Situational Awareness for Autonomous Ships in the Arctic: mMTC Direct-to-Satellite Connectivity

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[1] ***Abstract*—The maritime autonomous surface ships (MASS) promise a revolution in naval logistics by offering sustainability, safety, and operational costs reduction. The MASS can bring to Arctic and other hard-to-reach regions numerous social and economic benefits, thus contributing to equalizing the access for human and machine-terminals to connectivity, and equate the life quality of their inhabitants with that of the other regions. In this paper, we suggest a hybrid communication architecture that separates ship's data traffic into awareness and emergency components. For the former traffic, we advocate the possibility of Direct-to-Satellite (DtS) using massive machine-type communication (mMTC) and low-power wide-area network (LPWAN) technologies. To validate this hypothesis and investigate the potential performance and effect of different design and configuration parameters, we conduct simulations based on real-life positions of ships and satellites, traffic patterns, and the LoRaWAN connectivity model. Our results demonstrate the suggested approach's feasibility and clarify the different parameters' effects on the connectivity performance for the classical LoRa and novel long-range frequency hopping spread spectrum (LR-FHSS) modulation coding schemes. Notably, the combination of multi-connectivity of LoRaWAN LPWAN technology and multi-satellite visibility dramatically boosts the probability of packet delivery.**

I. Introduction

Marine transportation covers today more than 90% of the global trade. Therefore, the emergence of maritime autonomous surface ships (MASS) is seen as the next big step in the evolution of naval transportation and attracts substantial attention and resource investments from Academy and Industry. In this way, there is an urgent need to address the following three major connectivity-related challenges:

- **Safety.** From 2011 to 2018, 23,073 maritime causalities were reported, which happened mainly due to collision and loss of control. The on-board crew members are the most affected persons in maritime accidents. The smart ships, featuring intelligent on-board systems and presence of virtual captains (VC), simultaneously minimize crew and human error effect. Therefore, dependable connectivity solutions for different data traffic types are needed.
- **Sustainability and cost efficiency.** Rapid climate change is one of the greatest challenges of our era. Maritime transportation emits around 1 billion tonnes of Carbon dioxide (CO_2) annually, which accounts for 3% of the global greenhouse gas (GHG) emission. The International Maritime Organization (IMO) takes actions to improve energy efficiency, minimize pollution, and GHG emission.The innovative MASS, requiring novel connectivity solutions, will thus play an essential role in reaching the IMO and UN Sustainable Development Goals.
- **Ubiquitous coverage.** The ocean covers 71% of the Earth's surface. Even if located close to shore, maritime routes often go through hard-to-reach and unpopulated areas (e.g., Arctic) where the availability of connectivity infrastructure (e.g., 4G or 5G) is scarce. Today there is no viable solution that can offer global, secure, reliable and efficient situational awareness services to MASS. Therefore, there is an urgent need to develop efficient and omnipresent non-terrestrial networks (NTN) for wireless connectivity solutions to support today's ships and future autonomous ships.

Recently, several studies conceptualized the integration of LPWAN nodes with satellite-based gateways. The real-life practical trials and simulations suggest that machine-traffic can be send from the Earth to the space. In the current paper, we base on this concept and investigate the feasibility and scalability of LoRaWAN direct-to-satellite (DtS) connectivity to enable situational awareness of MASS. The contributions of this study are threefold. First, we discuss the traffic, connectivity scenarios, and technology options for MASS wireless connectivity. Second, we suggest a hybrid connectivity architecture for MASS operations in remote regions employing the traffic division into two major categories. The former composes the heartbeat awareness; automatic identification system (AIS) data traffic periodically broadcast to other ships and Remote Operations Center (ROC) and Vessel Traffic Management (VTM). The latter is the on-demand and emergency traffic for critical emergency situations, allowing assessment of the ship's status and the remote piloting of a MASS. Third, focusing on the situational awareness traffic, we conceptualize, investigate and provide, openly accessible, analytical models and simulation tools targeting the feasibility and performance of conveying AIS data over LPWAN technologies. Specifically, we convey

LoRaWAN traffic through Low Earth Orbit (LEO) satellite-based non-terrestrial gateways (GWs). Our results demonstrate the promising performance of this approach and reveal the effects of LoRaWAN configurations and the satellite constellation design parameters on the connectivity performance.

The rest of this article is organized as follows. Section II briefly presents the background of MASS. Section III reviews the maritime connectivity technologies and associated trade-offs. Section IV conceptualizes the proposed mMTC direct-to-satellite connectivity architecture for MASS. Section V details our modelling methodology. Selected results are presented in Section VI. In Section VII, we outline the key challenges and prospective directions for future research work. Finally, Section VIII concludes this work with final remarks.

II. Autonomous ships

A. MASS development status

According to the IMO, a MASS is *"a ship which, to a varying degree, can operate independently of human interaction"* [1]. To enable this, the digital pipeline of an autonomous ship comprises a rich set of data acquisition sensors, on-board artificial intelligence (AI), and wireless technologies.

Over the past years, the Industry invested significant efforts to bring autonomous ships to reality. For example, Rolls-Royce carried the projects focused on exploring promising technological solutions for autonomous ships [2]. In 2018, the world's first autonomous ferry journeyed in Finland, showing the potential feasibility of unmanned ships. Wärtsilä, General Electric, ABB, and Kongsberg Maritime are among the prominent players in the field. IBM, Google, and Intel offer big data and AI solutions for the maritime industry. The remote controlled and autonomous unmanned ships are expected to be operational in international waters by 2025 and 2035, respectively. The IBM's report prognoses the global autonomous ship market to reach $130 billion by 2030.

B. MASS data

To ensure safety and sustainability of operation and enable situational awareness and collision avoidance, the delivery of various types of data both to and from a MASS are required. These data can be subdivided into two major categories.

The first group accommodates periodic data traffic, which is primarily composed of situational awareness messages. Today, AIS, Dynamic Positioning (DP) and Voyage Data Recorder (VDR) are the major maritime data collection units and contributors to this traffic type. Among these, the AIS is the most prominent and primarily focuses on enabling surveillance, real-time geo-tracking, and collision avoidance at sea. It features three types of data: (i) the static data comprising the Maritime Mobile Service Identity (MMSI) number, vessel name, size, etc.; (ii) the dynamic data, which includes the vessel position, navigational status, speed, etc.; (iii) the route-related data, accumulated information about the destination, expected arrival time and the cargo category. The AIS data is relevant for the nearby ships and to the shore. Typically the AIS message, containing the information about a ship's identity, physical location and motion, is encoded in 21 bytes.

In the second group, we categorise all other data traffic of non-periodic nature, focused, e.g., on effectively reacting abnormal operations and emergencies. These include (i) the various command traffic, and (ii) the diagnostic and sensor data originating from the versatile sensors installed on a MASS. For example, the collision avoidance system of a MASS fuses the data from multiple sensors, such as video cameras, radars, LiDARs, and sound sensors. Due to on-board intelligence and the possibility to operate and manage the ship remotely, the transmission of these data is typically not required continuously. However, in the critical conditions when on-board intelligence cannot handle the situation, the need for reliably transferring big volumes of data from and to ROC [2] can occur.

III. MASS connectivity: options and challenges

In the past decade, the innovations and technology advancement have steered the focus of academia towards autonomous maritime communication needs. In [3], the authors discuss communication requirements and architectures for MASS considering the limits of existing communication infrastructure. Specifically, the authors discuss ship' status indicators and their associated report periods. Similarly, the connectivity challenges of unmanned ships in port areas, deep-sea and Arctic regions are also investigated in [4]. The study also conceptualizes a hybrid satellite-terrestrial system incorporating latest sensor technologies. A survey focusing on in-ship and ship-to-outside connections, 3GPP standardization, and simulating the ships in connectivity research is delivered in [5].

Fundamentally, the MASS connectivity options can be classified into three groups discussed in the following subsections.

A. Maritime connectivity technologies

This group consolidates the technologies and protocols designed and optimized for maritime use. Today's systems operate in the high frequency (HF) or very HF (VHF) bands to enable long-range link. The HF communications using carriers between 3 MHz and 30 MHz provide thousands of kilometres long links in good ionospheric conditions. The latest digital HF systems support 150 kbit/s transmission speeds at reasonable costs. A practical illustration of this is the KNL cognitive HF network, where each radio operates as a terminal and a base station creating an infrastructure-independent network with pole-to-pole coverage.

Another practical illustration of recent developments is the VHF Data Exchange System (VDES) for AIS and Application Specific Messages [6]. The VDES aims at digitizing VHF communications and increasing the performance of AIS by providing two-way data channel connecting satellite, ships and terrestrial components. The first experimental VDES satellite NorSat-2 was launched in 2017, providing a discontinuous access over the Arctic region. The bitrate provided by the VDES is up to 307.2 kbps while using simultaneously four 25 kHz-wide channels. As in the AIS, the main modulation technique in VDES bases on self-organized time division multiple access (SOTDMA), meaning that each vessel has to wait its own time slot. This introduces additional delays and synchronization cost.

Recently, it has been suggested that ships can construct a dedicated mega-constellation based on ship-to-ship links [4]. One significant challenge of this approach is that the link lengths are limited due to Earth curvature and antenna heights [5]. Consequently, the low density of the ships makes this concept infeasible in the regions like Arctic.

B. Terrestrial connectivity technologies and infrastructure

Alongside the coastline, the ships can utilize a terrestrial communication system, e.g., broadband cellular, LPWAN or mMTC technologies. However, the availability of this connectivity is rather opportunistic; these networks are typically present in the decently densely populated areas. For example, the statistics reveal that AIS communication is only available in coastal areas resulting in 47% of the ships' suffering from outage. Meanwhile, establishing large and dense terrestrial networks in remote regions, such as the Arctic, is not feasible due to economic reasons.

C. Satellite technologies

The satellite systems are the third and the most prominent means of communication for ships in the open sea. They are divided into three main groups: Low Earth Orbit (LEO, orbiting below 2000 km), Medium Earth Orbit (MEO, between 2000 and 35786 km), and Geosynchronous Earth Orbit (GEO–35786 km). With over 5000 active satellites, the Earth's orbit is dominated by 4078 LEO satellites as of March 2022. The number is expected to grow exponentially, and there are estimates that up to 100,000 satellites will be orbiting by 2030. On the negative side, GEO satellites cannot provide coverage to the Arctic areas. The conventional maritime hardware terminals can cost up to $60,000 and imply monthly liability of thousands dollars.

One of the most well-known LEO satellite systems is Iridium whose constellation consists of 6 polar orbits, 11 satellites in each, with 86.4^o orbital inclination at 780 km altitude. The constellation is designed for the minimum 8.2^o elevation angle from the ground. The recent generation of Iridium satellites receives real-time AIS transmissions from ships. Due to use of polar orbits, Iridium provides good coverage in the Arctic.

Currently, several other LEO satellite constellations such as Telesat, OneWeb, and Starlink are under development. The initial Telesat constellation plan comprised 72 satellites in the polar shell (6 planes and 12 satellites on each plane), with the sun-synchronous inclination of 99.5^o at the 1000 km altitude. The constellation is designed for a 10^o minimum elevation angle resulting in the maximum slant distance of 2791 km. Inclined shell designated primarily for mid and equatorial areas, comprising 45 satellites distributed on 5 planes with an inclination of 37.4^o and an altitude of 1248 km. Later, the constellation was modified to include 78 satellites in the polar shell and 220 in the inclined shell. The inclination and

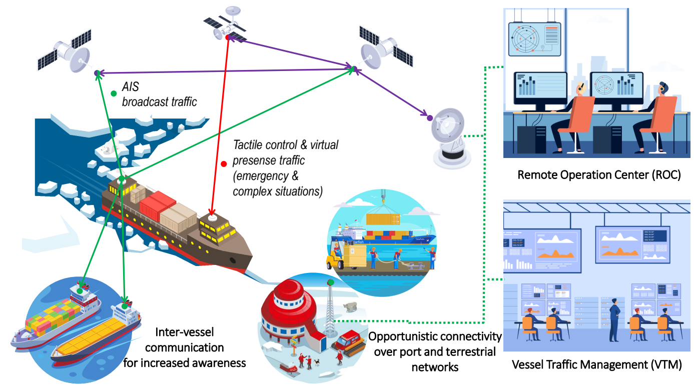

Fig. 1. Envisaged MASS connectivity architecture.

altitude of both constellations were also changed: 98.98^o for polar shell at 1015 km and 50.88^o for inclined shell at 1325 km. In the future, Telesat is planning to add 1373 satellites to the constellation to address future demands [7].

One of the most recent trends for satellite systems is their integration with the mMTC and LPWAN technologies. As discussed in 3GPP TR 38.821 (Rel. 16), the 3GPP considers the NTN based on satellites and high altitude platform stations perspective for enabling coverage in remote areas [8]. On the practical side, Lacuna Space has launched five LEO satellites with LoRaWAN gateways on board to prove LoRa message reception's feasibility in space [9]. Similarly, MediaTek and Inmarsat conducted a successful field trial of DtS network between the mMTC (NB-IoT) node and the GEO satellite. More than this, the recent research papers investigate and demonstrate the feasibility of DtS mMTC communication [10]–[13].

IV. LPWAN/MMTC AND LEO SATELLITE INTEGRATION

Motivated by the progress along the MASS and DtS LPWAN/mMTC networks, we conceptualize the convergence of these two in context of ships' situational awareness. Specifically, we note that the characteristics of the situational awareness data traffic (e.g., AIS) resembles the traffic of machines for which LPWAN/mMTC have been developed. This makes LPWAN/mMTC DtS connectivity a suitable solution for transferring AIS data. Therefore, we envisage the MASS connectivity architecture depicted in Fig. 1, where the traffic is divided into the two main categories. The former composes the situational awareness traffic (the AIS "heartbeat") for which we advocate the use of DtS LPWAN/mMTC networks. The latter, labelled in Fig. 1 tactile control and virtual presence traffic, includes all the other data transfers (e.g., live streaming of sensor data to ROC or commands from ROC to MASS) and should be carried through other means of connectivity (e.g., a broadband satellite or NTN channel; e.g., VDES or another technology out of this paper's scope). We imply that the latter traffic (i) is typically present only in an emergency case when the AI of the MASS cannot handle the situation; and (ii) connects MASS and ROC. Meanwhile, the small-data awareness traffic is (i) transmitted continuously; and (ii) is relevant both for ROC, VTM and the other nearby ships.

Compared to conventional satellite-based AIS systems, the transfer of situational awareness data over LPWAN-like technology has substantial advantage - the LPWAN technologies do not imply any handovers between GWs. This enables multiple recipients (i.e., in space, sea or shore) receive these data. Also, this permits to take advantage of multi-connectivity in the uplink channel if multiple satellite-GWs are above the horizon, thus increasing the chances of packet delivery. Notably, unlike the conventional AIS SOTDMA, LoRaWAN DtS imply ALOHA-like media access which does not inquire any connection establishment phase or waiting delays. We admit that the proposed connectivity architecture is more complex and implies the distribution of the two different data traffic types between the two different communication systems. However, the possibility of optimizing each of the systems for its dedicated traffic and distinguishing the traffic with different priority and quality-of-service requirements would, in our opinion, enable a more efficient in terms of performance and resource utilization operation overall.

To obtain an insight into the feasibility and to characterize the effect of the different design dimensions (e.g., modulation-coding-schemes (MCSs) and satellite constellation parameters), we have carried out simulations of MASS awareness data traffic transfer over LoRaWAN-like networks. Notably, we tested both LoRaWAN modulation-coding schemes:

- **LoRa**: It uses the chirp spread spectrum MCS. For LoRa, underlying the LoRaWAN protocol, the spreading factor (SF; range from 7 to 12 and correspond to data rates (DRs) 0–5) is one of the key elements of the network configurations. The higher SFs improve the GWs ability to demodulate a radio packet in the presence of noise. A unit increase in SFs almost doubles the on-air time, thus increasing the probability of collisions.
- **LR-FHSS**: In the most recent release, the LoRa Alliance introduced long-range frequency hopping spread spectrum (LR-FHSS) MCS into the LoRaWAN protocol. In the EU, the new data rates (DRs 8-11) exploit frequency hopping and offer robustness against the co-channel interference through increased number of radio channels and redundant physical headers and lower coding rate.

More information on these MCS is available in [9]–[11], [13].

V. Simulation models and parameters

A. Operation environment

For our simulations we have selected the Arctic region, which is very challenging for the ships. To understand better the numbers, distribution, and traffic patterns of the ships in Arctic, we have analyzed the real-life AIS data collected by the Arctic Data Center [14]. First, we divided all the AIS records into 10-minute intervals and estimated *(i) the number of ships; (ii) their location; and (iii) their activity.* Our analysis shows that in the busiest interval - August 31, 2016 from 18:51:36 to 19:01:36 - as many as 832 ships were operational. The locations of the ships and their distribution during this period are illustrated in Fig. 2. Our analysis reveals that 39.3% of the ships were *en route* in the deep sea followed by 25.96% in the internal waters. The territorial sea (i,e., area within 12 nautical miles away from the coastline) contained 22.35% of active ships. The remaining 12.37% were anchored or static.

TABLE I
System Model and Monte Carlo Simulation Parameters [9].

Parameters	Values/Requirements	
Operation environment	Arctic region	
Transmit power (P_{tx})	14 dBm	
Path loss exponent (η)	2	
Carrier frequency (f_C)	868 MHz	
Node's antenna gain	G_t = 2.15 dBi	
Gateway antenna gain	G_r = 31.8 dBi	
Elevation angles (E)	$10° \leq E \leq 90°$	
Rician Factor (κ)	$1.24 \leq \kappa \leq 25.11$	
Channel access	Pure-ALOHA	
LoRa	**Values/Requirements**	
LoRa Bandwidth (B)	125 kHz	
Spreading factor (SF)	7, 10 or 12	
Frequency Channels	16	
LR-FHSS	**Values/Requirements**	
Header replica duration (T_H)	233.472 ms	
Fragment duration (T_F)	102.4 ms	
LR-FHSS OBW bandwidth	488 Hz	
OBW minimum separation	3.9 kHz	
DR8/DR9 OCW Bandwidth (B)	137 kHz	
DR8/DR9 OBW Channels (C)	280	
DR8/DR9 OBW Channels/node	35	
DR10/DR11 OCW Bandwidth (B)	336 kHz	
DR10/DR11 OBW Channels (C)	688	
DR10/DR11 OBW Channels/node	86	
Header replicas (N)	DR8/DR10 = 3, DR9/DR11 = 2	
Coding rate (CR)	DR8/DR10 = $\frac{1}{3}$, DR9/DR11 = $\frac{2}{3}$	
Traffic model	**Values/Requirements**	
Report time (T)	2 s $\leq T \leq 30$ s	
Data transmissions	Unacknowledged	
Traffic pattern	Periodic	
Orbital parameters	**Iridium**	**Telesat (polar)**
Altitude	780 km	1015 km
Inclination	86.4°	98.98°
Number of satellites (planes x satellites per plane)	6 x 11	6 x 13

B. Satellite constellation and DtS LPWAN simulation

The analysis of DtS AIS data transfer were done by the specially developed MATLAB simulation and analytical models, which we made openly accessible for the research community (available from GitHub via [15]). We imply that a GW is onboard of an LEO satellite, being a part of either Iridium or Telesat-like constellation. Our constellation models were constructed using Systems Tool Kit (STK) using the parameters provided by the Federal Communications Commission. The key model parameters are listed in Table I.

We consider one LoRaWAN end-device (ED) terminal to be mounted on the top of each ship. The number and the position of the ships was modelled in accordance to the real-life situation during the busiest period as discussed in

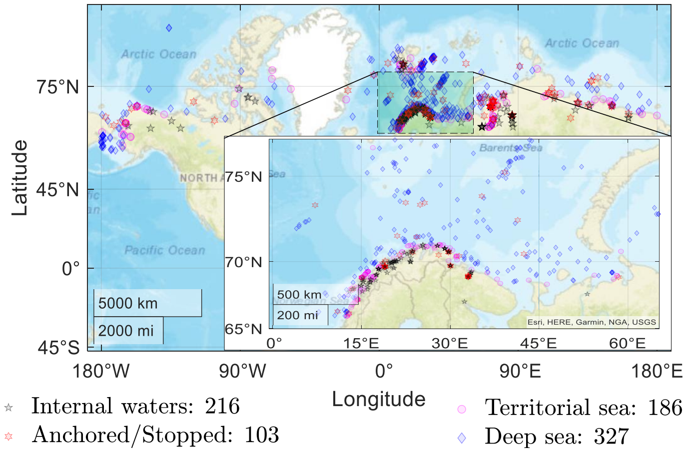

Fig. 2. Analysis of the ships activity in the Arctic region during the most busy period (based on AIS data; 18:51:36 to 19:01:36 August 31, 2016)

Section V-A. Each active ship transmits an 21-byte AIS uplink packet with an average period of $2\ s \leq T \leq 30\ s$, and each anchored ship - with a period of 360 s. Since traffic is one-way and accounting for the limited downlink resources of satellites, no downlink traffic is assumed. Also we imply that all the ships utilize the same MCS, and only the interference from the ships transmitting DtS awareness traffic within the satellite footprint is considered in this work.

We considered the two MCSs supported by LoRaWAN: the LoRa (i.e., DRs 0 to 5) and the LR-FHSS (DRs 8 to 11) introduced in the most recent release [9]. Following the conventional LoRaWAN configurations for the EU, we imply 16 frequency channels available for DRs 0-5, 280 channels for DR8 and DR9, and 688 channels for DR10 and DR11. The time-on-air ToA = 77.05, 452.6, 1810.32 milliseconds for DR5, DR2 and DR0, and ToA = 1929.5, 1084.5 milliseconds for DR8/DR10 and DR9/DR11, respectively. To model the packet loss due to attenuation, we imply that direct-to-satellite connectivity follows the classical logarithmic path loss model. The non-terrestrial GW can successfully receive a packet if the signal-to-noise ratio (SNR) is greater than the demodulator's DRs-specific SNR threshold D_{SNR} = -6,-15,-20 dB for DR5, DR2 and DR0, respectively [13]. Note that we assume that LR-FHSS receiver sensitivity is equivalent or higher than that of LoRa modulation's DR0, as in [9]. Therefore, we imply the $D_{SNR} = -20$ dB for LR-FHSS DRs 8-11. When modelling the collisions we implied that for LoRa any overlap in time and frequency causes packet loss [13], while for LR-FHSS modulation a packet is received in case if at least one header replica and sufficient (threshold depends on the data rates) number of payload data fragments are received (likewise [9]).

VI. Selected Numerical Results

A. DtS performance for a single satellite GW

First, we focused on the performance of the different LoRaWAN MCS for a single satellite. Conducting the analysis of the position of the ships and the satellites' trajectories, we saw that on average 590 ships were operating inside a single satellite's footprint. Of these, 529 ships were *en route* and 61 were stationary. Implying this number of ships, we analysed the probability of successful packet delivery (P_S) by different LoRaWAN MCSs, distances and AIS report periods. Our results reveal that a packet can successfully reach a LoRaWAN gateway deployed on a Telesat-like satellite at the maximum slant distance of 2791 km with over 0.99 probability for LoRa DRs 0, 2 and LR-FHSS DRs 8-11. However, LoRa DR5 shows the lowest success probability, around 0.92.

From Fig. 3 one can see that the DR selection, directly affecting on-air time, coding rate and MCS, strongly influences the probability of success (P_S). For the reporting period of 2 s the P_S for DR0, DR2, DR8 and DR9 stays below 0.01, and DR5 achieves around 0.07. When using LoRa DR0 the performance remains close to zero for the whole range of reporting periods $2\ s \leq T \leq 30\ s$. One can also see that DR8 and DR9 outperform the DR5 when the reporting period exceeds 8s and 10s, respectively. When using DR2 and DR5, at 30 s reporting period P_S is below 0.36 and 0.84, respectively.

Notably, the P_S curves for DR8 and DR9 show that the gateway can successfully receive a packet with probability exceeding 0.88 for reporting period higher than 20 s. However, the DR10 and DR11 can achieve the same performance when T is as low as 8 s. Note that DR10 and DR11 featuring 688 channels for frequency hopping demonstrate the best performance with P_S about 0.97 when T is 15 s which further grows to over 0.99 when ships report every half minute. The standard deviations (std) fluctuate quite significantly; however, generally, the std for LR-FHSS is lower than for LoRa. For example, for DR8 the std varies from 0.3788 at 2-second to 0.0873 for 30-second report periods. For DR5 std is 0.2685 at the lowest, and 0.3651 at the highest reporting period, respectively.

Overall, our results show that the performance of LR-FHSS is higher than that of conventional LoRa MCS. This is primarily due to the hundreds of frequency channels, frequency hopping spread spectrum techniques, the coding rates and physical headers' redundancy employed in LR-FHSS.

B. Satellite visibility

Next, we simulated how the number of visible satellites (NVS) to a ship changes in time. Fig.4 reveals the probability for observing the different NVS in a selected location of 70 degrees latitude (dotted line) indicating the busiest port and an averaged time percentage of NVS for a set of moving ships (in bars). The position of the moving ships was selected from 66 to 75 degrees latitude covering the busiest maritime routes. For each ship, the exact NVS was recorded. As the NVS changes with time and movement of the ship, the percentage of time was calculated for a certain NVS for each ship and averaged over a 7 day period to obtain different variations of NVS. An example of NVS variation for a moving ship over a one-day period for the two different satellite constellations is presented in the top right corner. The bar plot results reveal that the NVS fluctuated between 2 and 10 for Telesat-like constellation and

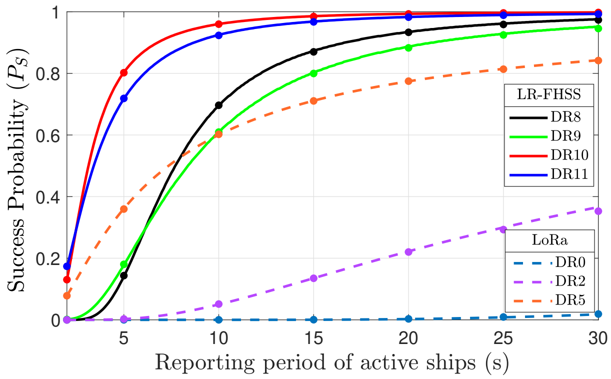

Fig. 3. Average packet success probability P_S as a function of AIS reporting period for single Telesat-like satellite, where the line plot denote the analytical and scatter points illustrate the Monte-Carlo based simulation results.

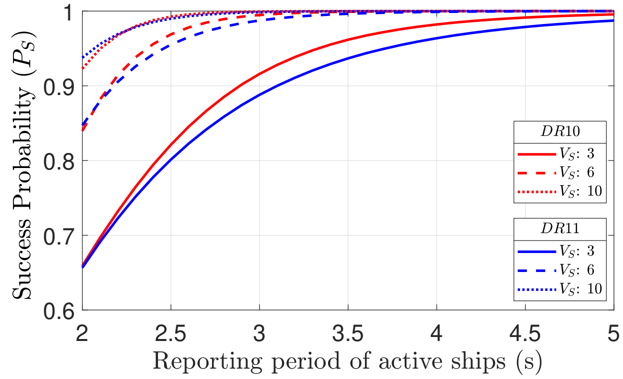

Fig. 5. Average success probability P_S as a function of AIS reporting period for DRs 10 and 11 for multiple visible satellites.

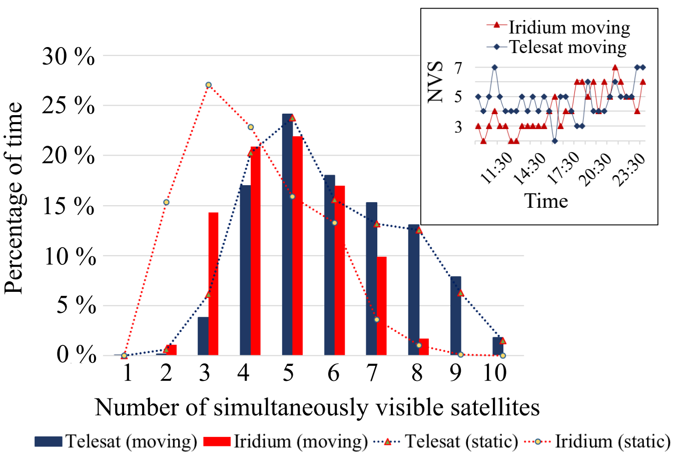

Fig. 4. Distribution of NVS for a selected static location (dotted line) and an averaged time percentage of specific NVS seen by a moving ship (in bars), where the top right corner compares the NVS for Telesat and Iridium constellation as a function of time.

between 2 and 8 for Iridium-like one. The average NVS (over multiple marine routes) was between 5 and 6 for Telesat, and 4 and 5 for Iridium. The NVS is highly dependent on the location of the ship and in the Northern regions the number is generally higher. At least 3 satellites are visible for both constellations most of the time. In general, the results suggest that Telesat constellation (polar shell) is able to provide higher NVS than the Iridium.

C. DtS performance for multiple satellite-GWs

Finally, we have extended our DtS simulations to obtain an insight into the performance of a multi-satellite system with a Telesat-like constellation. Figure 5 illustrates the overall success probability for the different NVS (V_S) and various reporting periods for the two LR-FHSS data rates, which demonstrated the best performance in single-satellite case. One can see that for V_S=3 when using the lowest reporting period a packet can be successfully received with P_S=0.65 for DR10 and DR11. When T exceeds 3 s, P_S stays above 0.88 for both DRs. With V_S=6, which is the average NVS based on our analysis in the previous section, the P_S for DR10 and DR11 is about 0.84 for the minimum report period and reaches 0.99 at T=3 s. Notably, for the maximum NVS (i.e., V_S=10) and the minimum report period the P_S exceeds 0.92 and demonstrate success probability of 0.999 at T above 3 s. These results illustratively show that visibility of multiple satellites combined with multi-connectivity offered by LPWAN technologies enables a great boost for the packet delivery probability. More than this, earlier studies on LoRaWAN DtS demonstrated that, e.g., for 100000 nodes, the capture effect, which we do not account for here, can recover up to 9.53% of all the collided packets [10].

VII. Challenges and Further Research Directions

Our results evince the feasibility and the promising performance of LPWAN/mMTC and LEO combination for MASS, but there are a number of challenges for its enabling.

- **Integration with other existing and coming connectivity systems:** The LPWAN/mMTC satellite systems will push the digitization of the maritime domain. However, other systems, including mega-constellations, are needed to support capacity-heavy applications such as multimedia streaming or transfer of tactile control data. We believe that co-optimization of these systems, intelligent access selection, resource management, and routing is needed to unleash the full potential.
- **Optimization of the design and configuration parameters**. Our results show that the performance of LPWAN/mMTC DtS systems is affected by many settings, including the number and orbital characteristics of satellites, their design (e.g., antenna and beamforming capabilities), selection of MCS, and configuration of the network. Therefore, optimizing a satellite constellation design for LPWAN/mMTC DtS mindful of multi-connectivity capability is crucial.
- **Adaptation of LPWAN/mMTC MCS and protocols for DtS**. The use of LPWAN/mMTC for DtS requires revisiting their physical, media access and network layers to (i) boost connectivity ranges and scalability and (ii) tackle the unprecedented mobility of the LEO satellites.

- **Performance improvement and new functionalities**. The performance metrics we obtained are quite promising and establish the baseline, yet these can be boosted further. This can be approached through utilizing different MCS orthogonality, beamforming, more sophisticated control of traffic and traffic aggregation.
- **Frequency regulations and legislation**. The LPWAN/mMTC DtS approach offers several challenges of non-technical nature. One of the most notable is the definition of the frequency bands and regulations (e.g., should DtS systems use the same spectrum as terrestrial ones?) for such systems. The numeric results obtained in this study implied no interference from the other systems.

VIII. Conclusion

The introduction of MASS features an enormous potential for boosting the maritime trade and transportation, which is especially crucial for remote areas, where the access to services is often very challenging. One of the most critical challenges in MASS is connectivity. Therefore, we conceptualize a MASS connectivity architecture and investigate the feasibility and performance of DtS LPWAN/mMTC-based AIS data collection. Our results demonstrate the promising performance of this approach under realistic scenario implications and highlight the effect of the different design dimensions and configuration parameters on the connectivity performance.

Importantly, our results show that the combination of multi-connectivity (of LoRaWAN-like technologies) and multi-satellite visibility significantly boosts packet delivery probability. This motivates the further research and development of such systems to take maximum advantage of this synergy. We hope, that the current work, which establishes the baseline, will motivate the further studies to take this concept further. Among the topics still to be addressed are the investigation of Doppler shift, capture effect and optimal data rate (DR) allocation for leveraging quasi-orthogonality for performance improvement. Similarly, we consider direct ship-to-ship communication and cooperation between terrestrial and NTN worth looking at.

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