applying the necessary modifications to keep their operation efficient in a significantly different environment.

A notable example of this approach is the TRITON project [25] proposing an adaptation of a well-tested and mature terrestrial solution of Wireless Metropolitan Area Networks (WMAN) group – WiMAX technology based on IEEE 802.16-2014 standard [26]. The technology itself seems well-suited for maritime communication. It allows its base stations to be deployed without the need to use the complex core-network infrastructure. Communication ranges can theoretically reach over 50 km, and throughput reaches tens of Mbps at short ranges (however, it is significantly reduced at longer ranges). Based on the on-shore practice, the good assessment of attainable throughput is at most 10 Mbps at a distance of 30 km [49]. Such values are attractive for the maritime environment since long distances between ships make transmission range an essential feature.

The technology includes sophisticated management mechanisms, employing dedicated management and control channels, allowing it to support Quality of Service (QoS) reservations enforced using a controlled TDMA medium access scheme. This approach results in high efficiency of channel access compared to other standardized technologies, like IEEE 802.11 (Wi-Fi) [50] or 802.15.5 [51], popular in on-shore deployments. WiMAX can be implemented to utilize different licensed and unlicensed frequency bands ranged between 2 and 66 GHz (as defined by IEEE 802.16-2004 specification [26]) making it a solution suitable for various deployment scenarios and different legal requirements in different countries.

Despite a relative sophistication of WiMAX technology, many extensions and modifications have been developed in TRITON to make it better suited for maritime applications. Specific solutions developed in this project cover both physical and data-link layers of the IEEE 802.16 standard. Moreover, although WiMAX provides Ethernet-compatible data-link layer connectivity [52], many sophisticated, network-layer mechanisms have been added to the standard version.

The physical layer has been extended as a remedy for wave-induced ship motions, by employing a dedicated antenna switching module and the associated multi-antenna system [25]. It integrates a group of antennas (twelve sector antennas with 90° horizontal and 5° vertical width beam) shown in Fig. 3 to automatically select the one being the most appropriate for communication. The antennas are organized to provide omnidirectional communications despite the wave-indicated motion of the ship (pitch/roll) and a relatively narrow vertical antenna beam. As described in [25], they are grouped into four units, each one containing three antennas. Units are placed in a way to cover all four cardinal directions relative to ship bow giving the system an omnidirectional capability. In each unit, three antennas are mounted with different tilts ($-5°$, $0°$, $+5°$) allowing for a compensation of the wave motion. Based on data from a gyro detecting pitch and roll motions, the switching module controls the units to select the best one for wireless transmission.

Despite a relatively long range of WiMAX technology, it has been extended with multi-hop communication mechanisms in the course of the TRITON project, allowing

FIGURE 3. **TRITON antenna system [25].**

vessels with TRITON equipment on-board to act as intermediate transit nodes for data exchange between a shore station and vessels outside its direct communication range. This capability has been introduced by developing a dedicated routing protocol operating in the MAC layer and a network switching middleware. The MAC-based routing protocol for TRITON [53] is a proactive solution allowing the creation of bidirectional, multi-hop communication paths between a shore station and vessels at sea. The protocol has been integrated with IEEE 802.16 management mechanisms and utilizes dedicated management channels to exchange routing information, which increases its reliability. It also allows multiple paths to be maintained towards a given destination node for a fast reaction to link failures.

Additionally, internal mechanisms of IEEE 802.16-2004 medium access control were modified to improve the efficiency of data transmission in a multi-hop mesh network. Instead of a standard Coordinated Centralized Scheduling (CCS) commonly used in point-to-multipoint WiMAX systems, an alternative Coordinated Distributed Scheduling (CDS) mechanism outlined in IEEE 802.16-2004 specification have been implemented [54]. The CDS provides a management framework for radio resource allocation in a mesh environment, ensuring a common allocation state for mesh nodes within a two-hop neighbourhood. However, its specification does not provide any specific algorithm for making allocation decisions. To address this issue, a Distributed Adaptive Time Slot Allocation (DATSA) mechanism [55] has been developed as a part of TRITON project, to handle the assignment of radio resources, based on knowledge of network conditions within a two-hop neighbourhood (provided by CDS).

To further improve the communication performance in a wireless mesh network, the Multi-Channel Transmission solution has been utilized in TRITON to differentiate the frequency channels for transmission in a two-hop neighbourhood [56], [57]. As a result, it was possible to reduce the intra-path interference (i.e., between traffic received and transmitted by a node as a part of one transit traffic flow). Moreover, a Fair Bandwidth Allocation (FBA) scheme was used to avoid the inter-flow fairness problem of exclusive resource reservation for nodes located close to a joint traffic destination (such as a shore station). TRITON communication terminals can also offer satellite communication capability via Network Switching Middleware (NSM) if the satellite equipment provides a better communication quality than the terrestrial TRITON mesh network.

TRITON uses the broadband communication technology tested in the on-shore environment and significantly modified and extended for its application in the maritime conditions. Multi-hop communications has been introduced along with several other mechanisms to prevent the majority of well-known mesh network problems (such as intra-path interference, traffic concentrations in gateway areas, etc.). Many changes have also been applied to the physical layer to improve the reliability of transmission. Such an in-depth modification of WiMAX technology allowed TRITON to improve its utility in communications at sea significantly and, thus, become highly efficient. Its maximum attainable bandwidth of over 5 Mbps positions TRITON well within a group of broadband solutions. Also, the communication range of at least 10 km is enough to allow the mesh structure to be created in many maritime scenarios. At the same time, the fact that the interference range of the WiMAX transmitter is also limited to similar ranges makes it possible to create a scalable mesh network taking advantage of the spatial frequency reuse. The modified IEEE 802.16 QoS mechanisms facilitate the efficient support of a high number of shipboard terminals within the mutual communication range.

However, TRITON is not compatible with any standard communication technology, resulting in several important disadvantages:

- the installed hardware cannot be used for any other purpose than to connect to non-standard TRITON installations;
- update to new versions of the base WiMAX standard requires dedicated TRITON modifications to be re-developed. It is thus possible that the updated mechanisms will make some of the modifications very difficult or even impossible to be applied;
- as a mesh network requires concentration of its nodes to form the continuous transmission paths, deployment of the system needs to be conducted all at once, with all vessels and shore stations receiving and installing the specialized hardware (antennas and terminals).

The above characteristics make the system better suited for local deployments of high efficiency than for use as a widely-recognized maritime communication solution. The above impression is further reinforced by a relatively little attention in the TRITON project to various aspects of integrating TRITON with the existing infrastructures. One can also expect difficulties when installing the proposed antenna solutions in small maritime units. Moreover, a high cost of the customized hardware and custom-built antennas probably further reduce its advantages over the available proprietary systems.

C. netBaltic–A HETEROGENEOUS WIRELESS SYSTEM FOR MARITIME COMMUNICATION

Taking into account the limitations of non-standard solutions based on modifications of a single, chosen transmission technology, in netBaltic we attempted to create a system which is transmission technology-independent in the maximum attainable degree. By implementing all critical mechanisms of the system in the network layer, we have gained the ability to transparently utilize any transmission technology which is capable of transmitting IPv6 datagrams. Therefore, as long as a given communication device can be connected to the netBaltic node by one of the popular network interfaces (as Ethernet or various serial interfaces), it will automatically be used as a part of netBaltic system.

The ability to transparently support such a wide range of communication devices and technologies (utilizing both licensed and unlicensed frequency bands) makes each netBaltic node capable of integrating various communication capabilities already present on board of a maritime vessel and automatically using them to obtain IP connectivity efficiently. At the same time, the fact that critical mechanisms of the system are independent of transmission technology makes it completely open to integrating any newly developed wireless technologies (which allows for the natural evolution of the system). In particular, it means that when new technologies become available, they can be integrated with the netBaltic nodes without any need to modify their mechanisms. Additionally, the ability to connect communication devices with a netBaltic node using popular long-ranged Ethernet and serial interfaces greatly facilitates the physical installation of the system. Multiple transmission devices can be located high on the vessel's superstructure or rigging and easily connected with a popular twisted-pair cabling to the netBaltic node located inside the vessel. They can also be easily powered using Power-over-Ethernet (PoE) [59] compatible power supplies. Such ability makes it easy to install a significant number of such devices and obtain the long-range antenna visibility without the need of unnecessarily extending the length of high-frequency device to antenna cabling.

To make the netBaltic system robust and applicable in different deployment scenarios, we have analyzed the most common communication environments a vessel can encounter at sea. The first such environment involves the vessel located within a communication range of on-shore access networks – the area referred to in the netBaltic project as Area A (Fig. 4). In this case, it is relatively easy to obtain network connectivity using popular access solutions such as an LTE. However, despite the standardization of cellular technologies, the necessity of obtaining and utilizing a correct Subscriber Identification Module (SIM) recognized and accepted by service providers capable of supplying the network coverage in locations likely to be visited by a moving maritime vessel, can be a significant complication.

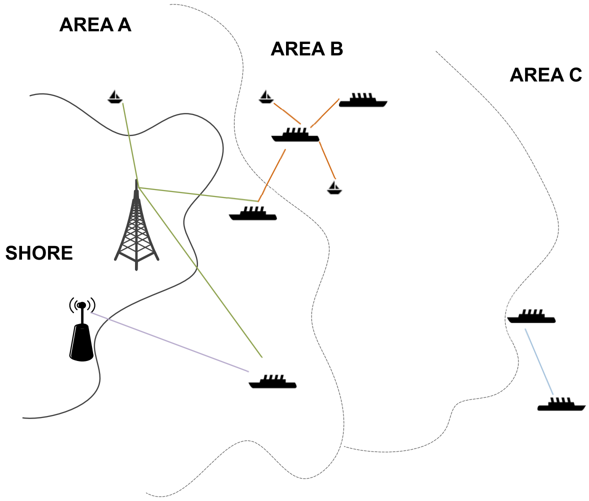

FIGURE 4. Communication areas of the netBaltic system (after [58]).

The situation is improving with the emergence of service providers recognized by multiple network operators and thus capable of offering their subscribers access to the network utilizing access networks created and maintained by multiple different network operators. However, the selection of the best network operator in the case of a number of them being available is still not a straightforward task. We should also remember that cellular networks are just one type of access technologies which can be used to provide the network connectivity for maritime vessels in the vicinity of land.

The second communication environment consists of vessels located outside the coverage area of the land-based communication infrastructure. It involves a multi-hop data transmission path possible via other vessels, which would re-transmit the data until it is received by its intended recipient or the on-shore infrastructure for further delivery. This scenario is common in areas where a significant concentration of vessels is likely to occur, as, e.g., along shipping lanes, in the vicinity of port approaches, or even during unplanned events such as Search and Rescue (SAR) actions. While IP networks, in general, operate similarly with routers forwarding data packets between themselves until they reach their intended destinations, there are few standardized solutions (for example the IEEE 802.11s amendment to the IEEE 802.11 standard [50]) capable of supporting this mode of operation (multi-hop network) in dynamically changing wireless systems. The area where such a real-time, multi-hop communication with the on-shore infrastructure is possible is referred to as Area B (Fig. 4) in the netBaltic system.

It is evident that even with successful employment of various on-shore access solutions and the introduction of multi-hop capability, there are still large sea areas (denoted as Area C in Fig. 4) where real-time communications with the on-shore infrastructure is impossible using terrestrial communication systems. However, vessels located there can potentially utilize a delay-tolerant method of data delivery, by creating information packages of considerable size, storing them for extended periods, and forwarding them when the movement brings those vessels to areas where one of the previously-described real-time connectivity scenarios is

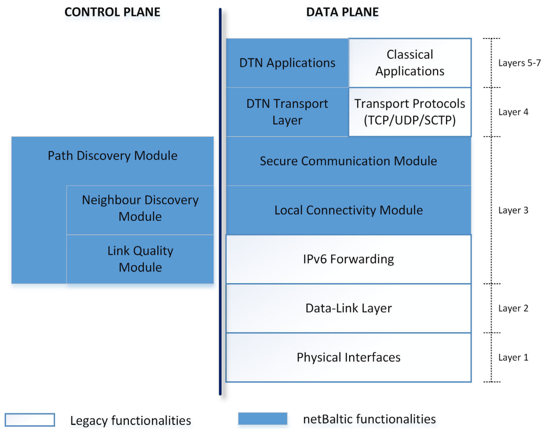

FIGURE 5. **ISO-OSI architecture of a netBaltic node (after [58]).**

possible or after entering the area of direct communications with other vessels. Such a store-and-forward mode of network operation is known as a Delay Tolerant Network (DTN) [60].

As each of these scenarios is highly likely to occur, the design of the netBaltic system includes mechanisms introduced to accommodate them all. For this purpose, the system utilizes the three integrated but distinct sets of mechanisms:

- a heterogeneous access system with soft handover and mobility management support in Area A;
- a self-organizing, heterogeneous mesh system in Areas A and B;
- a delay-tolerant system of end-to-end delivery of data packages in all three areas (in particular in Area C).

The use of different network mechanisms makes it possible for the system to function efficiently in various communication scenarios and provide the improved operation within the coverage of multiple access networks of different operators and technologies. It also extends the coverage over remote areas if the density of netBaltic nodes is high enough. Moreover, it enables the exchange of data in locations characterized by only sporadic opportunities of data transmission between passing vessels.

The overall architecture of the netBaltic node in ISO-OSI layered model is presented in Fig. 5. In this figure, it can be seen that all mechanisms required for the system to function (described in the latter part of this section) are located above the data-link layer (layer 2), which provides the flexibility of transparently employing different layer-2 communication technologies. Moreover, most of the netBaltic functional modules are placed above the majority of IPv6 mechanisms located in the network layer (layer 3) allowing for the reuse of many well-implemented and tested elements of this protocol, mainly belonging to the data plane and thus directly involved in traffic processing and forwarding. The operation of these mechanisms is configured and controlled by the netBaltic-specific functional modules, the majority of which belong to the system's control plane. As a result, netBaltic system offers standards-compliant IPv6 network connectivity, which facilitates its integration with a wide range of external ICT systems and services (both specifically maritime-oriented and general purpose offerings popular in on-shore environment).

Communication capabilities offered by devices connected to a node are utilized in a coordinated manner to provide the best data exchange capabilities possible for a given location of a vessel. Depending on the communication scenario and the application requirements, a different set of netBaltic networking mechanisms (summarized in Table 1) is employed for this purpose. The combination of easy communication device integration, soft-handover capability and effective mesh routing allows the users of a netBaltic node to obtain the uninterrupted network connectivity despite the occurrence of both horizontal and vertical handovers. This approach is also beneficial for the network-access provider. In this case, the infrastructure can be better designed and deployed if mobile nodes are able to change their network attachment points efficiently. To solve the limited cells capacity problem, dedicated access points covering areas where the highest vessel density is observed can be used to offload the traffic from the long-range wireless system.

The robustness of the system is based on three sets of integrated network mechanisms:

- a highly optimized point-to-multipoint access network support to be used in a range of the on-shore infrastructure;
- a heterogeneous self-organizing mesh network used to extend the area where real-time communications with the on-shore infrastructure is possible and to support communications between groups of maritime vessels;
- a Delay Tolerant Network to support many MS applications even without such real-time communications.

These mechanisms, supplemented by a scalable solution for traffic exchange between a wide-area mesh network Internet, make the netBaltic system a highly universal proposition for broadband maritime communication, capable of fulfilling the needs of modern e-navigation services declared in Maritime Services.

D. OTHER ONGOING WORKS ON BROADBAND MARITIME COMMUNICATION SYSTEMS

The issue of broadband maritime communications has been addressed so far also in several research papers. In particular, in [80], the authors present another maritime communication solution using a long-range (LR) Wi-Fi technology as a backbone network connecting standard Wi-Fi access systems on boats to the 4G LTE infrastructure on-shore. The solution offers a multi-level, automatically reconfigurable backhaul with three types of nodes of differentiated complexity and performing various tasks. Performance measurements over the Arabian Sea showed that LR Wi-Fi technology with directional antennas located at a high altitude of 56 m could offer data rates of up to 3 Mbps and connectivity extended up to 60 km (or more using relay nodes and multi-hop transfers).

TABLE 1. Summary of netBaltic architecture elements.

Architecture elements	Description	References
Link Quality Evaluation Module	The link quality assessment is conducted by observing the flow of user traffic in the network layer, supplementing the process with an active testing approach in which dedicated testing traffic is generated. The resulting metric is based on the average value of an effective link throughput, measured for a relatively long time (i.e., tens of seconds).	[61], [62]
Neighbour Discovery Module	The module can advertise the presence, identity and capabilities of the netBaltic node, periodically transmitting messages structured as IPv6 packets of a dedicated netBaltic protocol. Such a solution allows netBaltic nodes to verify the possibility of establishing bi-directional communications and gathering information about its two-hop neighbourhood.	[63], [64]
Path Discovery Module	Hybrid (proactive and reactive) mechanisms are employed for path discovery. All network traffic exchanged between the netBaltic system, and the Internet is forwarded through the root node capable of both participating in the netBaltic multi-hop network and Internet routing infrastructure, as well as exchanging traffic with other Autonomous Systems. The system supports multiple points of traffic exchange with external networks.	[65]
Secure Communication Module	The module is responsible for the protection of network traffic exchanged between nodes of the system and provides: a) authentication and access control based on X.509 certificates ensuring that only nodes using valid certificates issued by netBaltic certification authority can create links to the other nodes in the system; b) data-plane traffic protection including its privacy and integrity. The module employs a well-tested implementation of IPSec mechanism to fulfil its function.	[66]–[70]
Local Connectivity Module	The module is responsible for directing data flow between the connected communication devices and the remaining modules of the node, allowing multiple such devices to remain simultaneously connected to different access systems, but the selected one being utilized for data transfer. It provides mobility management mechanisms maintaining data sessions open even if wireless technology is changed.	[71]–[74]
DTN Transport Layer	Delay-Tolerant Network mechanisms in the netBaltic system were designed to maximize the delivery ratio and to minimize the delivery time. The data packages are compressed, encrypted and digitally signed with certificates of communicating nodes to ensure their confidentiality and integrity in transit. Each package has the lifetime parameter describing the period after which the package is to be deleted because it is no longer useful for the application for which it was intended. The delivery of packages has been implemented by by means of flooding.	[75]–[78]
DTN Applications	Custom DTN-aware application developed to work with DTN Transport Layer	[79]

TABLE 2. Comparison of selected maritime communication systems.

	VDES	TRITON	netBaltic
Bandwidth	Small	High	Technology dependent
Transmission range	High	Short in one hop, moderate in multi-hop strategy (limited to 3-4 hops)	Short in one hop, moderate in multi-hop strategy
Frequency usage	Defined by IMO/WRC (licensed)	2-6GHz (licensed)	Technology dependent (both licensed and unlicensed bands)
Cell capacity	Limited (depending on the number of active stations)	Moderate	Moderate and high (in the case of simultaneous use of several technologies)
Scalability	Limited	High	Very high
Interoperability	Strictly limited (dedicated application gateway required)	Provides internal link-layer connectivity	Native support of IP communications and interworking mechanisms
Openness to new wireless technologies	Closed system dedicated mainly to ensuring security – limited to one technology	Closed system dedicated mainly to ensuring security limited to one technology	The system can utilize any IP-compatible communication technology

Another research initiative conducted by BlueCom+ (a consortium of European organizations [81]) proposed the concept of affordable connections at remote sea areas. It uses Flying Wireless Routers (FWR) – tethered aerostats acting as relaying points for maximization of line-of-sight coverage. Simulation results presented in [81] show that this architecture enables radio ranges over 100 km and bitrates exceeding 3 Mbps using a two-hop land-sea communication chain. During the experiments, the 500 MHz or 700 MHz frequency bands were used, for to air-to-air or to air-to-shore communication. The results showed that the maximum achievable distance to the shore was 45 km for the first hop and about 10 km between two FWRs. During the test, Internet access was available for smartphones on board at rates above 1 Mbps [37].

In [22], the authors present an ongoing research project currently implemented in the Republic of Korea, called the LTE-Maritime system. Unlike some other recent proposals extending the range of communications using multi-hop and mesh networks, the authors propose a single-hop, long-range communication solution using a homogeneous LTE infrastructure. On-shore base stations (LTE-Maritime BS) with antennas located at high altitudes (even at 350 m above the sea level) communicate directly with ships to provide a relatively broad coverage and reliable communications. The LTE-Maritime network utilizes frequency ranges of 728-738 MHz for uplink (UL) and 778-788 MHz for downlink (DL). The experiments showed that LTE-Maritime system could support relatively high data rates of several Mbps while providing a range of about 100 km. During the tests, data rates of 3 and 6 Mbps were obtained (for UL and DL, respectively) for distances of up to 30 km.

IV. EVALUATION OF SELECTED COMMUNICATION SYSTEMS DEPLOYED IN SUPPORT OF MARITIME SERVICES

While all the systems mentioned in the previous section represent interesting approaches to specific maritime communication scenarios, systems like VDES, TRITON and netBaltic aim to provide a more comprehensive, general solution. Table 2 presents a general summary of their key characteristics.

In the following section, we intend to present the results of a series of experiments illustrating advantages of the selected communication systems. The presented scenarios are based on the predicted use cases of IMO-defined Maritime Services. They include a system deployment to provide services of local importance over an area of dense shipping in the direct neighbourhood of a busy port and a situation, where the system is utilized to distribute information farther off-shore, along a shipping lane.

A. SCALABILITY OF LOCAL AREA MARITIME SERVICES

Scenarios requiring communication in areas where there is a high concentration of communicating vessels and where communications is to be performed with the on-shore destinations are relatively frequent. Especially in areas such as port approaches or road-steads. These are also locations where the demand for various IT services is exceptionally high. Indeed, as a lot of port-related activities can be facilitated with their use, including the exchange of various formal and business-related documents, updates of maps, planning and filing the harbour approach, coordinating tug and piloting operations and many more.

There is a sizable group of Maritime Services defined and applicable in such an environment – these are mostly services benefiting from reliable, broadband communications between maritime vessels and local authorities or infrastructure, including, e.g.:

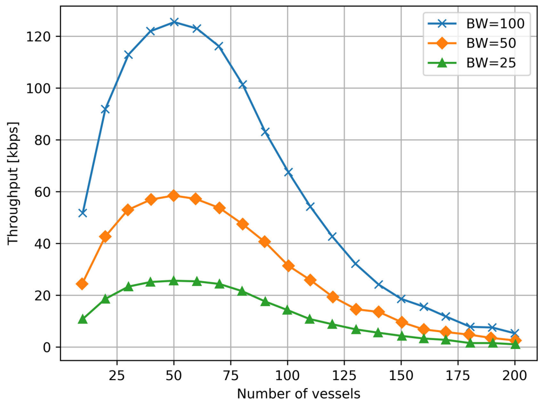

FIGURE 6. The aggregated VDES uplink throughput as a function of a number of ships in mutual communication range (based on results presented in [82]).

- Port Support Service (MS4);
- Pilotage Service (MS6);
- Tug Service (MS7);
- Vessel Shore Reporting (MS8);
- Telemedical Assistance (MS9);
- Maritime Assistance Service (MS10).

It can be expected that VDES with a theoretical bandwidth limitation of around 300 kbps for all its functions will be able to provide only a very limited support for such a wide range of IT services requested by a large number of clients simultaneously. One of its main advantages: a long range of communications of a single terminal, will prove to be a liability here, as the available throughput will be shared by terminals located over a large area, making the system poorly scalable with a growing density of terminals.

Fig. 6 illustrates this limitation of the VDES system. It shows the maximum aggregated uplink capacity for the growing number of ships equipped with VDES devices that are within a mutual communication range [82]. The figure presents the results for three standard channel widths: 25, 50 and 100 kHz. It can be observed that a competitive Random-Access Channel (RACH) procedure employed by the system leads to a significant efficiency loss and an aggregated throughput degradation in the case of a high number of VDES terminals attempting to transmit data. A study of the effect is presented in [83], where authors analyze the RACH algorithm efficiency in detail.

The results clearly show that in such an environment, even with a 100 kHz channel, the total bandwidth available for VDE-TER uplink communications does not exceed 130 kbps. Also, starting from around 50 VDES terminals in a mutual communication range, the available bandwidth is rapidly decreasing due to the inefficiency of its channel access procedures. For 130 terminals, the available aggregated bandwidth is only 20% (26 kbps) of the maximum theoretically obtainable value.

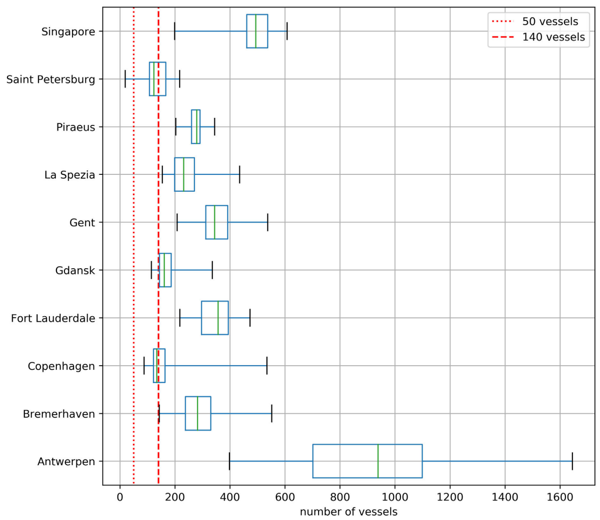

FIGURE 7. **The average number of vessels with an AIS transponder in the neighbourhood of selected ports.**

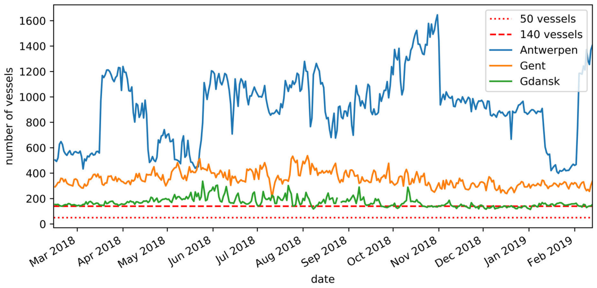

FIGURE 8. **The daily number of vessels with an AIS transponder in the neighbourhood of selected ports.**

To illustrate the possibility of encountering such a density of sea-going vessels in real-world scenarios, we present the analysis of real-world ship location data obtained from the AIS system. This data includes information about all passenger ships and ships over 300 of deadweight tonnage, but may or may not include smaller vessels which are not required to install an AIS transmitter. The results show the number of vessels equipped with an AIS transponder in the AIS range (15-60 NM, depending on the propagation conditions) of a group of well-known ports: Fig. 7 – the number of vessels averaged for one year (February 2018 – January 2019) and Fig. 8 – the daily values for the same period. In both figures, the value of 50 (corresponding to the maximum VDES efficiency) is marked with a red dotted line, while the red dashed line indicates the number of vessels for which the efficiency of VDES falls to 20% of its maximum value.

The above results indicate that the long-ranged but poorly scalable and low-bandwidth VDES technology cannot be relied on to provide communication capabilities adequate for the needs of modern IT services, even these designed for the communication-limited environment. On the other hand, deployment of a system relaying on many relatively short-ranged but high-throughput links forming a self-organizing, multi-hop a network should be able to satisfy communication requirements of services of previously mentioned MSs. Such a network, utilizing technologies such as Wi-Fi and WiMAX will be able to create a stable communication structure covering most vessels in the area due to a density of their placement. At the same time, the limited interference range of a single transmitter (in most cases sharply limited by a line-of-sight horizon) will allow a spatial reuse of frequency channels. The above analysis seems to validate the approach taken by projects such as TRITON and netBaltic, as their multi-hop network mechanisms are able to offer broadband connectivity, especially in scenarios where the demand on bandwidth is expected to be the highest – taking into account both a number of ships and characteristics (for example a relatively high data volume) of MSs which are most likely to be utilized.

The difficulty of such deployments lies in the need to ensure a sufficient concentration of ships equipped with a mutually compatible communication solution. Also, since the analysis of the involved MSs indicates that the main traffic volume will be exchanged between the seagoing vessels and the land infrastructure, there is a need for compliance with the latter. With a significant number of WLAN/WMAN and mobile access technologies (for example, EDGE, HSPA, LTE) to choose from and with the infrastructure divided between many infrastructure operators, the problem is a serious one. In this situation, it can be expected that any attempt to implement a solution based on one communication technology will result in a need to deploy both new shipboard communication terminals and a dedicated on-shore access infrastructure.

At the same time, the heterogeneous netBaltic approach has several advantages. As a netBaltic device can function simultaneously using many off-the-shelf transmission technologies its user equipped it with – a selection which the user decided is most likely to employ effectively in a number of different locations. All of these standard technologies will always be ready for use if an opportunity arises, both to participate in a multi-hop mesh network and to serve as client devices for the external, already deployed access infrastructures. This flexibility of use and ease of integration with the netBaltic system can be expected to serve as a powerful incentive in the deployment of the system.

Apart from the facility of deployment, the ability to utilize the existing access systems as the first hop between well connected on-shore resources and a multi-hop wireless mesh at sea positively impacts both reliability and performance of such communication. By providing multiple points of traffic exchange between these two environments, the system spreads the traffic and minimizes the potential contention in their vicinity. However, as the structure of the mesh is continuously changing due to the mobility of maritime vessels, the netBaltic capability of soft-handover (instead of a hard handover often deployed in traditional network solutions) and the mobility management prove to be of critical importance. To illustrate a negative impact of the connectivity gap caused

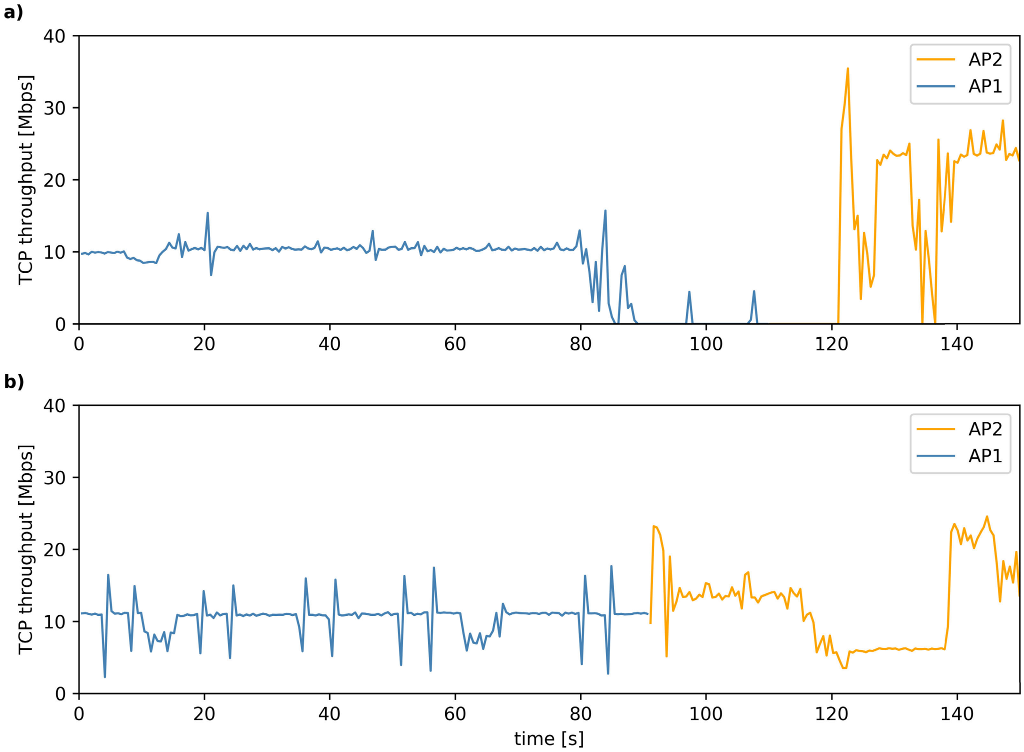

FIGURE 9. An illustration of TCP throughput for (a) Proxy Mobile IPv6 with a hard handover, (b) Proxy Mobile IPv6 with soft-handover (netBaltic case).

by a hard handover we have presented a comparison between momentary TCP throughput values of a client changing its point of network access with and without soft-handover capability (Fig. 9). During the test in each scenario, a mobile client changes its location between two access-points connected to different access networks in which our own implementation of Proxy Mobile IPv6 [71] was used. Due to this mobility management mechanism, the IP address of the client and routes to other nodes remain valid and do not need to be changed after connecting to a new point of network access.

It is evident that the disruption caused by momentary lack of IP connectivity during a hard-handover procedure is significant and observable for a considerable time even after the handover has been completed (Fig. 9a). Moreover, due to this expected handover-related disruption, most decision algorithms require the quality of the current connection to be severely degraded before the handover is initiated. In the case of popular implementations of some technologies (such as IEEE 802.11), the link must become inoperable due to the adverse propagation conditions before making the handover decision. That requirement leads to a period before the handover when communication quality is poor. The effect has a significant impact on the traffic flow, especially in the case of the TCP protocol which has been designed for highly reliable networks and interprets the degradation of connectivity parameters as caused by congestion, to which it reacts by drastically limiting transmission speed at the traffic source. After the handover, the TCP transmission speed is gradually increased, following a slow-start fast-backoff procedure [61], which induces the observable delay until the capacity of the new link can be fully utilized.

In contrast, the soft-handover process (Fig. 9b) introduces only a slight disruption of the TCP traffic stream as the connection to a new point of network access is established before the previous one is terminated, eliminating the time period when no link is active. This further allows a more proactive approach to be taken and the switch to a new connection to be performed before the quality of the old one becomes seriously degraded. Such capability provided by the netBaltic terminals even when performing cross-technology handovers (for example: from LTE to WiMAX or Wi-Fi), makes it possible for maritime vessels to utilize their installed communication equipment as an integrated system and choose the access technology and operator from a full range of options available in the current location. At the same time it allows the frequency of handovers to be freely adjusted for specific communication conditions and available communication options without risking the throughput reduction caused by frequent hard-handover connectivity gaps (aggressive handover strategy) or pre-handover link quality degradation (conservative handover strategy).

Results presented in this section illustrate the scalability limitations of long-range VHF communications and problems of employing such communications in support of e-navigation services. The use of a self-organizing network consisting of short-range communication devices seems to be a valid answer to the e-navigation needs. Furthermore, it can be observed that port-approach areas are a place where even if only a portion of ships is equipped with such a system, the density of nodes should be sufficient for a continuous network to be formed (based on real-world location data and transmission range measurements). Fig. 10 presents such an assessment for a scenario based on real-world AIS data: a mesh structure based on WMAN technologies such as WiMAX and a very limited number of on-shore points of network access (indicated by yellow X marks) offering LTE connectivity, located mainly in major port installations. AIS-equipped vessels are marked with green colour if they can obtain the real-time ship-to-shore communications in such a network environment (and with a orange colour if such communications is not possible at their indicated location).

Both TRITON and netBaltic projects offer self-organizing mesh networks designed to provide truly broadband access for a large number of maritime vessels in such conditions. At the same time, the heterogeneous netBaltic approach additionally allows a transparent use of the existing communication infrastructure, enabling seamless deployment of the system. The soft-handover and the mobility management mechanisms make it possible for client terminals to take full advantage of various access options and to provide a stable first hop (connection to shore infrastructure) for a self-organizing mesh. Also, the fact that client terminals can use different communication devices makes the system a universal solution for different locations (and their associated, different communication infrastructures). It allows a gradual upgrade as new communication technologies become available.

B. PERIODIC MARINE INFORMATION DISSEMINATION

As presented in the previous scenario, a broadband, self-organizing mesh network seems to be a good solution for connectivity in areas with a sufficiently dense concentration of participating maritime vessels. Analysis of AIS data shows that areas such as port approaches can provide concentration sufficient for a system based on WMAN or even WLAN technologies deployed in accordance to the ITU rules for the maritime environment [84] to create a stable mesh network structure [39]. Unfortunately, in most sea areas the density of vessels will not be sufficient to create a sizable mesh network using these relatively short-ranged technologies. The same AIS data indicate that even in the case of main Baltic shipping lanes, the communication range of WLAN/WMAN technologies is insufficient to provide a continuous communication path between vessels and the shore infrastructure (Fig. 10). This figure, prepared by means of the simulation model from [39], clearly shows that even communications between different vessels along the shipping lane will, most probably, be possible only within isolated groups of ships.

Such a geographically-limited communication capability may still prove very useful in specific e-navigation scenarios. Examples include, e.g., those related to Search and Rescue (SAR) operations (MS16), in which the real-time coordination is required between many ships located at a relatively short distance. However, in the case of many Maritime Services, the ability to transfer information between relatively remote vessels or between the on-shore infrastructure and a large number of vessels at sea will be required for the efficient performance of their services. Fortunately, in many practical cases, such communication possibilities do not have to be offered in real-time via a continuous mesh path. Indeed, relatively long delays (e.g., hours or even days) are allowed if the specified data set is finally completely delivered and with its integrity preserved.

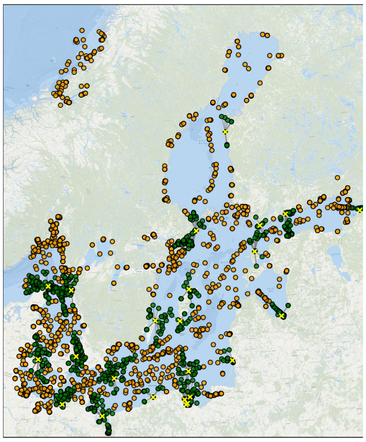

FIGURE 10. Visualization of a mesh network connected to the on-shore infrastructure using LTE access. Green dots – vessels with the ship-to-shore connectivity, orange dots – vessels with no ship-to-shore communication capability (the simulation model from [39]).

Examples of MSs which can efficiently utilize the above mode of communications (Delay Tolerant Network) include many services related to dissemination of different types of periodically updated information, typically (but not always) originating from the on-shore sources such as:

- Nautical Chart Service (MS11);
- Nautical Publication Service (MS12);
- Ice Navigation Service (MS13);
- Meteorological Information Service (MS14);
- Real-time Hydrographic and Environmental Information Service (MS15).

Of the solutions presented in this paper, only netBaltic system incorporates mechanisms enabling such a delay tolerant mode of communications – the VDES relies on its considerable range to deliver small messages. At the same time, TRITON clearly focuses on providing the optimized broadband service in the previously described areas of dense shipping.

Two separate scenarios based on real-world ship location information obtained from the AIS system are presented below to illustrate the usefulness of a DTN approach in the maritime data dissemination. The first scenario shows the dissemination of on-shore generated navigational information. The second one illustrates a situation, when the information has been generated at sea – for example in response to the discovery of the unexpected navigational hazard or adverse weather conditions. As the size of a standard, periodic update of nautical charts (including additional information such as e.g., meteorological data) for a given area can vary, we have decided to perform our analysis for an update package of a size based on current marine practice. For an efficient distribution of such updates using narrowband communication technologies currently in use, the size of a single update is kept as small as possible, at the cost of limited details and/or area the update describes. In keeping with the above practice and estimation of the real-world update sizes for the Baltic Sea area we have assumed the size of a single update package to be 64 kB. Additionally, we find it proper to proceed with the dissemination of the updates by delivering the same message to all the recipients instead of being individually prepared for each receiver. While the second case is relatively frequent (for example commercially available updates are often encrypted per recipient), our choice will allow the narrowband, long-ranged VDES to set a challenging baseline for the mesh-based solutions like TRITON and netBaltic systems.

To illustrate the case of the on-shore generated data dissemination, we have limited the process to a single point of origin for the sake of clarity and selected the port of Gdańsk as such a dissemination source. Ship locations and motion information for the 10th of September 2012 have been obtained from AIS data for the area. The port of Gdańsk, according to information presented in Fig. 7, should serve as a good example, as its concentration of ships is sufficient to make the use of mesh communication, but not so high that it would be possible to deliver the data to all vessels in the area. The MS information update package of the previously described size has been generated and transmitted using all three systems from a point within the port infrastructure. The TRITON employs its optimized WiMAX communication solution, while VDES utilizes a broadcast transmission using its most effective modulation-coding scheme and the frequency channel width of 100 kHz. In the case of the heterogeneous netBaltic system, its nodes have been equipped with IEEE 802.16 (WiMAX) transmission devices for shore-vessel communications and shorter ranged IEEE 802.11 (Wi-Fi) devices for vessel-to-vessel transmission. Based on the experiments made in the netBaltic project and due to the results presented in [85] and [22], we assumed the possibility for a direct ship-to-ship (Wi-Fi) communications within the range of 7 km with the effective throughput of 1 Mbps and up to 8.6 km with an effective throughput of 6 Mbps in the case of the shore-to-ship (WiMAX) links. It should be noted that these values should be taken as a general case and specific deployment characteristics can limit or extend the range/throughput considerably – for example using a sector antenna allowed us to extend the WiMAX range to over 14 km.

Fig. 11 shows the number of AIS-equipped vessels which received the update as a function of time. The advantages of long-range broadcast transmission employed by VDES are visible in this case, as the message is delivered to over 170 ships, which is the highest number reached by any of the systems. However, we must remember that even with such a small message size, the transmission took over 3.5 seconds. The larger message sizes would negatively impact the process, due to limited bandwidth and a higher number of message transmission errors. Moreover, in the case of information not suitable for broadcast dissemination (for example commercial navigational updates individually encrypted per recipient) and requiring separate point-to-point transmission for each receiver, each such transmission would take, at minimum, the indicated time.

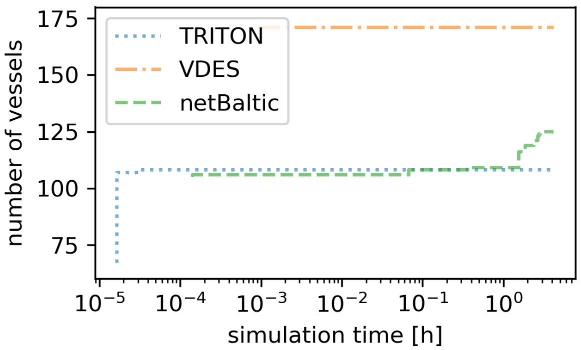

FIGURE 11. The number of vessels which received a 64kB navigational update generated on-shore, presented as a function of time.

Both TRITON and netBaltic efficiently deliver the update within the range of their mesh structures, with TRITON network covering a larger area (130 vessels) due to its use of longer-ranged WiMAX technology, compared to shorter-range Wi-Fi used in this particular deployment scenario of the netBaltic system, which still delivered the update to 127 ships. The average time of mesh-based delivery is well below the VDES best-case estimate, with TRITON requiring about 0.1 s and netBaltic a bit over 1 s to finish the process. The longer time in the case of netBaltic is caused by a lower throughput and a shorter range of Wi-Fi technology (resulting in a higher number of necessary transmission hops).

While in the case of both VDES and TRITON the above results are final, in the case of the netBaltic system, its DTN mode of operation allows further growth of the number of the updated vessels as these units which already received the update carry it to others. Due to a short range of communication technology chosen for the system in this scenario, the growth is slow, adding less than ten new ships during the first hour of the simulated time and about 20 ships during next 4 hours.

These results clearly illustrate that while the superior range of VDES makes it the most effective solution for broadcast dissemination of small messages, the utility of the high-bandwidth, multi-hop approach to maritime communications in areas of dense shipping traffic is evident. Message dissemination and delivery to all receivers within the mesh network is even faster than a direct VDES broadcast, making it a solution of choice for new e-navigation services, which can

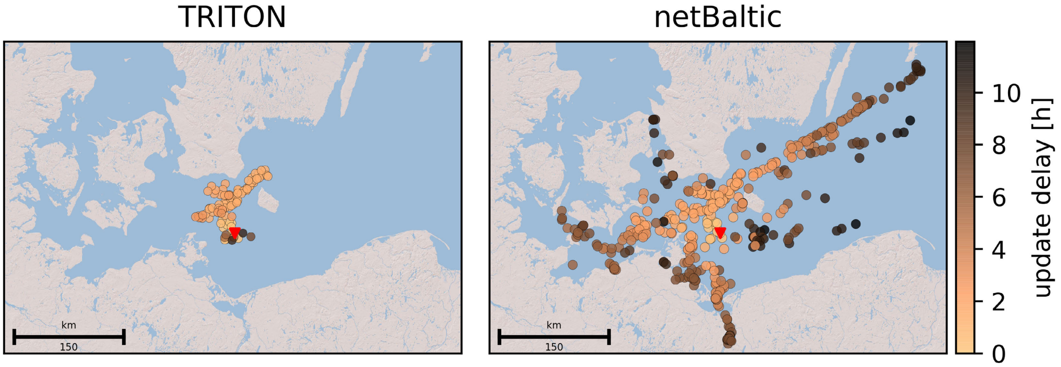

FIGURE 12. Visualization of the information dissemination delay.

be expected to cause the necessity for transferring a growing volume of data. This advantage of multi-hop solutions can be expected to grow, as the narrowband VDES will be unable to efficiently handle data packages of greater size. However, the span of the mesh network remains smaller than the VDES range even in the area well suited for its application. The DTN capability of the netBaltic seems to be useful, however, in the case of dense shipping areas its importance is secondary.

C. SHIP-TO-SHIP DATA DELIVERY ALONG SHIPPING LANES

This scenario depicts a case similar to the previous one. However, in this instance, the information source is located at sea in the area of moderate traffic density (a shipping lane). It corresponds to a common situation when a vessel detecting a specific event (most often safety-related) needs to inform the other approaching vessels. The scenario has been executed with the same network parameters as the port-related one, with the location of the update source shown in Figs 12 and 13 as a red triangle. In the case of the netBaltic system, the update message was generated only once (at the beginning of the simulation) to be disseminated using DTN mechanisms. In the case of the TRITON system, due to lack of DTN support, the message was resent every 5 seconds. The simulation covers 12 hours from the moment the message is generated.

The results make it evident that a lower density of vessels severely limits the utility of multi-hop communication, as the WiMAX transmission range is insufficient to create a mesh network structure reaching far along the shipping lane which results in reduced utility of the TRITON system. While the message is quickly delivered within the continuous mesh structure, further dissemination is limited to a small number of vessels joining the structure due to their movement along the shipping lane. The effect is clearly visible in Fig. 14, presenting histograms of dissemination range and update delay for evaluated systems. For TRITON the furthest node that received the update message was about 100 km from the source which makes it about 3.5 times shorter ranged than for the netBaltic system in this scenario. It can also be seen that the mesh structure of TRITON network which delivered the message to the greatest number of recipients was formed at about the second hour of the simulation. After that time, only single new nodes received the update. Eventually, after 12 hours, TRITON delivered the message to 93 recipients, whereas in case of netBaltic that message was delivered to 469 nodes.

Comparison with VDES is difficult in this case due to many variables influencing the range of ship-to-ship communications using this technology [40]. However, in the comparison based on VDES performance observed in the previous scenario, we can expect that the utility of VDES technology will be high, due to its significantly longer range and lower ship density in this case. Although VDES communication range for ship-to-ship communications is shorter than in shore-to-ship scenario [40], in most cases, it will be sufficient to ensure dissemination of a basic warning message far enough for approaching ships to take the appropriate action based on the information. VDES is naturally still limited in its ability to deliver messages of larger sizes. It, in turn, places severe constraints on e-navigation services being developed for such scenarios, e.g., detailed video/radar information sharing etc., which would allow the approaching vessels to take much more informed decisions regarding the situation in question.

While the utility of communications based purely on WLAN/WMAN mesh mechanisms seems to be limited in this case, the employment of DTN communications by the netBaltic system allows vessels passing the event site to carry detailed information along the shipping lane, informing vessels approaching the location. As time passes, the number of informed vessels increases steadily (Fig. 12). Moreover, the distance from the event site at which the information is available grows (Fig. 13), allowing vessels to use the shipping lane to obtain detailed information with a considerable lead time (as the size of data package can be expected to be of a relatively little consequence due to the broadband nature of the employed transmission technologies). The relation between the update delay the and dissemination range is depicted in Fig. 15. It can be seen that in the case of TRITON,

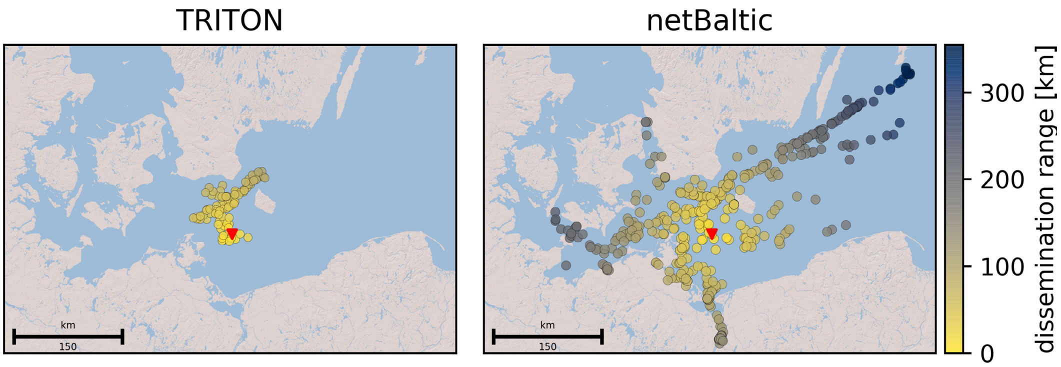

FIGURE 13. **Visualization of the information dissemination range.**

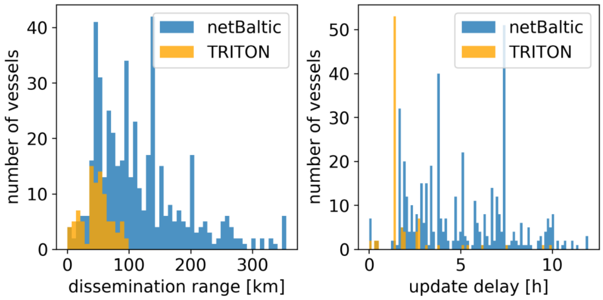

FIGURE 14. **Histograms of dissemination range and update delay.**

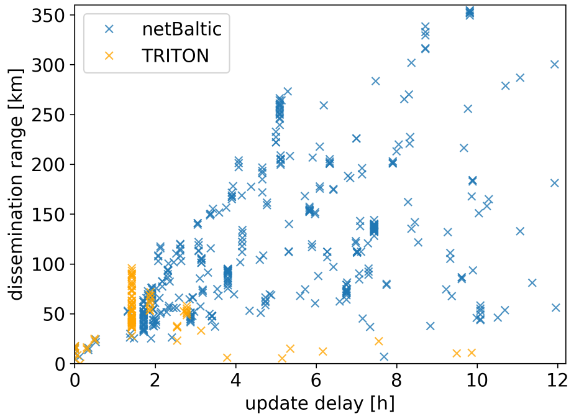

FIGURE 15. **The relation between information dissemination range and update delay.**

after taking advantage of a favorable placement of a group of vessels to efficiently utilize multi-hop communication (at about 2nd hour of simulation), the maximum dissemination range did not increase. Even if new nodes joined the mesh network, they had to be relatively close to the source to form a multi-hop path to the source of the update. At the same time, in the case of the netBaltic system, the dissemination range invariably increased with simulation time. We should also remember, that in case of TRITON the update had to be repeatedly re-transmitted by the source, while in netBaltic system, it had been sent only once.

The scenario clearly illustrates the utility of DTN communications in an environment where communication range offered by high-bandwidth digital transmission technologies is barely sufficient to create the isolated mesh network structures in places other than busy ports and their approaches. At the same time, while the VDES standard proposed by IMO as a default option for e-navigation services is capable of relatively long-range communications regardless of the location of a vessel, its limited throughput makes it a constraining solution for new services.

V. CONCLUSION

In the paper, we presented the current state of maritime ICT solutions and characteristics of their evolution in recent years. Due to the severe limitations of digital communication technologies employed off-shore, the evolution of maritime ICT systems does not follow the pattern observed in land-based environments. With only narrowband digital communications available outside the range of the on-shore infrastructure, the "technology push – business pull" model has not been applied to the maritime community. In its place, an approach where the currently available communication capabilities strictly determine the development of new services has been in effect, removing a significant incentive to develop both new services and communication technologies. To counteract this trend, International Maritime Organization created the e-navigation initiative aiming to stimulate the evolution of maritime ICT. This new approach is an attempt first to define a broad range of maritime ICT needs and to find technical means to implement solutions to address them subsequently.

The paper includes results of statistical analysis and simulation scenarios verified for selected popular maritime IT use cases and their respective IMO-defined MSs, including:

- the scalability assessment of VDES based on the real-world maritime vessel traffic in a group of well-known ports, and the analysis of its ability to support "local area" MSs;
- a simulation of a dataset update dissemination in a dense maritime traffic area (used in many MSs related to navigation);
- a simulation of ship-generated information dissemination along a shipping lane at sea, allowing implementation of many navigation-, safety- and administration-related MSs.

To assess the scalability of both VDES and broadband systems (i.e., TRITON and netBaltic), a statistical analysis of maritime vessel traffic on approaches to a number of well-known ports have been performed and compared with generalized operational parameters of systems in question, based on information obtained during off-shore measurement campaigns and theoretical analysis. Vessel location and movement information used in the analysis have been obtained from an archived, real-world AIS data. The results showed that, while VDES range makes it a good solution for broadcast delivery of small messages, both netBaltic and TRITON, utilizing broadband but short-ranged transmission technologies can offer a much better scalability by dividing the area in question into a significant number of independent cells. Additionally, netBaltic includes soft handover and mobility management mechanisms allowing to utilize many points of data exchange with on-shore infrastructure simultaneously and to deal with vessel movement. It, in turn, makes it an attractive solution for ''local area'' e-navigation services, such as Port Support Service (MS4), Vessel Shore Reporting (MS9) or Pilotage and Tug Services (MS6, MS7). VDES can efficiently broadcast small messages from a single source to a large number of receivers. It will cease to operate efficiently very quickly if the number of traffic sources or the size of messages increases. Analysis of vessel densities around major ports leaded to a conclusion that VDES is not able to satisfy the need for a general-purpose communication technology for the use of services listed in e-navigation MSs.

The simulation analysis concerning a widespread distribution of on-shore generated information has been performed to verify the efficiency of multi-hop systems in support of the globally-oriented MSs. To keep with the current practice (developed due to the lack of broadband means of communication) and to allow comparison with narrowband VDES, we have kept the message small (64 kB). As a source of the message, we have selected a mid-sized Baltic port (Gdansk). The simulation showed that while the area covered by netBaltic and TRITON mesh is smaller than the VDES broadcast area, the difference is not so big. Moreover, broadband technologies deliver the message faster than VDES even for such a short message size. The netBaltic DTN functionality allows it to keep propagating the message after the initial distribution. The results confirm that the mesh-based broadband solutions can support the shore-to-ship message distribution scenarios effectively, making them suitable for the update-based MSs such as, for example, Nautical Chart Service (MS11) or Meteorological Information Service (MS14). A much higher throughput offered by these systems allows for the future development of these services. At the same time, the DTN capability of netBaltic makes it suitable not only for local but also for wide data dissemination scenarios.

The final simulation scenario further illustrated the utility of a DTN capability unique to the netBaltic system. In this case, the source node of information was located at sea (on a shipping lane). With the density of vessels much lower than in the case of port areas, a simple mesh network was of a limited utility. However, ship movement still allowed the netBaltic system to employ its DTN functionality and to distribute the information along the lane relatively fast and over long distances.

The analysis and experiments showed that all the described systems have their dedicated use cases in which they perform effectively. The IMO-supported VDES is going to be a mandatory equipment deployed in all vessels over specific legal limits. It is well suited for a broadcast distribution of small messages, providing a significant improvement over systems employed today for critical maritime communications (such as high-reliability distress signalling). TRITON is, in turn, a broadband system optimized for the efficient use over local areas and groups of ships under a shared administration (which allows a coordinated deployment of the necessary hardware). Its throughput and scalability are not only sufficient to support currently developed e-navigation services but leave a significant margin for further extension of their functionality.

netBaltic is by far the most versatile one of the three – its ability to simultaneously use different communication technologies allows it to be employed in various scenarios, requiring different levels of parameters such as throughput or cell capacity. It is also easy to deploy, being able to utilize different frequency bands and make use of client hardware and access infrastructure already in place. Its combined universal access client/mesh network/DTN capabilities make it a system capable of supporting a full set of currently defined Maritime Services. At the same time, its heterogeneous nature allows it to seamlessly integrate new communication technologies as they become available, ensuring a natural evolution of the system and making it a long-term investment. The netBaltic system has been implemented in the form of the proof-of-concept architecture and deployed in the maritime testbed created in the Gulf of Gdansk. It, in turn, allowed us to verify its operation in real-world conditions and obtain measurement values used in simulations presented in this paper.

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