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LEO SATELLITE BASED 5G CONNECTIVITY FOR AUTONOMOUS VESSELS

A simulation study

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ABSTRACT

Anastasia Yastrebova: LEO Satellite Based 5G Connectivity for Autonomous Vessels
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Autonomous and remotely controlled vessels operating in the Arctic areas will need a level of connectivity that cannot be provided with current systems. The required connectivity implies very low transmission time for delay-sensitive applications, high data throughput for large amounts of data transmission, and link robustness for timely service provision.

A satellite constellation placed in the low Earth orbital (LEO) plane allows reduced transmission time in comparison to satellites in medium and geostationary Earth orbits. However, the only notable polar LEO constellation does not meet the requirements for the link properties for autonomous vessels.

This work studies what kind of satellite communication system would be needed for reliable operations in the defined area when the main application is a drone-assisted situational awareness system for autonomous vessels.

In this thesis, a study of the current state of satellite systems to support autonomous vessels in the Arctic region was conducted. The focus was on the satellite constellation design, link properties for reliable autonomous vessel operations based on the defined use cases, as well as the communication architecture between the autonomous vessel and the Remote Operations Centre.

The conducted work defines the constellation needed for reliable communications. The results show that the defined megaconstellation system is able to meet throughput and coverage requirements. Additionally, a description is provided of the developed methodology of satellite constellation design, with the aim of assisting future mission planning.

Keywords: Satellite communications, 5G, autonomous vessels, mega-constellation, URLLC

PREFACE

This Master of Science thesis contains essential results of the research work on satellite connectivity for autonomous shipping, which I started to do as a new member of the Autonomous Connectivity Research Group at the VTT Technical Research Centre of Finland, VTT Ltd. I also acknowledge support from RAAS Connectivity RTF framework.

First and foremost, I express my deep gratitude to my supervisors, Dr. Marko Höyhtyä and Mr. Mikko Majanen, for their competent guidance, valuable ideas, constructive criticism, constant support, and help. Under their supervision, I have gained valuable experience while developing this thesis.

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I’m very grateful to all my friends who I met in Finland; without you it would be impossible for me to be so far away from my family.

Oulu, 3rd November 2019

Anastasia Yastrebova

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LIST OF SYMBOLS AND ABBREVIATIONS

$\mathbf{F}$	inter plane phasing designation
$\mathbf{M_0}$	mean anomaly
$\mathbf{P}$	number of planes in constellation
$\mathbf{S}$	number of satellites per plane
$\mathbf{T}$	total number of satellites in constellation
$\boldsymbol{\Omega}$	right ascension of the ascending node
α	semimajor axis
ω	argument of perigee
ε	elevation angle
$\mathbf{e}$	eccentricity
$\mathbf{i}$	inclination
3GPP	3^{rd} Generation Partnership Project
5G	fifth generation cellular network; any system that uses 5G NR software
5G NR	5G New Radio
AIS	Automatic Identification System
AR	Augmented Reality
BER	Bit Error Rate
BS	Base Station
BSS	Broadcast Satellite Services
CDMA	Code Division Multiple Access
CYGNSS	Cyclone Global Navigation Satellite System
DBS	Direct Broadcast Satellite System
DL	Downlink
ECU	Engine Control Unit
ESA	European Space Agency
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
FoV	Field of View

FSS	Fixed Satellite Services
GEO	Geostationary Earth Orbit
GLONASS	Global Navigation Satellite System
GMDSS	Global Maritime Distress and Safety System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSO	Geostationary Synchronous Orbit
GW	Gateway
HAPs	High Altitude Platforms
HEO	Highly Elliptical Orbit
HF	High Frequency
HTS	High Throughput Satellite
HTTP	HyperText Transfer Protocol
IMU	Internal Measurement Unit
INS	Inertial Navigation Systems
IoT	Internet of Things
IP	Internet Protocol
ISL	Inter Satellite Link
ITU	International Telecommunication Union
LEO	Low Earth Orbit
LiDAR	Light Detection and Ranging
LoS	Line of Sight
MEC	Multi-access Edge Computing
MEO	Medium Earth Orbit
MF	Medium Frequency
MSS	Mobile Satellite Services
NAVDEC	Navigational decision support system
NFV	Network Function Virtualization
NGSO	Non-Geostationary Satellite Orbit
PDB	Packet Delay Budget
PER	Packet Error
PSTN	Public Switched Telephone Network
QoS	Quality of Service
RAAN	Right Ascension of the Ascending Node

RAN	Radio Access Network
RAT	Radio Access Technology
RN	Relay Node
ROC	Remote Operations Centre
RTT	Round Trip Time
SANSA	Shared Access Terrestrial-Satellite Backhaul Network enabled by Smart Antennas
SAR	Synthetic Aperture Radar
Sat5G	Satellite and Terrestrial Network for 5G
SatNex	Satellite Network of Experts
SDMA	Space Division Multiple Access
SDN	Software Defined Networks
SMS	Short Message Service
SONAR	Sound Navigation Ranging
TAU	Tampere University
TDMA	Time Division Multiple Access
TUNI	Tampere Universities
UAVs	Unmanned Aerial Vehicles
UE	User Equipment
UHF	Ultra High Frequency
UL	Uplink
VHF	Very High Frequency
VSAT	Very Small Aperture Terminal
WSN	Wireless Sensor Network

1 INTRODUCTION

1.1 Motivation

Autonomous and remotely controlled vessels operating in the Arctic areas will need a degree of connectivity that cannot be provided with current systems. This work studies the problem and provide answers to the research question: what kind of satellite communication system is needed for reliable operations in the defined area when the main application is a drone-assisted situational awareness system for autonomous vessels? The problem is studied by simulations.

Currently, there are no Low Earth Orbit (LEO) constellations available that will support broadband connectivity in such remote areas as the Arctic region, although a number of proposals are presented annually. In this regard, the following research questions arise: how many satellites will be needed for reliable communications in the defined area based on the specific application requirements? What is the optimal satellite constellation configuration that meets the required Bit Error Rate (BER) values and communication delay?

1.2 Objectives of the Thesis

The main aim of this thesis is to analyse the 5G satellite-terrestrial system and its use to enable autonomous shipping. The study concentrates on the design and analysis of a satellite constellation for service provisioning for autonomous vessels, with the intention of facilitating practical development of satellite systems for particular applications. Multiple parameters are considered, such as altitude, inclination, elevation angle, number of satellites in the constellation, etc.

The main objectives of this thesis are:

- Literature review, including 3^{rd} Generation Partnership Project (3GPP) standardization on satellite-terrestrial integration.
- Definition of a vessel-satellite communications use case, architecture and system model for simulations.
- Analysis of communication links between the satellite and the vessel under different conditions.
- Analysis of the designed constellation.

1.3 Structure of the Thesis

In the current section the content of the thesis is briefly explained. The thesis consists of five (5) chapters.

- Chapter 1: Introduction. A brief introduction to the topic is given and the research problem is stated. The objective of the thesis and the structure of the work are also explained.
- Chapter 2: Theoretical Background. In this chapter, the theoretical background of the concepts related to the thesis is given. This chapter describes the state of the art of current LEO satellite systems and future megaconstellations, the state of the art of autonomous vessels and the integration methods of satellite and terrestrial networks. Chapter 2 also describes maritime operations in the Arctic region, as well as navigational challenges and their mitigation.
- Chapter 3: Materials and Methods. In this chapter, the methodology of satellite constellation design is described. Importantly, the use cases for delay-tolerant and delay-sensitive maritime applications are described, as well as service requirements for their realization.
- Chapter 4: Constellation Design and Analysis. In this chapter, satellite constellation is designed. The main aspects of constellation design are explained. After a mathematical analysis of the constellation, the verification of the model is given. Analysis of simulation results is provided.
- Chapter 5: Conclusions. The conclusions of the work are summarized in the last chapter of the thesis. Some future work directions are also listed.

A short organizational introduction is given at the beginning of each chapter.

2 THEORETICAL BACKGROUND

The current chapter is split into four parts. It begins with an introduction to the satellite systems, their categorization by type of services, altitude, and formation. The first part of the chapter also shows the current state of the satellite systems, especially the communication problems experienced in the Arctic, and reviews the proposed satellite solutions to solve the problem.

The second part explains the satellite-terrestrial network architecture and the main network connectivity elements. The main requirements of satellite-terrestrial integration are summarized in the second part.

The third part focuses on the definition of the autonomous vessels, and provides examples of practical trials of such vessels. This part identifies the communication requirements for the autonomous vessels based on the applications and outside- and inside-vessel system requirements, explains the communication architecture between an autonomous vessel and the Remote Operations Centre.

The last part of this chapter focuses on the maritime operations in the Arctic region and navigational challenges and their mitigation. This part also provides a ground for developing the use cases in Chapter 3.

2.1 Satellite Systems

Satellite systems vary depending on the purpose for which they are designed. Satellites can be categorized by the type of services they provide, including:

- Fixed Satellite Services (FSS): used for voice, data and video transmission. Additionally, FSS are used as feeder links for other types of satellite services (e.g. transmission of broadcast television to the satellite and feeder links for Mobile Satellite Services (MSS)). Examples of FSS are Intelsat and Telesat. The satellite stations are permanently placed at a fixed position.
- Broadcast Satellite Services (BSS): radio communications service, in which signals transmitted or retransmitted by space stations are intended for direct reception by the general public. Examples of BSS applications are services such as direct broadcast television, as well as satellite radio.
- Mobile Satellite Services (MSS): used for communication provision between a mobile station and a space station. This service includes maritime mobile services

Table 2.1. *Frequency band designations.*

Frequency range (*GHz*)	**Band designation**	**Satellite service**
0.1 – 0.3	VHF	MSS
0.3 – 1.0	UHF	MSS
1.0 – 2.0	L	MSS, Navigational satellite services
2.0 – 4.0	S	MSS, BSS, FSS
4.0 – 8.0	C	FSS
8.0 – 12.0	X	BSS, MSS
12.0 – 18.0	Ku	BSS, FSS
18.0 – 27.0	K	FSS, BSS (up to 18.4) [4]
27.0 – 40.0	Ka	FSS

(MMSS), land mobile (LMSS), and aeronautical mobile (AMSS). Examples are Thuraya, and Iridium.

- Meteorological Satellite Services: surface measurements and weather monitoring, such as the Cyclone Global Navigation Satellite System (CYGNSS) [1].
- Radio-navigational satellite service for tracking and location awareness applications. Examples are Orbcomm [2], Global Positioning System (GPS), and Global Navigation Satellite System (GLONASS) [3].

Satellites for different services use specific frequencies, shown in Table 2.1. Typically, lower frequencies have better propagation characteristics but low bandwidth. Above $10\ GHz$ the propagation channel causes degradations e.g., due to cloud attenuation, although wide bandwidths are possible. Use of the frequency range of K-band ($18\ GHz$ – $26.5\ GHz$) is limited for radio communications due to the strong absorption of radio waves caused by water vapour and therefore, the ranges below and above the K-band are usually used for long-distance applications: Ku- and Ka-, respectively. FSS and BSS are used in K-band only up to $18.4\ GHz$ [4]. Current work is focusing on higher frequencies, especially on Ka-band due to its potential for higher bandwidth communication. Ka-band antennas have higher gain compared to antennas of similar size, operating at lower frequencies. However, Ka-band systems are more susceptible to rain attenuation than, for example, the Ku-band [5].

Satellite systems can be categorized by the altitude they are designed for. The satellite position on the orbit is a trade-off between the altitude of the space system and number of satellites needed to provide the desired coverage. Therefore, Low Earth Orbit (LEO) satellites can provide high-speed connectivity, require less power to transmit a signal and may enable low-latency services due to limited propagation delay. However, LEO constellations require a larger number of satellites in order to embrace the entire globe in comparison to Geostationary Earth Orbit (GEO) satellite systems. The altitude of LEO satellite systems varies from 160 to $2000\ km$ [6]. Figure 2.1 illustrates the difference between different types of satellite orbits. In the figure, satellite systems are compared

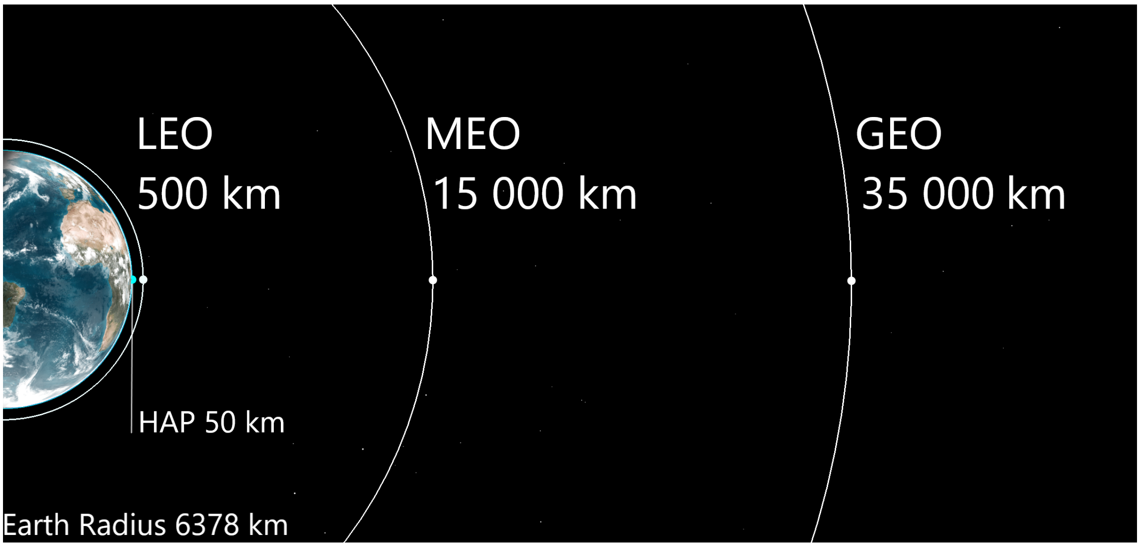


Figure 2.1. *Comparison of different satellite orbits.*

to High Altitude Platforms (HAPs) that are meant for data transmission and placed at an altitude of 20 to 50 km between terrestrial and satellite networks. HAPs will be further explained in more detail.

2.1.1 Satellite Formations

There are different methods to group the satellites in the orbit or around the Earth, depending on the required coverage [7]. Different satellite formations are presented in Figure 2.2.

Trailing refers to the type of formation, where several satellites share a single orbit and follow each other at a specified distance. This formation can be used either to observe a fixed target at different times or to obtain varied viewing angles of the target. Trailing satellites are especially suited for meteorological and environmental applications.

Cluster formation refers to the grouped satellite network, where each of the satellite groups are deployed in a specified orbit, being close to each other in order to cover a

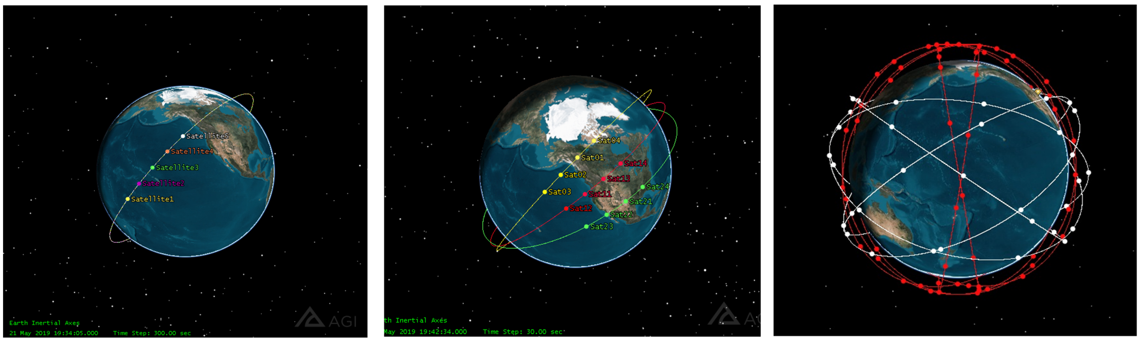

a) Trailing formation
b) Cluster formation
c) Constellation formation

Figure 2.2. *Satellite formation patterns. Screenshot from the STK simulation tool.*

Table 2.2. *Keplerian element set.*

Element	Definition
α	Semi-major axis. Gives the shape of the ellipse.
e	Eccentricity. Gives the shape of the ellipse.
M_0	Mean anomaly. Gives the position of the satellite in its orbit at a reference time known as the epoch.
ω	The argument of perigee gives the rotation of the orbit's perigee point relative to the orbit's line of nodes in the earth's equatorial plane.
i	Inclination relate the orbital plane's position to the earth. Orbital inclination measures the tilt of an object's orbit around a celestial body.
Ω	RAAN relate the orbital plane's position to the earth. It is the angle from a reference direction (longitude), to the direction of the ascending node.

specific part of the Earth. These clusters might be used for producing the maps of the Earth.

A satellite **constellation** is a system of satellites, placed in several orbital planes and distributed around the Earth. A constellation might consist of multiple sub-constellations of different altitudes and different inclinations. Satellites in the constellation move in a synchronized manner and serve the same purpose [8]. The number of satellites depends on the type of service and the required coverage. The satellites in the constellation are usually operating under shared control, which allows synchronization, optimization, and monitoring of the satellites. A satellite constellation can consist of several orbits.

Earth-orbiting satellites are defined by six (6) orbital elements referred to as the *Keplerian element set*, which includes: semimajor axis α, eccentricity e, mean anomaly M_0, argument of perigee ω, inclination i, and right ascension of the ascending node (RAAN) Ω [9]. The elements are described in Table 2.2. In Figure 2.3 are illustrated the argument of perigee ω and the right ascension of the ascending node Ω that is measured eastward, in the equatorial plane, from the Υ line to the ascending node [9].

For the satellites orbiting in the planet's equatorial plane the satellite's orbital inclination is $0°$. The value of the inclination for a polar constellation varies between $70°$ and $90°$ [10].

The most used constellation notation is the *Walker notation*, based on the contributions by J.G. Walker [11], which is defined as $i : T/P/F$ where $\mathbf{T}$ is the total number of satellites in the constellation, $\mathbf{P}$ is the number of planes and $\mathbf{F}$ is an interplane phasing designation. The number of satellites per plane is defined as

$$S = T/P. \tag{2.1}$$

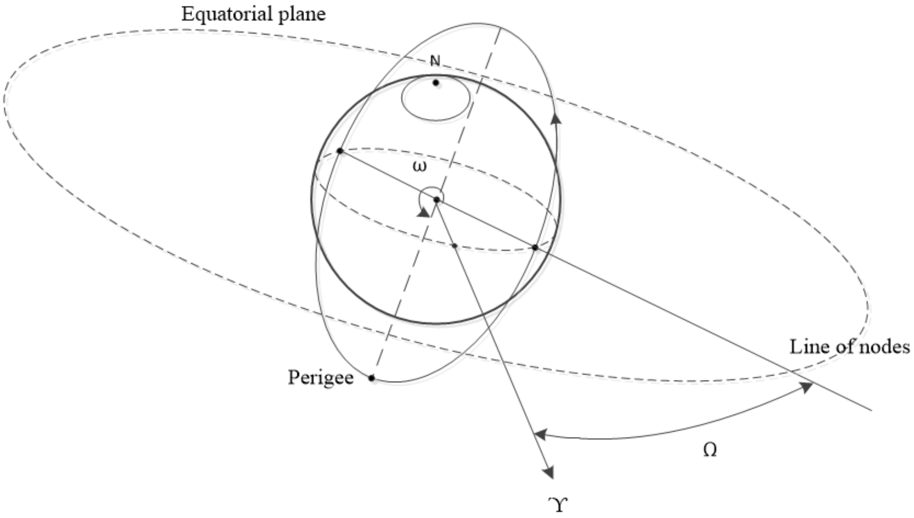


Figure 2.3. *The argument of perigee ω and the right ascension of the ascending node Ω. Adopted from [9].*

2.1.2 Current Status of Satellite Systems

The new generation of satellites is under development for increased satellite lifetime, transmission speed, coverage, and reliability. In the case of the last three indicators, the current satellite systems are especially poor in the Arctic region. As an example can be taken the GEO telecommunication satellites Inmarsat, which are intended to provide coverage up to $81°$N, although in practice the limit is around $76°$N [12].

LEO satellites are also experiencing difficulties with coverage provision in the Arctic. For example, Globalstar does not provide coverage in the Arctic at all because of the very inclined satellite orbits (Globalstar has an inclination of $52°$). The LEO satellite constellation Orbcomm has limited coverage in the Arctic despite the near-polar inclination of $108°$. This satellite system also results in very long communication delays of up to $20\ min$ [13].

Relatively low data rates are provided by the LEO multi-purpose near-polar satellite system "Gonets", developed in Russia, with an inclination of $82.5°$. The constellation consists of 13 satellites, providing global coverage and a mobile satellite service, and provides data rates up to $64\ Kbps$ [12].

The LEO satellite constellation Iridium, developed by the USA for telecommunication purposes, is situated at an altitude of $781\ km$ with an inclination of $86.4°$ [14, 15]. The constellation consists of 66 active satellites, and it operates in L-band, providing a bit rate of up to $134\ Kbps$ in a bidirectional link with Iridium Pilot marine terminals [16]. However, it has been reported that the current system results in very high latencies due to its multi-hop architecture, and in general it is unreliable [17].

The transmission data speed should improve in the second generation of satellites Iridium NEXT that will support the new multi-service platform, Iridium Certus, designed especially for maritime purposes. The new platform is expected to be in use in 2020 and will allow data rates in the narrowband from $22\ Kbps$ to $88\ Kbps$ and up to $352\ Kbps$ in the broadband [18].

To solve the communication problem, a new multi-purpose satellite network "Arktika" is under development in Russia, and will be launched in 2021. The system is designed for a variety of remote-sensing tasks, such as monitoring of environmental conditions, and provision of reliable communications and navigation in the Arctic region. The constellation is composed of 10 satellites positioned at different orbital planes. The satellites for mobile communications will be placed in Highly Elliptical Orbit (HEO) at an altitude of $50000\ km$ and will operate in the Ku-/Ka-band. The data transmission rate of the system remains unknown.

High-throughput satellites (HTS) are being developed by a number of companies. HTS are used for communications purposes, providing higher throughput than typical FSS or MSS satellites for the same amount of allocated spectrum. The increase in capacity is achieved due to high-frequency reuse and spot beam technology. Frequency reuse accrues through multiple narrowly focused spot beams (of the order of 100 kilometres). In comparison, classical satellite technology uses a broad single beam (of the order of 1000 kilometres) to cover broad regions. HTS are deployed to provide broadband Internet access service to remote areas with poor communication conditions. An example is the satellite platform Intelsat EpicNG that provides $25 - 60\ Gbps$ of total capacity in C-, Ku-, and Ka- bands [19]. The tests showed that for a maritime use case while transmitting data over the GEO Intelsat's HTS it was possible to achieve a throughput capacity of approximately $9\ Mbps$ by a single user utilizing $9.7\ MHz$ of allocated bandwidth, compared to the non-HTS GEO Intelsat Galaxy 3C, for which the transmission speed has reached $1.8\ Mbps$ utilizing the same bandwidth allocation [20].

Another example is GEO HTS ViaSat-2 (Telesat), which is considered to be the world's highest capacity communications satellite with a capability to deliver data at a speed of $100\ Mbps$ and total capacity of $240\ Gbps$. However, in the process of deployment, ViaSat 3 is expected to have $1\ Tbps$ of total network capacity and to provide a data rate of $1\ Gbps$ for use in maritime and enterprise scenarios [21].

The latest solution of Inmarsat is the Global Xpress (I-5) series GEO satellites for global data services provision. Inmarsat started the launch of the new (HTS) Global Xpress in 2013 for provision of seamless, high-speed broadband communications. Currently, there are four (4) satellites operating in Ka-band. The bit rate provided by satellites is $50\ Mbps$ for DL and $5\ Mbps$ for UL [22].

Currently, HTS are mostly GEO satellites, but there are also HTS designed for Medium Earth Orbit (MEO) [23].

Table 2.3. *Parameters of megaconstellations. The minimum elevation angle is stated for a specified altitude and inclination.*

Ref.	**System**	**Altitude [km]**	**i [deg]**	**P**	**S**	**T**	**ISL**	**Frequency band**	**min ε [deg]**
[27]	Telesat	1 000	99.5°	6	12	117	Yes	Ka	10°
		1 248	37.4°	5	9				
[27]	OneWeb	1 200	87.9°	18	40	720	No	Ku, Ka	50°
[28]	Starlink	1 150	53°	32	50	4 425	Yes	Ku, Ka	35°
		1 110	53.8°	32	50				
		1 130	74°	8	50				
		1 275	81°	5	75				
		1 325	70°	6	75				
[29]	Leosat	1 400	90°	6	14	84	Yes	Ka	10°

2.1.3 Emerging Megaconstellations and their Characteristics

Megaconstellations are broadband constellations, placed in non-geostationary satellite orbit (NGSO), mostly in LEO, with a large number of satellites placed in such a way as to provide global coverage. They are associated with many terrestrial gateway (GW) terminals. In some cases, megaconstellations have inter-satellite links (ISL), depending on the constellation configurations [24]. Megaconstellations aim to provide better capacity performance in comparison to current constellations due to the use of a higher number of satellites, advanced modulation techniques, coding techniques, multi-beam antennas, and different frequency reuse schemes. Some companies have made several proposals regarding the megaconstellation designs presented in Table 2.3. Some of the companies are at an advanced stage of production and are launching their satellites to orbit (OneWeb [25], SpaceX, and Telesat [26]).

Every constellation is designed to meet specific needs. Some companies aim to provide global Internet connectivity (OneWeb), others aim to provide broadband connectivity for aviation, maritime (Leosat), or back-hauling cellular data (Telesat). The aims are different and thus the constellation design is also different.

The purpose of the constellation affects strongly the type of constellation and number of satellites to be used. Other factors that affect the type of constellation and the type of connections between satellites and between satellites and ground stations are the number of end-users, delay requirements, single-user data rate requirements, etc.

The largest constellation has been proposed by SpaceX (Starlink constellation). It will include up to $4\,000$ satellites, involving 5 different altitudes. Starlink is designed to provide such services as FSS, MSS, military services as well as scientific research missions.

OneWeb has proposed a constellation, consisting of 720 satellites to provide FSS with broadband connectivity in low Earth orbital plane. However, OneWeb is planning to expand their constellation to $1\ 260$ LEO satellites. According to the new constellation design, the number of orbital planes could be increased from 18 to 36 and the number of satellites per plane from 40 to 55. So far only 720-satellite constellation is authorized by the Federal Communications Commission (FCC) [30].

For FSS, Telesat's initially composed constellation includes 117 satellites, although it will be possible to increase the constellation up to 292 satellites. The constellation design consists of two sub-constellations: one polar constellation at an altitude of $1\ 000\ km$ and inclination of $99.5°$, the second one inclined with $i = 37.4°$ at an altitude of $1\ 248\ km$.

Leosat has proposed a less ambitious constellation design for MSS consisting of only 84 satellites. The constellation is polar and is to be placed at an altitude of $1\ 400\ km$. In comparison, the current Iridium system utilizes for the same purpose and has 66 satellites situated at $781\ km$.

It is important to note that companies include polar orbital planes in their constellations, since the lack of communication in Arctic regions presents challenges not only for autonomous vessel deployment but also for current human-operated vessels. Nowadays, Arctic areas bring significant value not only in research but also for energy and mining companies, fisheries and cruise ships. Expected future growth of traffic on trans-polar shipping routes will definitely make the situation poorer for current communication infrastructure.

2.2 Integrated 5G Satellite-Terrestrial Networks

Satellite technologies can provide characteristics that are not possible with other technologies, such as very wide coverage. Terrestrial systems are limited by Line of Sight (LoS). Moreover, satellites can be compatible with many terrestrial technologies for the last mile communications (3G, LTE, etc.).

There are several studies concerning the integration of satellites to terrestrial networks [24, 31, 32, 33]. Many on-going projects develop technologies for future integrated systems, such as the Shared Access Terrestrial-Satellite Backhaul Network enabled by the Smart Antennas (SANSA) project [34] and the Satellite and Terrestrial Network for 5G (Sat5G) project [35], both funded by the European Commission Horizon 2020 [36]; and the Satellite Network of Experts (SatNex) project [37], funded by the European Space Agency (ESA), etc.

LEO megaconstellation deployment appears to be a promising solution for worldwide coverage provision and reliable backhaul network realization. This deployment will also enable many remote-operational applications, even delay-critical ones. Thus, it is important that satellite systems fully support terrestrial technologies, as the indicators such as coverage, bit rate, security level, handover performance, etc., will highly depend on the interoperability of space and terrestrial technologies.

2.2.1 Common Payload Architectures

Common satellite-terrestrial payload architectures can be classified to three categories [38] presented in Figure 2.4:

1. *Wide Area Bent Pipe architecture.*

   In Bent Pipe architecture the signal received by a satellite is retransmitted without processing to the destination point in the same coverage area of the beam. The terrestrial terminals that are within the coverage area can communicate with each other via the satellite. A disadvantage of this architecture is that the frequency reuse method cannot be efficiently applied.

2. *Spot Beam Bent Pipe architecture.*

   Spot Beam Bent Pipe architecture can efficiently apply the frequency reuse method. Each terrestrial terminal can communicate with others within the same spot. However, terrestrial terminals which are not located within the same beam cannot communicate via the satellite due to the fact that the system does not support the switching necessary for inter-beam connectivity. With this architecture, the terrestrial infrastructure is required to handle interconnections between GW terminals. A GW is required for every spot beam in order to provide access to networks for terminals. A network management centre (NM) is needed for connection control.

3. *An Onboard Processing architecture.*

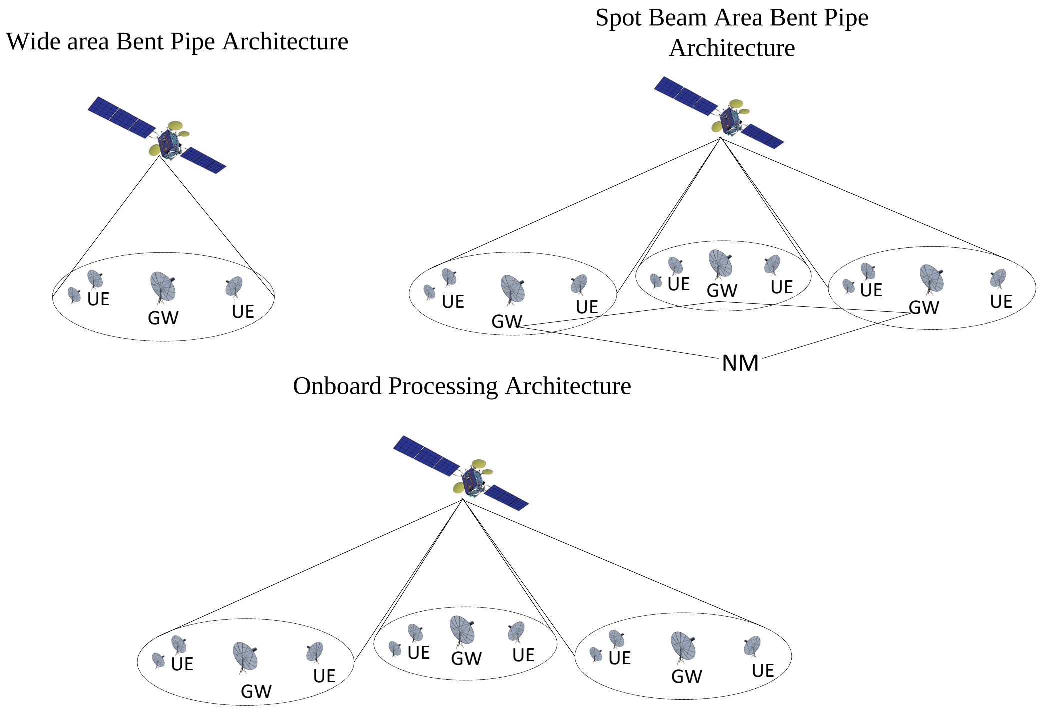


Figure 2.4. *Types of payload architectures.*

> An Onboard Processing (OBP) architecture provides inter-beam connectivity allowing user terminals (or user equipment (UE)) to access any other terrestrial components in other beams. This architecture allows flexible resource allocation. The capacity of the network with this infrastructure is higher than that of the Bent Pipe due to frequency reuse without terrestrial infrastructure support.

Current work considers general Bent Pipe architecture, without considering any specific inter-beam connectivity.

2.2.2 Network Elements and Connectivity

Independently of payload architecture, communications can be divided into two segments: ground and space segments. As 5G satellite-terrestrial architecture has not yet been standardized, based on public information it is possible to define what the overall system architecture might be. The architecture is presented in Figure 2.5.

Ground segment. Satellite-enabled utilities are the GW terminals (also called teleports or hubs [39]), which provide an extension for the terrestrial network coverage with the advantage of reduced cost. Satellites are connected to GW through a feeder link. GWs provide access to the 5G base station (gNB). GW gNB is connected to the 5G Core Network (5G CN), providing access to the Internet, and at the same time it provides connectivity to the terrestrial network. Besides GW, the ground segment consists of 5G supported (UEs), which can be connected to GW for terrestrial access link provisioning. The connection between UE and GW is made through a Uu interface, which is the radio interface between mobile and radio access network (RAN).

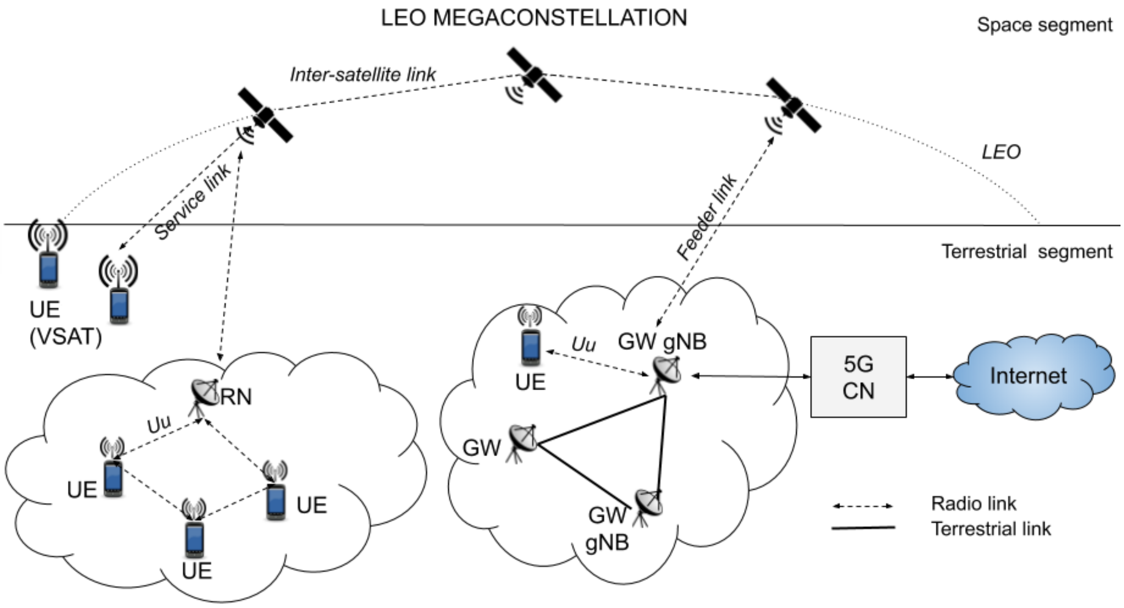


Figure 2.5. *Satellite RAN architecture with Bent Pipe payload (eMBB scenario).*

UEs can also be connected to the relay nodes (RN) in order to extend the network coverage. An RN can also be deployed on a vehicle in order to provide wireless connectivity service to the end-user inside the vehicle. The connectivity between UE and RN is made through a Uu interface.

Space segment. The space segment consists of satellites, grouped into a constellation with or without an inter-satellite link depending on the constellation properties. Satellites are connected to a satellite GW. The satellite can also be directly connected to UE or it can be connected to the GW terminal. In this complex network, GWs must have a certain degree of redundancy in order to reduce the outage probability during bad weather conditions. They should also be interconnected using a terrestrial link to support handover functions.

2.2.3 Integration Aspects and Requirements

Radio Access Technologies (RAT). According to the International Communication Union Radiocommunication Sector (ITU-R), the main applications of 5G are enhanced mobile broadband (eMBB) that stands for high data rates and seamless operation networks; massive machine-type communications (mMTC) that stands for large number of devices in the network with low data rate and long battery life; and ultra-reliable and low latency communications (URLLC), which is the requirement for many emerging services. In this relation, by integrating the satellite network with 5G, it will be possible to meet the demands of these applications by means of redundant communication links, low propagation delay and global coverage.

3GPP, which is the main standardization body for 5G, have developed the radio access technology 5G New Radio (5G NR), which is the global standard for air interface in 5G networks. 5G NR was designed to support a range of systems included in communications as well as to enable a range of services provided by a diverse set of devices with different performance capabilities and latency requirements.

In addition to 5G radios, several radio access technologies (RAT) can be implemented such as 3G, LTE, etc., as a last-mile solution.

Orchestration mechanisms. To enable seamless integration and efficient convergence of heterogeneous networks, cloud computing and orchestration mechanisms such as Multi-access Edge Computing (MEC), Network Function Virtualization (NFV), and Software Defined Networks (SDN) will play an important role.

The MEC is used to provide localized computing and storage resources for non-real time and real-time services, depending on network conditions. This mechanism provides great possibilities for delay-critical services by performing service-related processing tasks on the cellular customer side, reducing network congestion and latency [39].

NFV provides separation of the user plane (the traffic data) and the control plane (management of the traffic) and enables the realization of the network as several logical units (i.e logical routers, logical GW). This method is important for the differentiation of data traffic classes and the definition of virtual networks that are sharing the same physical infrastructure. Each network slice has its own set of logical network functions that are optimized to provide resources for a specified traffic class or service.

SDN realizes programmable network infrastructure, allowing centralized management of the network. Each service is associated with the specified layer. Thus, the application layer is responsible for hosting the applications and communications with the SDN controller; the control layer is responsible for the definition and management of network slices. The physical network infrastructure layer includes all physical nodes and the transport network management [24].

Requirements for the QoS. Based on the standardized 5G Quality of Service (QoS) requirements, presented in Table 2.4, it is possible to define the needed communication link quality. In the table the following parameters are indicated:

The Type of data classifies information in three categories in order to identify specific packet forwarding rules: Guaranteed Bit Rate (GBR), Non-Guaranteed Bit Rate (Non-GBR) and Delay-critical GBR. The GBR is used in 5G to define the expected bit rate that the bearer can provide. GBR bearers that carry the data cannot experience packet losses. For the delay-critical GBR data type, a packet that is delayed more than the value of the Packet Delay Budget (PDB) is counted as lost.

The Packet Delay Budget (PDB) defines an upper limit for the time that a packet may be delayed on the way between UE and GW.

The Packet Error Rate (PER) defines an upper limit for the rate of Internet Protocol (IP) packets that are not successfully delivered by the receiver to the upper layer.

Maximum Data Burst Volume denotes the largest amount of data that is required to serve within a period of time.

Besides the QoS requirements, it is possible to define the general key requirements of the network:

1. *Seamless connection.* For some applications, it is critical to provide seamless connectivity from space to Base Station (BS). Satellite integration with 5G networks will fulfil requirements such as universal coverage and allow the implementation of many use cases.
2. *Network reconfiguration capability.* To provide sufficient internet connectivity, terrestrial networks must be capable of dynamic reconfiguration depending on the traffic congestion. Satellite integration can be used as a method of network off-loading due to different techniques such as data aggregation and re-routing (instead of terrestrial links, traffic can go through the satellite link), which will benefit not only in supporting the network capacity at the required level, but also from the point of view of deployment cost and energy consumption as the result of implementation of "sleep modes" on some of the nodes during low-demand traffic.

Table 2.4. *Standardized 5G Quality Identifiers to QoS characteristics mapping [40].*

Type of data	**Priority**	**PDB [ms]**	**PER**	**Max Data Burst Volume**	**Use cases**
GBR	High	75	10^{-2}	N/A	Mission Critical user plane Push To Talk (MCPTT)
	Low	300	10^{-6}	N/A	Buffered video Streaming
Non- GBR	High	60	10^{-6}	N/A	Mission Critical delay sensitive signalling (e.g., MC-PTT)
	Low	300	10^{-6}	N/A	TCP-based services (e.g., www, e-mail, chat, ftp, p2p file sharing, etc.
Delay-critical GBR	High	10	10^{-4}	255 bytes	Discrete Automation
	Low	30	10^{-5}	$1\ 354$ bytes	Intelligent transportation system (ITS)

3. *Efficient spectrum coexistence of both segments.* Spectrum is a limited resource that needs to be used efficiently both to support required services and to manage interference between satellite and terrestrial segments. Spectrum sharing has been studied e.g., in [36] by utilizing frequency reuse schemes between ground stations and between ground and base segments. Multiple use cases in different frequency bands including C- and Ka-band are also considered in [4].

2.2.4 Use Cases of Satellite-Terrestrial Communications

3GPP defines a few key sets of scenarios for satellite-terrestrial networks, including ubiquitous coverage, critical communications, and network scalability. First of all, deployment of megaconstellations will allow providing coverage for isolated or remote regions, or vehicles (air-crafts or vessels). The motivations for satellite connectivity include:

- the inability of deployment of terrestrial networks due to financial factors, geographical location, etc.;
- the absence of a direct line of sight between transmitter and receiver (inability for vessels to communicate with BS on deep-sea missions).

Secondly, Integration of megaconstellations with 5G will provide a reliable communication link, continuity of the service, and an increased data exchange rate for many use cases.

Finally, 5G features will make it possible to easily expand the network, leading to improved network scalability.

In the following, some of the possible applications are collected with regard to the satellite-terrestrial cooperation, based on 3GPP developed use cases [41].

1. ***Requirements of the service.***

   This use-case includes instant service requests that must be provided immediately, such as system maintenance requests or vessel/container tracking. Such unforeseeable situations as air valve leakage can end very badly for the vessel. This risk can be eliminated by sending a request through a satellite megaconstellation to the Remote Operations Centre (ROC) controlling the vessels. The tracking requests should be made in response to the item tracking services such as location, or other information.

2. ***Optimal network utilization.***

   In cases, when there is no terrestrial coverage, the communication link should be addressed through a satellite operator which will provide support along the way without terrestrial network coverage. If both satellite and terrestrial networks are available, an optimal network should be selected.

3. ***Global content distribution.***

   This use case considers the distribution of mission characteristics, or system updates, video guidance during on-demand maintenance or other essential information to a number of vessels distributed across the globe, or to a single vessel that is not in the range of BS. The use case also considers the simultaneous distribution of relevant information (such as system parameters, updated policies of the system or security configuration updates) to a set of vessels in the sea. Satellites that are supporting global massive content distribution will complement terrestrial data distribution. Similarly, not only down-link content distribution but also frequently data aggregation from vessels will provide additional security, ensuring that none of the unmanned vessels have been hacked.

4. ***Alternative redundant connectivity.***

   This use case is meant for offloading terrestrial network or providing alternative routes to the destination point in case of failure of an intermediate node. In cases when the network is overloaded and there is data that needs to be sent to/from the vessel, a satellite link can be used as an alternative one. It can also be used in order to prevent network congestion by separation of non-latency constrained data, which can be sent through a satellite network, from latency constrained data that is sent through a terrestrial network.

5. ***Temporary usage of satellite network.***

   Satellite communication links can be utilized as a backhaul in case of natural disasters, or war. When several BS are down, due to efficient routing techniques satellites will ensure that transmitted information has reached the destination point. This use case does not apply only to vessel communications, but to many other segments such as healthcare, institutions, logistics, etc.

Original 3GPP use cases can be found from [41].

2.3 Autonomous and Remote-Controlled Vessels

In current work, a vessel is defined as an overwater transport (ship or boat) that can be used for transportation of people or goods, for manned or unmanned operation.

2.3.1 Autonomous Vessel Regulations

The International Maritime Organization (IMO) has started a working process regarding the standardization of operational aspects of autonomous vessels [42]. Such vessels are named as «Maritime Autonomous Surface Ships (MASS)» [43]. Despite the fact that the process of standardization has only just begun, some of the maritime agencies already have a clear vision on the operation process.

The Norwegian Forum for Autonomous Ships (NFAS) has collected a list of definitions, describing what is an autonomous vessel, the context it operates in, and the functions it needs to implement to operate safely [44]. NFAS describes an autonomous vessel as a vessel with some degree of autonomy. According to NFAS, there are 4 degrees of autonomy:

Degree 1: Decision support. The vessel is equipped with relatively advanced anti-collision radars, electronic chart systems and common automation systems such as autopilot or track pilots. The crew onboard is in direct command of the vessel operation. This degree of autonomy corresponds to "No autonomy".

Degree 2: Automatic. The vessel is equipped with more advanced automation systems which can complete certain operations without human interaction, e.g. dynamic positioning or automatic berthing. Normally, the system follows a pre-programmed command and will request human intervention only in cases of unprogrammed events. The ROC or onboard crew are always available to take control when necessary.

Degree 3: Constrained autonomous. The vessel can operate fully automatically most of the time. It is equipped with an automatic decision-making system with a defined number of options for solving often encountered problems, e.g., collision avoidance. It will call on human operators to intervene if the problems cannot be solved with the help of defined options. The ROC or onboard crew continuously monitors the vessel and is available to take immediate control, if needed.

Degree 4: Fully autonomous. The operating system of the vessel is able to make decisions and determine actions by itself. The vessel is not constantly controlled by the ROC and it operates without a crew on-board.

Table 2.5. *Projects of autonomous vessels.*

Company	Purpose	Length	Max speed	Ref.
DARPA "Sea Hunter"	military	40 m	27 knots 50 km/h	[45]
ST Electronics "VENUS"	military	16.5 m	35 knots 65 km/h	[46]
Rolls-Royce "Falco"	Car ferry	53.8 m	-	[47]
ABB "Suomenlinna II"	Passenger ferry	9 m	9 knots 16 km/h	[48]
Yara International ASA "Yara Birkeland" (under development)	Container vessel	80 m	13 knots 24 km/h	[49]
DNV GL "ReVolt" (under development)	Container vessel	60 m	6 knots 11 km/h	[50]

2.3.2 Practical Trials of Autonomous Vessels

Currently, several projects are focused on autonomous vessel development for goods and passenger transportation, presented in Table 2.5. These projects developed by Rolls-Royce, DNV GL, Kongsberg and others, will have a great impact on autonomous maritime infrastructure. Nowadays many of the companies have already begun practical trials of the developed vessels. The size of the vessels varies from 9 up to 80 meters long, and the purposes of the vessels from leisure autonomous small boats to large military ships.

1. ***Sea Hunter (DARPA)***. The Sea Hunter is an autonomous unmanned surface vessel that was launched in 2016 as a part of the DARPA Anti-Submarine Warfare Continuous Trail Unmanned Vessel (ACTUV) program [45]. It is an unmanned self-piloting vessel, powered by two diesel engines with a maximum speed of 27 knots. The weight of the vessel is 135 tons, including 40 tons of fuel that would be enough for a 70-day voyage. The vessel was successfully tested in 2016 in terms of manoeuvrability, stability, seakeeping, acceleration/deceleration, fuel consumption, and mechanical systems reliability in the open ocean.

2. ***VENUS (Singapore Technologies Electronics Limited (ST Electronics))***. The VENUS is an unmanned surface vessel built by Singapore Technologies Electronics Limited (ST Electronics) [46]. The vessel can be built in 9, 11, and 16-meter options and has a varying design for different payloads; the maximum payload can reach 10000 kg. The VENUS can achieve a maximum speed of 40 knots. It can operate autonomously as well as remote-controlled.

3. ***Falco (Rolls-Royce)***. In December 2018, Rolls-Royce together with the Finnish

ferry operator Suomen Lauttaliikenne Oy (Finnferries) successfully demonstrated a fully autonomous car ferry "Falco" [47]. The voyage from Parainen to Nauvo was performed autonomously without human intervention, and the return trip was conducted under remote control. The ferry is equipped with a number of advanced sensors that make it possible to obtain a detailed picture of the surrounding area. The detection of the objects was possible due to sensor fusion combined with artificial intelligence.

4. ***Suomenlinna II (ABB)***. Later, in December 2018 the automation company ABB performed a remote control of the passenger ferry "Suomenlinna II" from Helsinki to the Suomenlinna fortress with the ROC situated in Helsinki [48]. The passenger ferry is 9 meters long and is equipped with advanced dynamic positioning systems. The situational awareness system is supported by real-time visualization of the vessel's surroundings independently of the time of day or weather conditions.
5. ***Yara Birkeland (Yara International ASA)***. Yara Birkeland is a fully electric and autonomous container ship that is being developed by Yara International ASA in cooperation with Kongsberg [49]. In this partnership, Kongsberg is responsible for sensor, control, communication, and electrical system integration. It will be ready for launch in 2020. A scaled-down version of the autonomous container vessel is currently being tested.
6. ***ReVolt (DNV GL)***. The ReVolt is a 60 meters long container ship that is battery-powered and autonomously operated [50]. The vessel is still under development for short sea segments. The operational speed of the vessel is expected to be 6 knots, with a capacity of 100 containers. A prototype 1:20 scaled model has been built for testing of the vessel.

ReVolt and Yara Birkeland are electric-powered vessels with zero emissions that will replace hundreds of trucks. The prototypes of these vessels are currently being tested.

2.3.3 Internal and External Communication Requirements for Autonomous Vessels

Inside-vessel communications. Part of the payload in communications between a vessel and the shore will be data from inside vessel systems. These systems include several main blocks, responsible for example for information management between the systems, positioning, navigation, and communication. The information also includes the measurements from the sensors for vessel status monitoring. This includes data from temperature and pressure sensors, extinguishing systems and optical sensors, from sensors for mechanical equipment monitoring, as well as monitoring of the status of engines, propulsion system, ballast tank, etc. [51]. Navigation systems include Automatic Radar Plotting Aid (ARPA) for collision avoidance, Automatic Identification System (AIS), autopilot, GNSS and position sensors, etc. Both wired and wireless technologies can be employed inside the vessel for data transmission, although it is usually wired in order to guarantee reli-

Table 2.6. *Message types and period of the reporting.*

Data type	Description	Report interval	Priority
Position messages	Navigational information	2 sec - 3 min	1
Voyage related data	Heading, speed, trip specific information	6 min	4
Binary messages	Binary data for communications	As required	4
UTC/Date inquiry	Obtain time and date from a BS	As required	3
Static data	Vessel IMO number, call sign and name, length and beam, etc.	6 min	4
Safety-related data	Safety-related data for addressed communication	As required	2 1 for ACK

able and robust connectivity. Nevertheless, wireless technologies can be employed to complement the existing ones [52].

All data that is collected from inside vessel systems must be frequently transmitted to the ROC in order to enable constant monitoring of the system. Table 2.6 represents some of the data from vessel systems and the reporting times.

The Global Maritime Distress and Safety System (GMDSS) is a set of equipment and communication protocols used to increase safety at sea and to ease monitoring of the vessels. GMDSS employs different maritime technologies that utilizing medium-, high-, and very high-frequency radios (MF, HF, VHF). These include Emergency Position Indication Radio Beacon (EPIRB), AIS technology (NAVTEX) for instantly distributing navigational and meteorological warnings, and forecasts, as well as urgent Maritime Safety Information (MSI) to other vessels, Digital Selective Calling (DSC) for transmission of predefined digital messages, satellite communications, through which most of the messages are transmitted, and many others [53, 54]. From Table 2.6 [55, 56] it can be seen that an autonomous vessel often sends general messages from GMDSS equipment that includes positioning, heading, messages needed for communications, detailed voyage information including distance to the shore, type of communication, speed anomalies, temperature, humidity, etc. [57]. A message with priority 1 indicates very important traffic. Such traffic must be provided with decreased latency. The priority must be granted first of all to navigational information and acknowledgement messages (ACK message).

Outside Vessel Communications. Navigation of the vessels in the water is mostly based on navigation systems. Most of the navigation systems are operating through satellite communications. When the satellite communications are unavailable, infrared cameras and light detection and ranging technologies (LiDAR), and other sensors can assist with navigation. However, these sensors must have a direct line of sight to the

Table 2.7. *Link parameters for different applications.*

Application	**Data rate**	**Additional**	**BER**	**REF**
Image transmission	$4 - 20\ Mbps$	$1\ 080\ p$ quality	$10^{-5} - 10^{-4}$	[60]
Control command transmission	DL $300 - 600$ $Kbps$		10^{-7}	[60]
Video transmission	UL$\sim 15\ Mbps$	MPEG 4	10^{-4}	[61]
AR support	UL $\sim 10\ Mbps$			[62]
Engine Control Unit ECU	UL 100 $Kbps$	Engine temperat. etc.		[63]
Vessel state	UL $\sim 100\ Kbps$	Vessel's speed		[63]
LiDAR	UL $10 - 70\ Mbps$ up to $200\ Mbps$	Sensing, night vision	>10^{-7}	[63] [51]
Delay	**RTT**	**Network**	**Application**	
	$< 400\ ms$	$< 40\ ms$	Video transmission	[60]
	$< 100\ ms$	$< 20\ ms$	Remote control	
	$< 20\ ms$	$< 7\ ms$	AR support	[62]

object in order to distinguish the objects.

An Unmanned Aerial Vehicle (UAV) employed on the vessel and equipped with technologies for object recognition can assist autonomous vessels to provide full surroundings observation. The UAV can operate at low altitude ahead of the vessel or close to its planned path. Obstacles can be recognized, identified and tracked with higher possibility using signal processing techniques, machine vision, and pattern recognition [58].

Thus, the outside vessel data includes imaging and sensory data from outside vessel sensors and the UAV systems. Monitoring data from outside vessel systems includes imaging or video information from cameras, measurements from sensors for water temperature and chemicals condition, etc.

All data from the vessel is transmitted to the ROC for further analysis. The ROC in turn sends the control commands to the vessel. These commands include parameter requests about the mission, control commands, safety, and emergency commands. Response information to commands includes sensor measurements from the vessel. Furthermore, ROC provides the interface for remote vessel operation in cases where human intervention is needed [59].

Table 2.7 represents some of the data types from inside- and outside- vessel systems with requirements for data link, where the required data rate is mainly determined by image/video size and quality. For example, a bit error rate (BER) of 10^{-4} would be needed for $30\ min$ of MPEG-4 compression format of video streaming with a constant rate of

$1\ 150\ Kbps$ and resolution 640×480 pixels [61]. MPEG-4 is a standard for a group of audio and video coding formats, introduced by the Moving Picture Experts Group (MPEG). The bit rate of $3\ 177\ Kbps$ of high definition video resolution $1\ 920 \times 1\ 080$ would require a maximum BER of 10^{-8}. In the case of streaming hypertext transfer protocol (HTTP)-based video, the value of the BER should not exceed 10^{-8} for high bit rate video [64]. For Augmented Reality (AR) support the delay is estimated to be not more than $20\ ms$ of round trip time (RTT)) [62].

Monitoring data from the vessel side needs to be transmitted to the ROC. The information needs to be aggregated and managed for transmission, which can be difficult due to various inside-vessel and outside-vessel technologies, where each technology provides different requirements for the transmission. In addition, different applications might need different interfaces. A single management system could possibly be implemented, but this is out of the scope of the current work.

2.3.4 Autonomous Vessel - Shore Communication Architecture

Vessel-to-shore communication architecture includes many subsystems. These subsystems are terminal points (maritime Very Small Aperture Terminal (VSAT), ROC), technologies for long-distance data transmission (satellite systems, HAPs), the last-mile connectivity technologies (Wi-Fi, LTE, etc.), and technologies for data orchestration (connectivity manager) [39]. The communications between the vessel and the ROC can be direct or it can be conducted via a satellite or HAP. The communication architecture is presented in Figure 2.6.

High Altitude Platforms (HAPs) are meant for data transmission and placed in the middle layer between terrestrial and satellite networks. ITU-R has defined HAP as a station located on an object at an altitude of 20 to $50\ km$ and at a specified, nominal, fixed point relative to the earth [65]. The HAPs can be a flying aircraft (manned or unmanned), or a balloon. A single HAP can reduce a number of wired communication links between the BS by replacing them with a wireless link. An integrated HAP system can provide mobile cellular coverage or fixed wireless communications. The HAPs are connected to the terrestrial network (Public Switched Telephone Network (PSTN)) via the backhaul communication link through the BS. The deployment of HAP systems does not require integration of additional stations into existing infrastructure, but provides instant telecommunication coverage for the specific areas. Like satellites, the HAPs can create different formations and they could be used e.g. to cover main shipping routes while interlinked to each other. Additionally, the HAPs can provide improved connections for satellites (longer communication link length beyond the horizon and longer data download time from LEO satellites compared to ground stations) and also communicate to systems at lower altitudes such as UAVs, providing reduced latency compared to satellites. HAPs can be interconnected directly, through the satellites or PSTN. In the architecture con-

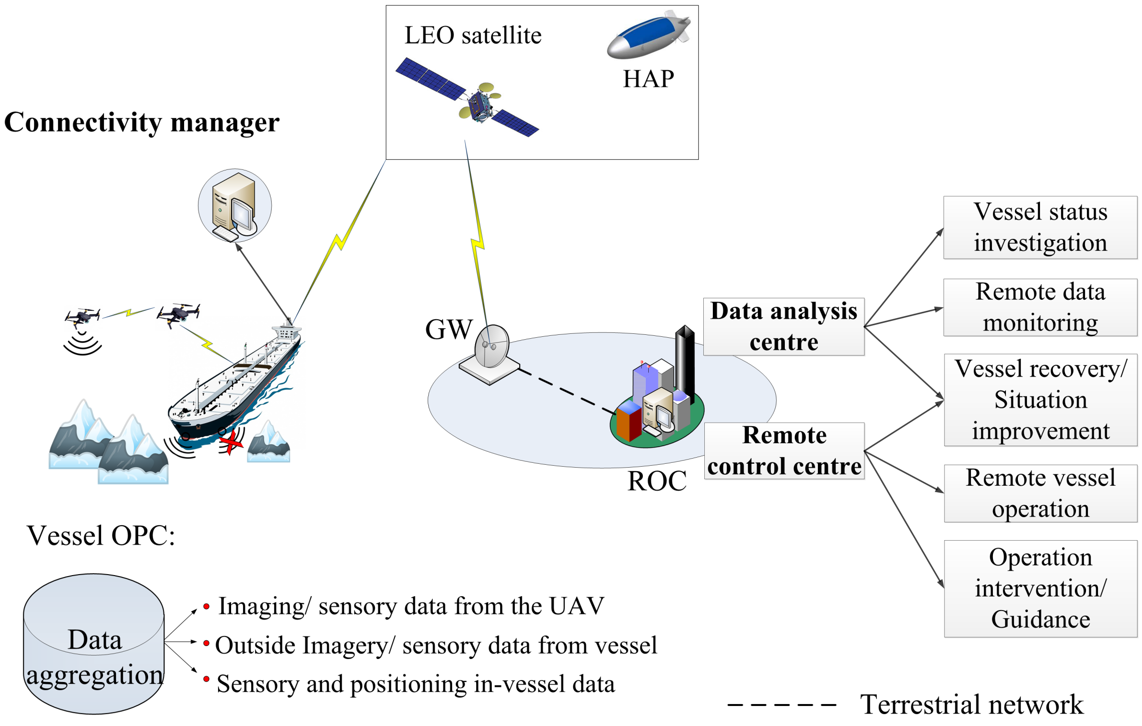


Figure 2.6. *Communication architecture.*

Table 2.8. *Global HAP frequency allocations.*

Frequency	Allocation	Applications	Additional information
27/28, 31* GHz	North America, South America, Asia, Africa	Fixed broadband user links services (data, voice, and video)	*300 MHz in each direction
47/48 GHz*	Worldwide	GW feeder links for fixed broadband services (data/voice/video)	*300 MHz in each direction
2.1 GHz*	Worldwide**	User links for 3G mobile services (data, voice, and video)	*IMT-2000 (up to $50/60$ MHz total bandwidth, to be used as alternative to terrestrial BS) **amount of bandwidth varies slightly by the region

sidered in Figure 2.6, HAPs can be used instead of the satellite to provide connectivity with a smaller delay between a vessel and the ROC, although the service area of a single HAP is much smaller when comparing to satellites. Thus, a vessel and the ROC must be within a single HAP service area, or many HAPs should be employed with an inter-HAP link. Table 2.8 describes HAP frequency allocations by region and application [66].

Maritime Very Small Aperture Terminals (VSAT) provide communications between a moving vessel and a satellite or a HAP. Due to vessel and satellite movements, the antenna on the vessel needs to be stabilized with reference to the horizon and true north and must provide sufficient tracking capabilities with high duty cycles. These antennas are typically circular. Parameters of some commercial VSAT are presented in Table 2.9. The maritime antennas range from $60\ cm$ to $1.5\ m$ for Ku-band and up to $2.4\ m$ for C-band. The data rates typically vary from $64\ Kbps$ up to $8\ Mbps$, but can reach $100\ Mbps$ and more. Compared to others, Ka-band provides an increased spectrum and allows more traffic to be transmitted. However, in Ka-band it is required for antenna to have more accurate pointing, due to greater rain attenuation.

Remote Operations Centres (ROC), also called Shore Control Centres (SCC) [57], are responsible for management and remote control of the vessel. ROC also serves as a data analysis centre. The ROC is responsible for the following tasks:

- *Remote data monitoring*. This task includes outside vessel data analysis. This data can represent certain characteristics of water (temperature, water content, etc.), the presence of obstacles in the path, or other factors that will influence the decision to take remote control of the vessel.
- *Status investigation and system update*. This task represents the necessity of the checking procedures of other subsystems, data updates, and examination of vessel status indicators.
- *Remote vessel operation* task implies manual vessel control in emergency situations such as failure of autonomous components, or other situations that require human intervention. This task requires the transmission of up-to-date navigational data from a vessel, including image- or video- data if needed.
- *Operation intervention or guidance* task is needed for resolving system failures, such as engine or other systems failures, or guidance of the vessel in difficult areas.
- *Tasks assigned to loss of communication*. The system is changed to this mode in case of total loss of communication with the vessel. In this case routing techniques including a variety of systems must be provided in order to re-establish the communication link. In order to minimize failure situations related to communication

Table 2.9. *System parameters of different VSAT.*

VSAT	**Max data rate** $Kbps$	**Frequency band**	**Size** $[\varnothing\ cm]$	**Ref.**
Comtech	235	X, Ku, Ka	85	[67]
Thuraya	444	L	$27\ cm\ in\ height$	[68]
SAILOR 60 GX	4000	Ka	82	[69]
TracPhone V11	1000 (up)	C, Ku	120	[70]
Sealink	6000 100000 on request	Ku	100	[71]

outage/ communication loss, multiple ROCs should be available for a vessel.

The actual ROC can be placed anywhere and connected to the satellite network through the GW via the terrestrial network.

Onboard Processing Computer (OPC). On the vessel an onboard processing computer (OPC) is employed that is responsible for the following tasks:

- sensor control, which controls all the individual sensors according to the commands from the ROC;
- sensory data storage;
- time synchronization;
- sensor fusion and image compression, which is needed to transmit the data in real time via a wireless link due to their large volume;
- data transmission.

Communication link between the vessel and the ROC remains the most critical component of the architecture. Connectivity methods need to provide a reliable, bidirectional link that would be supported by a number of technologies. Onboard the vessel, a Connectivity Manager (CM) must be employed in order to provide reliable connectivity between the vessel and the ROC. CM ensures that communication between two units has determined QoS. It manages radio access technologies, the information routes and end-to-end resources. The main tasks of a connectivity manager are:

- management of communication channels and routes;
- management of the capacity for data transmission;
- guaranteed procuring of integrity data delivery within latency requirements;
- cooperation with other vessels to ensure everyone's service satisfaction.

Capacity of the communication link is a very important factor, due to the need for several megabit per second of data from different sensors and video cameras transmission, as well as remote control operations, as was described in Section 2.3.3.

In the proposed architecture, the vessel has a communication link to the ROC, consisting of multiple subsystems. Together with 5G solutions described in Section 2.2.3, such a network could provide a reliable and high-speed environment. Expansion of communication links to satellite-terrestrial solutions, in addition to network congestion resolution problems, will enable accurate localization, navigation, information exchange with ROC or other vessels, etc. The procedure of vessel to satellite communications can be seen in the block-diagram 2.7 [72].

According to the diagram, the vessel first sends the message (msg) to a communication satellite. The satellite forwards this message to the GW on the ground, or the satellite can forward the message directly to the ROC. The ROC analyses the message and depending on its content applies certain actions: the response to the message can be

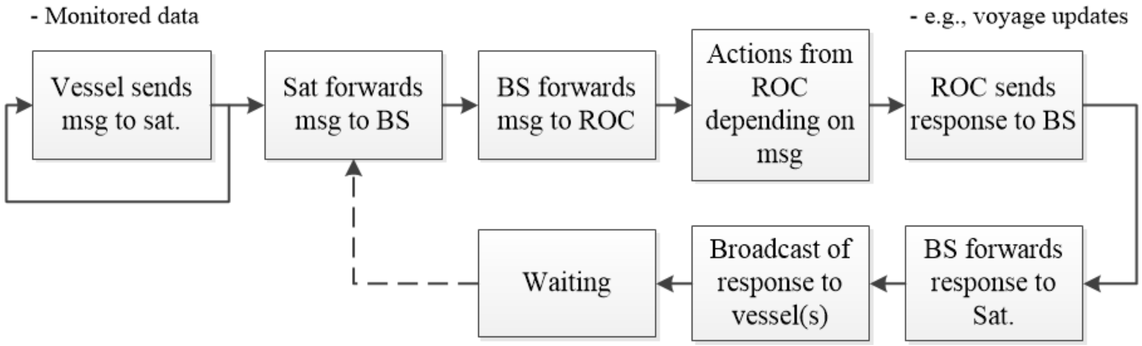


Figure 2.7. Vessel-satellite communication flowchart (based on the satellite-ship communication patent [72]).

transmission of system or voyage updates to a vessel or several vessels, or remote-controlled operation.

Multihop communication links. It is possible to create a maritime mesh-network to make the communications more redundant. A vessel could be connected to the ROC through multiple redundant systems to ensure reliable communication. The communication link can be through several HTS and/or HAPs to ROC. The delay in multihop propagation should be studied more deeply.

2.4 Operations in the Arctic Region

2.4.1 Maritime Operations in the Arctic

Four main maritime paths are used by vessels to navigate through the Arctic region. Three main shipping routes connect the Atlantic and Pacific oceans: the North-east Passage, the North-west Passage, and the Transpolar Sea Route, which is considered to be the main future route of 2030 due to global warming. Two other significant routes are the Arctic Bridge, which is a seasonal route, and the Northern Sea Route linking Russia and Canada and the Russian East and West parts respectively. The routes are presented in Figure 2.8.

The shipping routes are challenging due to the expanse of the flow, complex straits, multilayer ice, and other factors. Nevertheless, there are many ongoing maritime activities in this region.

1. ***Cruise vessels.*** Arctic cruise ships are becoming more and more popular. Study [73] shows that in 2012 the number of cruise tourists reached 100 000. According to the source [74], in 2019 there will be 11 more specialized ships, in addition to the already operational 80 that will sail North. Increased numbers of cruises will increase the probability of an accident occurring. Although cruise ships are not yet autonomous, improvement of communication links and sensor systems must be considered, since the Arctic area is a dangerous and unpredictable environment where a catastrophe can occur unexpectedly.

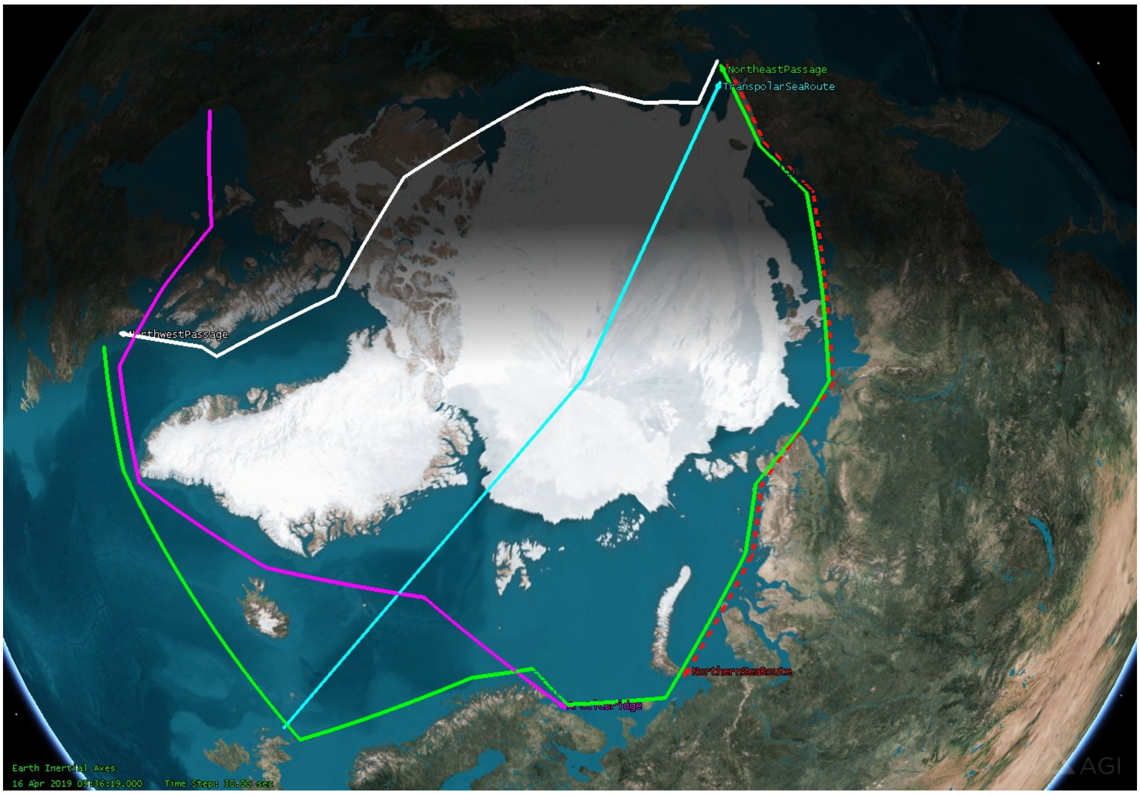


Figure 2.8. *Arctic maritime routes. On the figure are Transpolar Sea Route (blue), Northwest Passage (white), Northeast Passage (green), Northern Sea Route (dashed red line), and the Arctic Bridge (violet).*

2. ***Industrial vessels.*** It is important to take into account the industrial operations that are taking place in the Arctic area. Industrial activities include oil and gas production, mineral extraction, fishing industrial activities, etc. Operations in the Arctic waters involve great risks and may result in unforeseen catastrophes (such as oil and chemical spills). In addition to different resource production, many trading ship routes are going through the Arctic area.

3. ***Commercial vessel trading routes.*** Global warming will affect the increase of new trading routes in the Arctic region. Due to this factor, the International Maritime Organization (IMO) approved internationally recognized routing measures for increased marine traffic in the Northwest Passage in May 2018.

4. ***Scientific vessels.*** Because the Arctic is mostly an unknown area, and because of the increased industrial activities operations, it is important to take measurements and monitor the area in order to obtain more information about the environment and e.g. for future climate change actions. By replacing onboard captains with fully autonomous ships, more thorough scientific missions can be accomplished.

2.4.2 Challenges of Marine Operations

1. Harsh weather conditions.

The weather in the Arctic region is often hard to predict. Due to rapidly changing weather, the problems such as icing of equipment very often cause difficulties in maintaining connectivity. Icing is caused by snow precipitation or due to sea spray. The antenna of the vessel represents the most critical part of the communication system. Icing of the antenna is one of the most serious problems that can limit communication.

The sudden sticking of ice on the vessel hull quickly reduces its speed and manoeuvring capabilities. This introduces the danger of collision with other vessels during the performance of ice management operations or when leading a convoy [75].

2. Antenna tracking.

Antenna systems on a vessel must point to the intended satellite for communication link provisioning. Because of strong movement of the vessel due to bad weather conditions, it is required to have a nominal elevation angle greater than 5°.

3. Lack of communication infrastructure.

The lack of communication infrastructure in the Arctic is a limiting criterion for region exploration. The only current notable LEO constellation Iridium provides maximum voice and data service up to $130\ Kbps$. The Iridium constellation employs ISL, and due to multi-hop architecture very high latencies exist in the system (up to $500\ ms$ for voice and $20\ s$ for data transmission) [17]. As well as high latencies, unsteady performance has been reported at high longitudes [76].

Currently, existing communication systems for vessels include medium-, high- and very high-frequency band technologies, which provide limited data rates, suitable for voice transmission only. 3G and 4G terrestrial services are available only in coastal areas, thus limiting the operations in deep sea.

4. Presence of ice.

It is hard to navigate through Arctic waters due to the presence of heterogeneous types of ice. The thinner ice may combine with ice sheets or floes riding over each other. The thicker ice is likely to develop into ridging or hummocks. When drift ice is driven together into a large single mass, it is called *pack ice*. Wind and currents can pile up ice to form ridges three to four meters high, creating obstacles difficult even for the most powerful icebreakers.

The difficulty of navigation is also defined by the season. It is much more difficult to navigate during the winter season due to the thicker ice cover. Furthermore, an important feature during this season is *fast ice*, which is characterized as stable and immovable ice at the coastline, which is very difficult to pass through and is better to avoid [77].

Normally, the visible top of a ridge, known as the *sail*, is significantly smaller than the downward extension below, known as the *keel*. The keel represents the most danger for vessels, as radar sensors may not spot it in advance, which can lead to a collision [75].

In order to navigate safely and efficiently in ice, even for ice-capable vessels, it is important to avoid as much as possible difficult ice conditions and to maintain the freedom to manoeuvre.

2.4.3 Use of the UAV as a Collision Avoidance and Coverage Extension System

If the problems (1), (2) can be mitigated with appropriate vessel protection against icing, and for (3) a suitable communication architecture is needed, the problem of navigation through ice and collision avoidance can be solved by employing a UAV platform on the vessel.

The main disadvantage of vessels that are equipped with collision avoidance sensors is the small visibility area in the immediate vicinity of the vessel. Additionally, the increased complexity caused by moving ice and icebergs in the Arctic waters can lead to difficulties for sensors to avoid collisions. Moreover, some measurements might be limited due to incorrect sensor positioning (for example above the sea level, in which case icing of the sensor can occur) or malfunction.

In Table 2.10 some other limitations of radar, Sound Navigation Ranging (SONAR), and other technologies for collision avoidance are described, adopted and modified from [78]. Concluding from this table, UAVs could be used as a "vessel vision extension" and supportive system. Having a UAV, or more simply a drone, onboard the vessel will have a positive impact not only for unmanned but also for manned vessels. UAVs can assist the captain along the route, increasing safety on board and preventing accidents by serving as an additional collision avoidance system. UAVs can also assist autonomous vessels in research purposes as well as navigate through the route by providing additional measurements and images of the environment and of the vessel. In case of catastrophe with people being displaced overboard, the presence of the UAV on board would help in safety and rescue operations due to the possible presence of several sensors (thermo-sensors, hyperspectral cameras, etc). In Table 2.11 some of the applications of UAVs for maritime operations are presented, with an indication of possible technologies for the particular applications.

Table 2.10. *Limitations of collision avoidance technologies.*

Sensor	Limitations
Radar	Distorted data in case of fast turnings, high waves Limited ability of small and dynamic obstacles detection
Sonar	Limited detection range
Infrared sensor	Dark environment use only
LiDAR	Sensor noise and calibration errors
AIS	Not security reliable, easy to spoof [79]. A ghost-vessel can be created

Nowadays mini UAV communication distances can extend more than $16\ km$ from the home place, and the flight time of a UAV can be up to 90 minutes [80]. Communication capabilities of the UAVs are not sufficient to transmit acquired data directly to the satellite due to several limitations such as small antenna size and power. A vessel can be used in this case as a data aggregation and charging platform for UAVs and for data transmission to the LEO satellite.

Table 2.11. *UAV application examples.*

Task	UAV application examples	Technology	Ref.
Situation awareness	- Monitoring of icing of the vessel's hulls; - Acquisition of high-resolution sensory and imaging data	- Camera - LiDAR - GPS/Internal Navigation System (INS) - Synthetic Aperture Radar (SAR)	[81]
Vessel remote operation support	- Providing information for remote vessel driving support in order to minimize risk of obstacles; - Acquisition of high-resolution imaging and video data	- Camera - LiDAR - GPS/INS	
Water quality monitoring	- Water chemicals/temperature measurements; - Acquisition of high-resolution sensory data;	- Camera - GPS/INS - Infrared pyrometer	[82]
Monitoring of Polar ice sheets	- Monitoring of sea ice thickness; - Study of new Arctic maritime routes; - Detection and tracking of icebergs	- LiDAR - SAR - IR camera	[83] [84] [85]
Wildlife monitoring	- Monitoring of whales and polar bears	- Camera - Thermal Infrared sensors - GPS/INS	[86]
Weather condition monitoring	- Wind monitoring	- IMU	
Oil/ chemical leakage	- Monitoring clean-up operations; - Examination of oil removal equipment condition and efficiency; - Examination of vessel's hull after contact with slick; - Validation of borders of oil spilling area; - Continued monitoring of the accident; - Acquisition of high-resolution sensory and imaging data; - Monitoring of oil under ice sheets	- Camera - LiDAR - Hyperspectral camera	[87] [88]
Rescue operations	- Determination of crew or passengers in the water	- Thermal camera - Camera	

3 MATERIALS AND METHODS

This chapter defines use cases for autonomous vessel operation, the assessment criteria of the communication analysis, and the link properties to enable reliable operation of the system. The main scenario that will be addressed is the drone-assisted situational awareness application for autonomous vessels.

The aim of this work was to develop a satellite constellation that could be used to enable defined use cases. The work was started by developing a step-by-step procedure for a constellation design, depicted in Figure 3.1. The constellation design depends on the applications. The diagram illustrates the simplified process of system planning and sequencing. It can be split into 5 main steps, which include: (1) definition of the area of interest as well as exploration of communication technologies, presented in the defined area; (2) definition of the applications for a particular area, from which follows step (3) - a study of appropriate satellite connectivity for particular application; after the definition of required link properties, an essential part is (4) to define the input parameters for the constellation, based on which it would be possible (5) to make conclusions on the performance of the system.

The results of step (1) were presented in Chapter 2. Steps (2), (3), and partly (4) will be considered in the current chapter, while Chapter 4 will cover steps (4) and (5).

3.1 Definition of the Use Case

The Arctic region is not only a remote but also a very challenging environment [89]. Sailing in this area is problematic even for the most experienced crew. However, as was pointed out in Chapter 2, the Arctic region is becoming busier in terms of marine traffic due to new trading opportunities, increased mineral and oil drilling activities, increased touristic expeditions, etc. Shipping traffic has increased during the past decade to almost threefold from 1990 [90]. Maritime operations in this region are also becoming more difficult due to global warming causing rapid movement of ice and icebergs. These factors will lead to a higher probability of catastrophes occurring, such as an oil spill, or collision of a vessel with an iceberg. Thus, there is a need for constant areal monitoring in order to be able to react quickly to problems arising.

Autonomous vessels could be employed as an autonomous monitoring system, thereby increasing safety in this area. For the proposed use cases, described further, and based on [91], we assume that for Arctic region operations, the main tasks of autonomous ves-

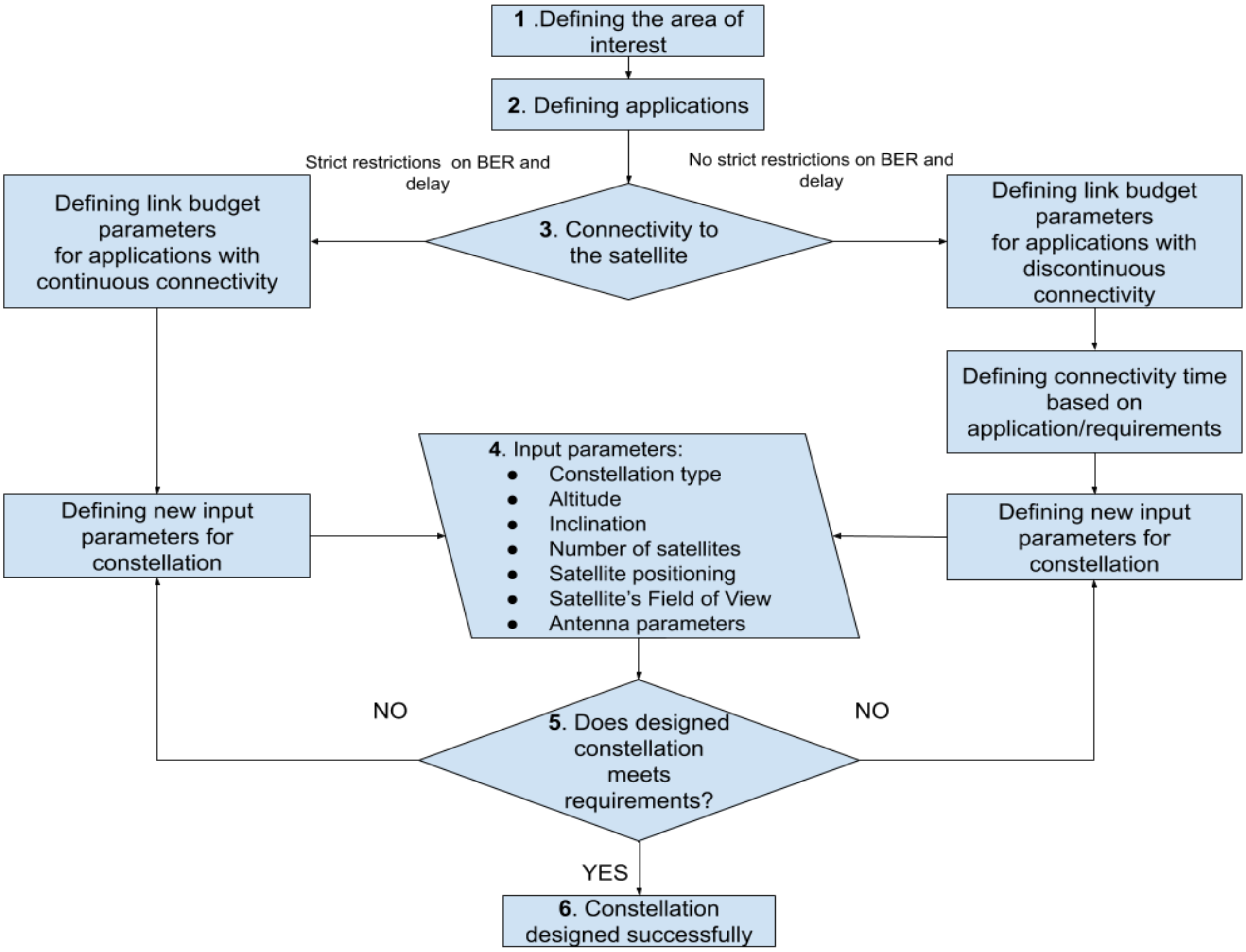


Figure 3.1. *Process flow of designing the constellation.*

sels could be scaled down to:

1. Detection and tracking of the obstacles (mainly ice or other vessels), in order to avoid collisions during the monitoring operations.
2. Detection and tracking of chemical leakage, in order to eliminate pollution, when the problem is discovered.
3. Procedures after obstacles/leakage are detected.

In order to employ autonomous vessels in the Arctic, the communication channel between the vessel and the ROC must be robust, since some of the situations will require constant monitoring and ability of the ROC to react and act quickly. These situations include:

- unforeseen weather conditions;
- collisions at sea;
- chemical or oil leakage.

In some cases, video streaming will be needed e.g. for rescue operations.

The connectivity to the satellite is defined by the application. Autonomous vessel applications are divided into two groups: (1) delay-sensitive applications (here considered as use case with continuous connectivity), and (2) delay-tolerant applications (use case for discontinuous connectivity) [92]. In the case of delay-sensitive applications, when the applications such as remote operation are considered, satellites must support very strict requirements on BER and latency. In the second case, requirements on BER and latency are not strict, and scheduled connectivity to the satellite can be deployed.

For both types of applications, it is important to define constellation parameters such as satellite altitude, inclination, number of satellites in the constellation, Field of View (FoV) of a single satellite and antenna parameters, as these are the main factors that will influence latency, BER, and connectivity time.

Each use case will be described further with respect to the potential application of LEO satellites.

3.2 Supporting Systems for the Use Cases

For both use cases the following supporting systems are considered. Other supporting systems can be employed, depending on the practical applications.

Vessel supporting systems. On the vessel, multiple technologies are employed for collision avoidance support and situation awareness provisioning. These technologies include acoustic sensors [93], underwater LiDAR [94], radar, and SONAR obstacle detection system [95]. Other collision avoidance systems are possible. The sensors can be placed around the vessel hulls and at the bottom of the vessel. One of the main supporting systems is a single or several video cameras, installed on the upper deck of the vessel, which provide an environmental view to ROC. This camera provides 180° view in front of the vessel and can be used together with AR technology. AR technology provides a suggested path based on the information from radars, AIS, GPS, as well as sensors for collision avoidance.

The autonomous vessel can also serve as a charging platform for the UAV.

The onboard processing computer (OPC) is employed on the vessel for sensory and imagery data aggregation both from the vessel and the UAV. It is also responsible for data compression and transmission to the ROC.

Vessel supporting systems such as radars and GPS are required to send data to the ROC within a specified time interval for situational awareness and collision avoidance. The transmission intervals are specified in Table 2.6.

UAV supporting system. A UAV is employed for situation awareness and collision avoidance support, with imagery data about area provisioning. UAV is intended to provide better situational awareness to the side of the vessel, as vessel sensor vision is limited to the area around the vessel (up to a few meters). Thus, the UAV can be used for monitoring of icing on the vessel's hull or ice thickness observation. The UAV can employ a camera with

Table 3.1. *Supporting systems on the vessel and UAV.*

Technology / Data	**UAV**	**Vessel**	**Data rate [Kbps]**	**Ref.**
Situational awareness systems				
Camera 180° for video transmission		•	800-1500	[51]
Camera for image transmission	•		6000	[96]
Hyperspectral camera	•		50000	[97]
SAR	•		100000	estimated
LiDAR		•	2000	[51]
IR camera	•		1000	[51]
Radar		•	100	[51]
Dynamic positioning system				
Navigational decision support system (NAVDEC)		•	25.5	[98]
GPS	•		4.8	[98]
Connectivity system				
Control data		•	10	[57]
Navigational supportive systems				
AR		•	10000	[99]

radar or other technologies (i.e., SAR for two- or three-dimensional reconstruction of objects, IR camera for ice condition monitoring, hyperspectral camera for oil determination, etc.) for image data acquisition. The UAV employed on the vessel has a programmed trajectory of flight and image accumulation since the range between the UAV and the receiver antenna outside the autonomous vessel might experience significant variation. The UAV sends all accumulated data to the vessel, where all data from both systems is collected and transmitted to the ROC. The UAV is supposed to transmit only imaging and sensory data to the vessel, since the power of a UAV is limited and distance to the satellite might be rather large. The objective of the UAV system is to complement the autonomous vessel. It provides extended coverage and additional information on the environment.

Table 3.1 depicts an overview of systems and their applicable sensor types which are relevant in both use cases with estimation on data rates. In the table, the SAR data rate is an estimated value of the downlink row data rate from a SAR satellite.

Transmission path. The transmission occurs through one of the networks that was chosen by the connectivity manager (CM) (see Chapter 2). In this work, the transmission is considered to occur via the LEO satellite network.

3.3 Continuous Satellite Connectivity Use Case: Collision Avoidance with Remote Control

This use case describes the process of UAV-assisted remote control of the autonomous vessel with constant video transmission and AR support. The autonomous vessel sails in the Arctic region away from the shoreline without terrestrial network access. Connectivity to the ROC is maintained through the LEO satellite constellation. On the vessel, multiple collision avoidance (CA) and situational awareness (SA) sensors are employed. A video camera is installed for environmental view provisioning to the ROC operator. The vessel is constantly monitored by the ROC. The operator of the ROC is already an authorized user. He or she is able to request a video view from the vessel any time. The UAV is equipped with radar and an Infrared (IR) camera. The AR technology is used as navigational support regardless of the time of day and the weather conditions. It is presented as the navigational data, overlapping with the real-world objects on the operator's display. The provided data includes obstacle information (location, dimensions, etc.) and the suggested sailing path based on the information from vessel CA sensors and UAV radar and IR camera. AR technology can be employed as support for navigation. It combines virtual reality with a view of the real world, enabling visualization of information such as routes, obstacles, and targets regardless of the weather or time of day. The use of AR technology as an additional navigation method has proved to increase the operator's ability to concentrate and perform multiple tasks more successfully under stress situations [100].

Remote control operation is needed in order to ensure that the vessel operation is safely executed, and in case of CA system malfunction. During the remote operation of the vessel, the operator can always verify the data from the CA system of the vessel with the data from the UAV systems. On the basis of imaging data from the UAV, the ROC operator can detect an iceberg well in advance and avoid it, even if it was not recognized with the sensors on the vessel. Additionally, based on the information from the UAV, the AR suggested path is more accurate.

3.3.1 Flow of Events

1. The vessel sails through the ice-dense area in autonomous operation mode, following the pre-programmed path and scanning the area for the presence of obstacles. The UAV is flying ahead and in the neighbourhood of the vessel at a certain distance; it scans the area for the presence of obstacles using the radar. The UAV and the vessel are in constant communication with each other.

2. The vessel sends the status information every 1-3 min to the ROC. When an obstacle is determined, the vessel immediately sends a message to the ROC.

3. Using the radar, the UAV detects an iceberg in front of the vessel and sends the alert message to the vessel together with additional information on the obstacle: geographical positioning, dimensions of the iceberg, timestamps, the distance to

the obstacle, etc. The UAV also sends the data from the IR camera to be forwarded to the ROC operator.

4. The vessel slows down, and using its own CA sensors confirms the obstacle in front, when the obstacle is in the detection range.
5. The vessel sends an alert message to the ROC, notifying about the obstacle together with the suggested path to avoid the obstacle. In addition to the alert message, all sensory data from the vessel and imaging data from UAV's IR camera are sent to the ROC. If there is no reply from the ROC, the vessel follows its suggested path according to CA support.
6. After receiving sensory and imaging information at ROC, the operator makes the decision to take the remote control and sends a video streaming request to the vessel. The vessel responds with the video streaming together with the AR support.
7. The operator may reject the path suggested by the vessel and may send new control commands to the vessel. These commands include the directions of the vessel, increase or reduction of speed, etc.
8. The vessel approves the new sailing path based on the information from the CA sensors.
9. When the iceberg has been passed, the operator can return the vessel to the initial autonomous state.

3.3.2 Potential Requirements

[Requirement 1.] To guarantee safety in the Arctic, an autonomous vessel shall have constant connectivity to one of the satellites during the remote operation of the vessel. For this use case at least one of the satellites from the constellation must be available throughout the period of remote control. The network must provide high enough QoS with the BER value and latencies not greater than a defined threshold (Table 2.7). Therefore, the link interruptions must be minimized in order to provide a safe service.

[Requirement 2.] From the regulations (STCW,Ch. VIII, Reg. VIII/2): "Officers in charge of the navigational watch must be physically present on the navigating bridge or in a directly associated location at all times" follows that, the autonomous vessel must always be controlled by the operator by means of all technological capabilities (sensory, imagery, and video information).

[Requirement 3.] For cases, in which no satellite connectivity is available, the OPC must employ an automatic collision avoidance algorithm decision support system. In this case, the vessel must slow down.

[Requirement 4.] For AR realization, the network must guarantee a latency of less than $20\ ms$, as was shown in Table 2.7, and a minimal bandwidth of $4.15\ MHz$, as calculated in Section 3.5.1.

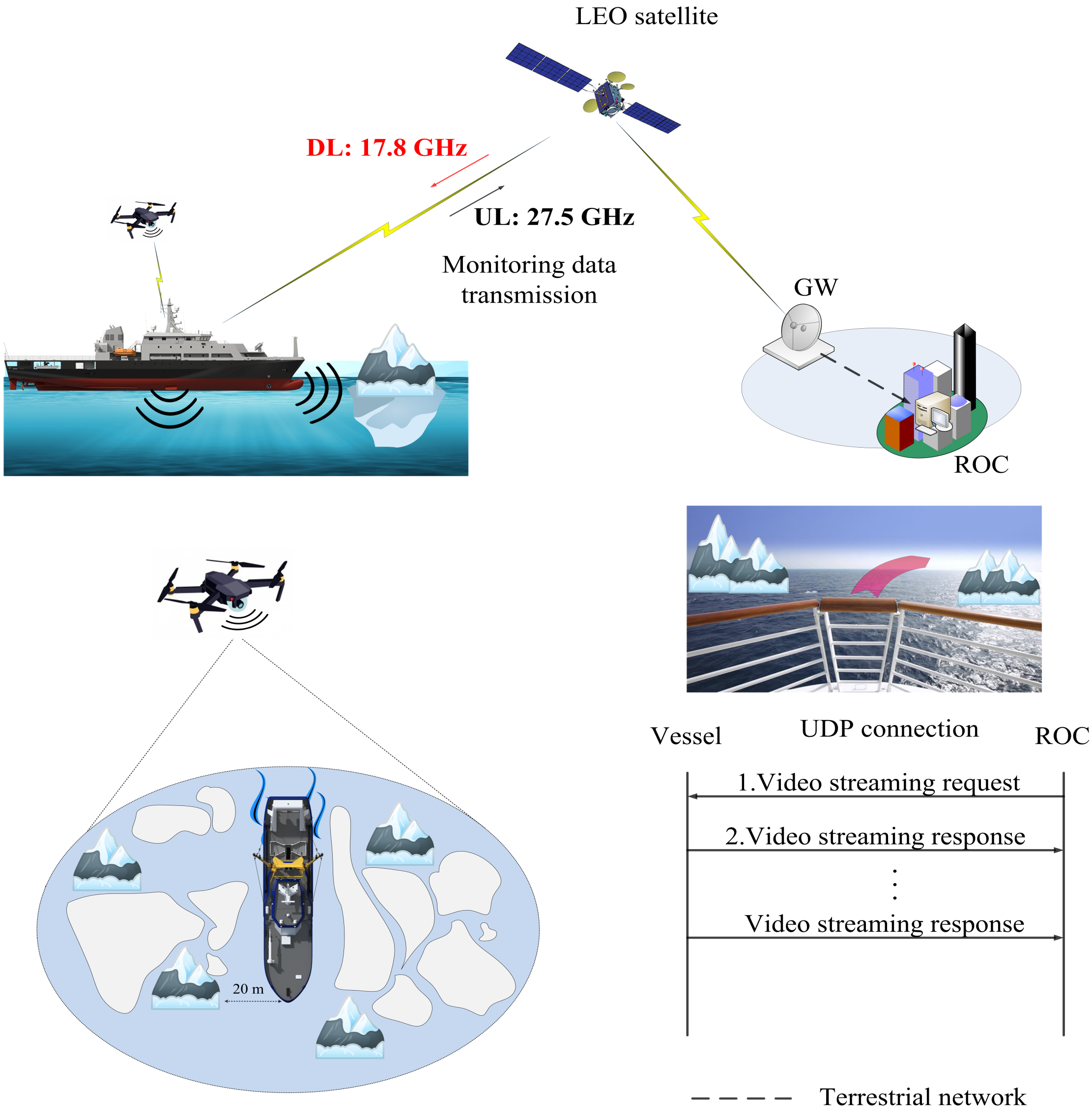


Figure 3.2. Autonomous collision avoidance operation with a UAV support system.

3.4 Discontinuous Satellite Connectivity Use Case: Scientific Fully Autonomous Monitoring Operation

This use case describes the process of drone-assisted autonomous operation of an autonomous vessel. In this use case the vessel operates in the Arctic region in fully autonomous mode. In this scenario operations on (1) ice management and (2) oil leakage determination are performed. (1) Ice management is a compulsory stage required for oil and gas exploration or production drilling operations [91] and support of safe journeys of marine vessels. The ice management allows estimation of ice parameters such as thickness, roughness, coverage, crystallography, surface tension, etc. It is significant to estimate these parameters since the ice strength and drafts depend on it. Due to ice management operations, the consistency of ice can be predicted, which will support safe operations and the vessel's passage through the Arctic region. Ice management procedures include:

- ice detection;
- ice observation;
- data collection;
- collision with ice avoidance;
- event forecasting.

(2) As the second task, oil leakage determination will be performed. Pollution in the Arctic ecosystem is caused mainly from two sources: drilling activities and oil spills during transportation. Oil spills in Polar regions are an especially serious problem due to the hazard to the environment and the difficulties in detecting and tracking the full extent of the oil leakage under the sea ice sheets. The ice cover of the Arctic seas can be considered as heterogeneous. Therefore an assessment of the dangers posed by this region requires a detailed examination of ice characteristics at the scale of individual ice floes, before the oil spill containment. For the ice management operations, UAV employs SAR and IR cameras. For oil detection a hyperspectral camera is used. Several UAVs can be employed on the vessel for task separation.

3.4.1 Flow of Events

1. The vessel follows a predetermined trajectory of the area of interest to detect potential oil spills. The vessel is monitored by the ROC operators by means of sensory and imagery data transmission within a predetermined interval of time. The vessel remains in autonomous operation mode before the operator takes over control.
2. The vessel avoids icebergs and ice using CA support, and sails at reduced speed.
3. The UAV assigned for oil determination and the UAV assigned for ice management operation follow a pre-programmed path ahead or in the neighbourhood of the vessel and scan the area for the presence of oil and perform the ice characteristics condition measurements. Measurements from the UAVs are transmitted to the vessel to be forwarded to the ROC.
4. The oil spill in the water or even under a thin layer of ice sheets is determined by the UAV's hyperspectral camera [101]. The UAV sends warnings on suspicious oil spill with the camera data, time and the location to the vessel to be forwarded to the ROC.
5. After the operator confirms the oil spill, he or she sends the command to the vessel to begin the process of containment of the oil spill at the specified position. The autonomous vessel uses a skimmer [102] for collecting and removing oil.
6. After the oil has been collected by the vessel, it is brought to the nearest oil utilization station.
7. After the vessel has cleaned the area and brought the oil to the oil utilization station, it automatically returns to the previous operational area, where it continues to take measurements.

3.4.2 Potential Requirements

[Requirement 1.] This use case does not require continuous connectivity to the satellite over a specified period of time. The connectivity must be made through the LEO satellite constellation. For this use case at least one of the satellites from the constellation must be available throughout the period of vessel autonomous operation. In the link some interruptions are allowed. The communication interval gaps are determined by the frequency of typical information from the vessel transmission. This information includes messages described in Table 2.6. The position messages are sent most often (from 2 sec to 3 min, see Table 2.6).

[Requirement 2.] The OPC must employ an automatic collision avoidance algorithm decision support system, and must be able to retransmit information.

[Requirement 3.] For autonomous applications of the considered use case the minimal bandwidth should be at least $1.91\ MHz$, as calculated in Section 3.5.1. However, it is recommended, that the minimum bandwidth is the same as in use case 3.3, as remote control operation of the vessel might be performed.

3.5 Service Requirements for Different Applications

In order to realize the previously described use cases, certain service requirements must be fulfilled.

1. Coverage Area.

The coverage area determines the regions in which the communication system is to be used. The coverage area mainly depends on satellite altitude and minimum elevation angle. The satellite coverage area can be expressed (in percentage) as a fraction of the Earth's area [8]:

$$Coverage = \frac{S_{cov}}{S_{Earth}} = \frac{2\pi R_e^2(1 - cos\theta)}{4\pi R_e^2}, \tag{3.1}$$

where S_{cov} is the area covered by the satellite and S_{Earth} is the area of the Earth. For the use cases 3.3, 3.4, the Arctic region must be covered by a satellite constellation.

2. Availability of the System and Link Duration.

The system availability is usually defined as the availability of the link from the transmitting terminal to the receiving terminal. The availability of the system in the mobile-satellite services is defined by the following formula:

$$A(\%) = (1 - \frac{t_u}{t_o}) \times 100\% \tag{3.2}$$

where t_o is the operational time of the system, considering that during this time it operates without interruptions, t_u is the cumulative time of unavailability of the system, caused by interruptions within the required time, and represents the cumulative percentages of time of link interruption. The system availability consists of equipment availability, and transmission path availability and is calculated according to the following formula, modified from [103] and [104]:

$$A_{sys} = A_{TX} + A_{RX} + A_{path} + A_{const}, \tag{3.3}$$

where A_{TX} is the availability of the equipment on the transmitting side, A_{RX} is the availability of the equipment on the receiving side, A_{path} is availability of the radio path, taking into account interruptions caused by propagation and interference, and A_{const} is constellation availability, that is related to orbital configurations.

For the use case 3.3 this parameter 3.2 must be 100 % during the time of autonomous vessel operation. In the use case 3.2 the parameter A can be clearly less than 100% and is taken into account in constellation design.

The coverage time of one satellite should be maximal without handover procedures. For use case 3.3; there should not be any communication gaps during the time of the vessel operation. For the use case 3.4 the minimum satellite link duration time to any vessel must correspond to the time period, specified in Table 2.6. If the remote-control operation is executed in the use case 3.4, the requirements for the system must be kept the same as for the use case 3.3.

3. Throughput.

Throughput is the rate at which the information bits are transmitted. The link throughput depends on the link budget parameters. The bandwidth is calculated in Section 3.5.1.

4. Transmission delay.

The propagation delay is limited by the speed of light in the air ($299\ 792\ 458\ m/s$) and around 2/3 of the speed of the light in case of fibre connection [105]. In this regard, $1\ ms$ of one way of propagation latency can be mapped to a distance of $300\ km$ in the air or $200\ km$ for transmission through the fibre. In this case, LEO constellation can provide improved latency performance, reliability, and end-to-end security, and can meet requirements of delay-sensitive applications. Delay requirements of such applications are less than $400\ ms$ for the image or video transmission, and less than $100\ ms$ for remote-control applications (2.7).

Transmission delay is the time taken to transmit a single data packet at the network data rate. It includes propagation delay, buffering delay, switching and processing delays. The propagation delay consists of at least 2 segments: source ground transmitter to satellite receiver, and satellite transmitter to ground destination receiver. An additional propagation segment might include inter-satellite links (ISL). ISL may employ high delay variation due to the satellite movements and link changes [106].

In the case of non-continuous coverage, the transmission delay is also the waiting time for the satellite to be in view.

5. Quality of Service (QoS).

The QoS describes the overall performance of a service that a user is experiencing. QoS consists of two parameters: link quality and system availability. Link quality refers to incorrect transmitted information, or information received with delays due to network interruptions. One of the measures of link quality is the bit error rate (BER). The BER value must correspond to a specific application, specified in Table 2.7. For use case 3.3, the maximum BER value should not be higher than 10^{-6}, for use case 3.4, the BER value is 10^{-4}.

Undelivered information can be referred to as system availability.

6. Service cost.

The cost of the service includes investment and operational costs for the system. The investment cost depends on the number of satellites, satellite architecture, and technology, launching procedures, etc. The operational costs include maintaining the constellation (e.g. replacement of old satellites, control of the orbit) [104].

3.5.1 Bandwidth Calculation for the Use Cases

The minimal bandwidth B_{min} was calculated for three applications: one for remote control and the other two for autonomous operation. For the autonomous operation oil monitoring and ice management operations were considered. Table 3.2 shows the considered traffic depending on the application. The data rates are estimated on the basis of Table 3.1.

In the table, the SAR and hyperspectral imaging data may occupy lower bandwidth since the data is not required to be constantly transmitted but one picture can be transmitted on request or in specified time intervals. Thus, the rate of a few Mbps for SAR and hyperspectral imaging would be sufficient for successful data transmission for the proposed use cases. In comparison, the AR data transmission will need to be constant and delay-less, in order to provide robust services. In this way, AR technology will occupy most of the bandwidth.

For the particular use case, taking into account estimated traffic generated by systems from Table 3.2, maximum data rate, minimum SNR, and corresponding bandwidth can be calculated according to the Shannon equation:

$$C = B \cdot log_2 \left(1 + \frac{S}{N}\right), \tag{3.4}$$

where C is the maximum data rate in bits per second, B is the bandwidth in Hz, and $\frac{S}{N}$ is the power ratio (signal power divided by the noise power).

Table 3.2. *Applications and considered data.*

Application 1 Remote control	**Data rate**	**Application 2 Oil monitoring**	**Data rate**	**Application 3 Ice management**	**Data rate**
Video, imagery data	1500	Hyperspectral camera	5000	IR camera	1000
Navigational data (NAVDEC)	25	Navigational data (NAVDEC)	25	Navigational data (NAVDEC)	25
Control data	10	Control data	10	Control data	10
AR data	10000	Images from UAV	1500	Images from UAV	1500
Radar, SAR	5100	Radar, SONAR	100	Radar, SAR	5100
Total kbit/s	**16 635**		**6 635**		**7 635**

The relationship between data rate and baud rate is illustrated by the Hartley equation:

$$R_b = f_s \times log_2(M), \tag{3.5}$$

where R_b is the maximum data rate in bits per second, f_s is the baud rate and M is the number of symbols used. This formula gives the minimum bandwidth needed to transmit at a specified baud rate with a specified modulation scheme. f_s can be found according to

$$f_s = \frac{R_b}{Q_m}, \tag{3.6}$$

where R_b is a bit rate in bits per second, and Q_m is the modulation order. In that case the number of symbols used is $M = 2^{Q_m}$.

Link bandwidth is the maximum throughput of a communication path. The maximum data rate is limited by the Shannon-Hartley theorem on channel capacity, which depends on the bandwidth in Hertz and the noise of the channel. To calculate the minimum bandwidth, we can substitute eq. 3.5 into eq. 3.4:

$$B = \frac{f_s \cdot log_2(M)}{log_2(1 + \frac{S}{N})}. \tag{3.7}$$

The calculation results for minimum bandwidth for defined applications and use cases are presented in Table 3.3.

Increasing the modulation order naturally leads to lower bandwidth requirement, in which case in order to keep desired data rate and have robust connection one needs to increase the SNR. Lower order modulations provide reliable connections over long distances and in harsher communication environments. Thus, adaptive modulation and coding schemes over the satellite links might provide the best option for connectivity. Reduction of data rates between the vessel and the remote operator is possible by optimizing the sensor data update intervals according to needs of remote operators and by efficient sensor

Table 3.3. *Minimal bandwidth* B_{min} *values for different modulation schemes and applications.*

Modulation scheme	SNR_{min} **[dB]**	B_{min} **[MHz] for application 1 R = 16.6 Mbps**	B_{min} **[MHz] for application 2 R = 6.6 Mbps**	B_{min} **[MHz] for application 3 R = 7.6 Mbps**
QPSK	11.7	4.15	1.65	1.91
16QAM	24	2.07	0.82	0.95
64QAM	36.12	1.38	0.55	0.63
256QAM	48.16	1.04	0.41	0.47

fusion mechanisms at the vessel.

3.6 Simulation Model Building

Once the application and requirements are defined, one can proceed to the step of satellite constellation design and verification by means of simulation model building.

The process of constellation design is described in detail in Chapter 4. The model verification was made in a simulation environment provided by the Analytical Graphics, Inc. (AGI) System Tool Kit (STK) [107].

The simulation tool allows use of the graphical interface as well as the programming language CONNECT. Using this language, it is possible to automatize the process and work in the client-server environment. CONNECT language can be used together with Python.

The following add-on modules were used:

- STK Pro that allows the use of sophisticated modelling through advanced access constraints, flexible system setup, complex visibility links, object tracks, and digital terrain data.
- STK Communications that allows definition and analysis of more detailed communications systems, generates detailed link budget reports and graphs, visualizes dynamic system performance in 2D and 3D windows, and incorporates detailed rain models, atmospheric losses, and RF interference sources in their analysis.
- STK Integration that enables automation of repetitive tasks from outside the STK software.

4 CONSTELLATION DESIGN AND ANALYSIS

The current chapter presents the methods of satellite constellation design for defined use cases in Chapter 3. It starts with a detailed explanation of the satellite constellation trade-offs and finishes with an analysis of simulation modelling.

Satellite constellation design plays an important role in network robustness and a certain level of link quality provisioning. Suitable constellation design will increase network efficiency and management and reduce overall network costs. A number of new constellation designs arise annually, but for specific applications a certain constellation pattern is needed. There is no unique constellation design that would be suitable for all services. To demonstrate this, the satellite constellation Telesat was analysed for service provisioning to autonomous vessels in the Arctic region.

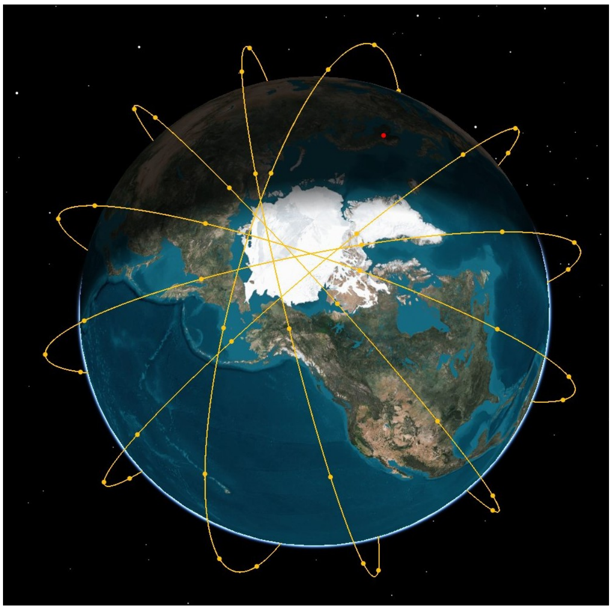
The Telesat constellation is designed for FSS services and consists of two sub-constellations: polar constellation and inclined. After the model building of the constellation in STKv11, analysis of the constellation has been carried out. During the analysis it was found that the polar constellation causes interruptions in the link *vessel - LEO constellation - GW* (Figure 4.1b). The "weak spot" is the widest place between the orbits. Such interruptions will repeat every time the orbits return to the same position. This might be an issue when realizing defined use cases since for a fully autonomous system it is essential to have no interruptions in the link. The inclined constellation does not cover the Arctic region. The current example shows that there is a need to define an optimal constellation for particular services.

In the rest of the current chapter, the methods of constellation design are described.

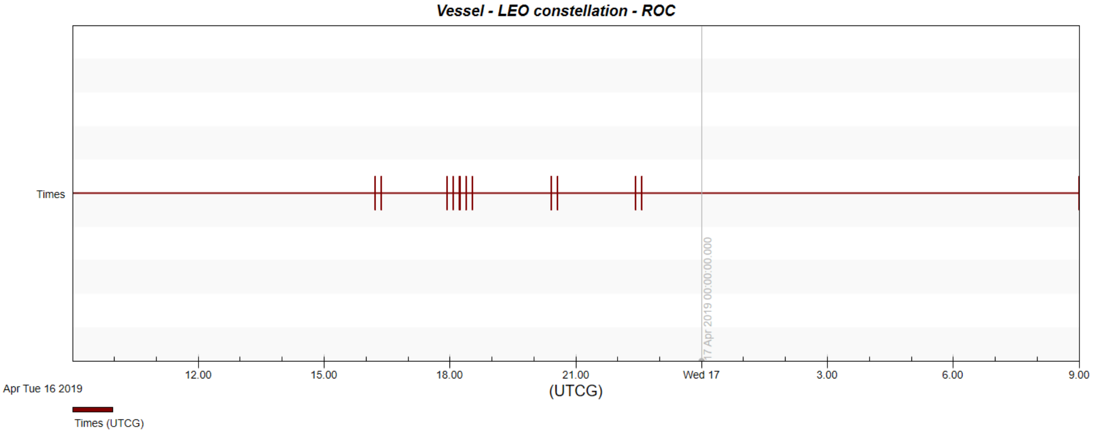
4.1 Constellation Trade-offs

Many problems regarding the orbital configuration have already been studied and therefore there are several methodologies proposed for optimizing orbital configurations of satellite constellation [11]. The goal of orbital configuration methods is to achieve global or local coverage with a low but sufficient number of satellites, supporting the economical and production development.

Constellation design requires various trade-offs in order to determine the necessary communication level for specific purposes. The constellation design objectives must satisfy the requirements, presented in Section 3.5 and can be summarized as follows:



(a) *Telesat's polar constellation (yellow lines). Red dot represents GW.*



(b) *The interruption (vertical lines) in the link Vessel - satellite - GW with Telesat's constellation.*

Figure 4.1. *Simulated Telesat polar constellation.*

1. 100% Arctic area coverage by LEO satellites.
2. No interruptions to the transmission path *vessel - LEO satellite constellation - GW* with a constrained BER value for the continuous connectivity use case.
3. The minimum satellite link duration time to any vessel must correspond to the time period specified in Table 2.6 for the discontinuous use case.
4. The satellite link duration time to any vessel (connectivity without handovers) must be maximal.
5. The duration of continuous coverage by one satellite (connectivity without handovers) must be maximal.
6. The number of satellites and orbits is a minimum for the set requirements.

4.1.1 Altitude Selection for Satellite Constellation

The orbital height is an important parameter that will directly influence the number of satellites in the constellation, the parameters of the antenna, and the overall cost of the system.

Atmospheric drag. At lower altitudes, the atmosphere is denser. At these altitudes, the collision of gas molecules with the satellite will cause an atmospheric drag. Due to atmospheric drag, the altitude of the satellite will decay. Moreover, frequent collision with gas molecules will erode the body of the satellite. Satellite decay and erosion have been found to have a significant effect in the altitude range of $250 - 1000\ km$ [108].

Van Allen radiation belt. A Van Allen radiation belt is a zone of energetic charged particles, originating from the solar wind and captured by a planet and kept around it due to the magnetic field. There are at least two of these belts around the Earth. The inner belt extends from $1000\ km$ to $6000\ km$ of altitude, and the outer belt is in the range from 13000 to $60000\ km$ above the Earth. Satellites launched close to the Van Allen belt zones must be accordingly protected and kept away from the high radiation zones [109].

4.1.2 Revisit Time

In order to easily control the satellite operation, the constellation should be able to return to its initial state after a specified period of time. The orbits are designed as recursive orbit, meaning that the satellite will pass the same point after a certain time interval during the day. The satellite running cycle T_c can be calculated according to Kepler's third law:

$$T_c = 2\pi(R_E + h)\sqrt{(R_E + h)/GM}, \tag{4.1}$$

where R_E is the radius of Earth, h is the satellite orbit altitude, G is the universal gravitational constant, M is the weight of Earth. $R_E = 6378.14\ km$, $G = 6.67 \times 10^{-11} m^3 kg^{-1} s^{-2}$, $M = 5.97 \times 10^{24}\ kg$.

When designing a multiple-layer constellation, consisting of LEO, MEO, and GEO, the running cycle of the entire constellation must be taken into account, since the entire running cycle of the multi-layered constellation (LEO, MEO, GEO) should be the least common multiple of the running cycle of the satellites of each layer [110]. In this work, only a one-layered LEO constellation will be considered.

The connectivity time (or passing time) from a specific location on the ground to a passing satellite without taking restrictions of elevation angle into account is calculated according to [111]:

$$T_p = \frac{T_c}{\pi} arccos(\frac{R_E}{R_E + h}), \tag{4.2}$$

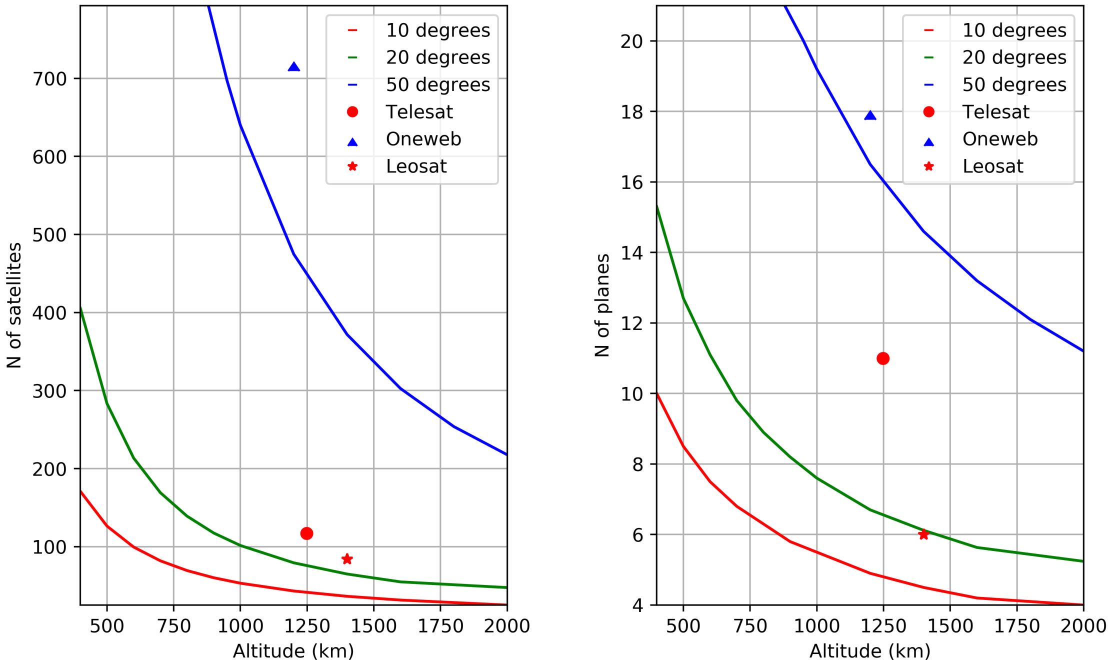


Figure 4.2. *Relationship between the number of planes (right figure) and the total number of satellites in the constellation (left figure) and the elevation angle.*

where time T_p also defines the maximum handover time between the satellites. Usually the time T_p is less in practice due to a margin to guarantee the connectivity and also due to the minimum elevation angle of the ground antenna.

4.1.3 Elevation Angle Impact

The elevation angle is the satellite height above the horizon as seen from the vessel [112]. If the elevation angle of the antenna is zero degrees ($0°$), the antenna is pointing at the horizon, whereas $90°$ will point the antenna at the zenith (directly overhead). In the simulation, we set the minimum elevation angle to $10°$, since communication under low elevation angles (below $10°$) can be interrupted by natural barriers [8]. It should also be taken into account that by choosing a high minimal elevation angle, the distance between the satellite and a ground station can be minimized, and thus, the propagation delay will be reduced.

Elevation angle also depends on the depth of rain fades and gaseous absorption. Gaseous absorption contributes to the total attenuation of radiowaves, especially at low elevation angles, although the contribution is small. Rain attenuation contributes significantly to the total path attenuation for low elevation angles in some regions at certain altitudes, where snow and ice precipitation are converted into rain precipitation, called the melting layer [113].

Elevation angle choice can also be affected by the Noise Temperature. The antenna will absorb from the surrounding environment a part of the noise power as

$$N_A = kT_aB, \tag{4.3}$$

where B is the receiver's bandwidth and T_a is the temperature of the antenna [114]. The authors of [114] demonstrated that with a higher antenna elevation angle the antenna temperature is lower, which leads to lower BER.

It should also be noticed that when choosing a higher elevation angle of the antenna, the number of satellites in the constellation should be increased. The direct relationship between the antenna elevation angle and the number of satellites in the constellation is presented in Figure 4.2, in which the lines represent the minimal approximate number of planes and satellites in the constellation for a specified altitude and elevation angle, in comparison to real examples: the circle, triangle, and star markers represent the constellations Telesat for $\varepsilon_{min} = 10°$, OneWeb for $\varepsilon_{min} = 50°$, and Leosat for $\varepsilon_{min} = 10°$ respectively.

4.1.4 Link Budget Impact Parameters

Antenna setup of the vessel and satellite includes the following important parameters:

- Elevation and Azimuth angle: azimuth angle is the angle between the North line and horizontal satellite direction as seen from the vessel. The range of azimuth is from $0°$ to $360°$.
- Modulation technique: when a higher number of bits per symbol in a type of modulation is used, a higher C/N value is required to achieve the same probability of error compared to those in a lower number of bits per symbol. In the simulations, QPSK modulation was used.
- Antenna gain: this describes the performance of the antenna in terms of conversion of radio waves into electrical power and *vice versa*.
- Polarization type: most communications systems use either vertical, horizontal or circular polarization. In the constellations described in this work, circular polarization was used.
- Size of the antenna: the antenna sizes from different vendors vary, as can be seen from Table 2.9. For the Ka-band the typical size of a VSAT antenna is around $100\ cm$.
- Antenna pointing: VSAT antennas are highly directive and must be pointed accurately at the satellite in order to achieve optimal quality of the link. Usually, the auto-tracking system keeps the antenna pointed at the satellite.

Table 4.1 provides information on what kind of antenna model was used for ground and space segment in the simulations. The vessel's VSAT antenna is based on the SAILOR

600 VSAT KA SYSTEM characteristics for the Ka-band [69]. A phased array antenna was used for the satellite, with 9 elements and spacing between the elements of 0.75.

Table 4.1. *System antenna parameters used in the simulations. Parameters are adopted from [115], Section A8.*

Parameter	LEO satellite	VSAT
Antenna type	Phased array	ITU-R -S465-5
Antenna diameter	$1\ m$	$0.82\ m$
Polarization	RHCP(DL, UL)	RHCP(DL, UL)
Antenna power	$50\ dBW$	$50.4\ dBW$
Modulation scheme	QPSK	QPSK
G/T performance	$19.5\ dB/K$	
System noise temperature	$850\ K$	$290\ K$
UL EIRP(min-max)	$30.6 - 39\ dBW$	$37 - 39\ dBW$
Frequency	$17.8\ GHz$ (DL)	$27.5\ GHz$ (UL)
Throughput	$17 - 23\ Gbps$	$100\ Mbps$
Signal bandwidth	$30133\ kHz$	
VSAT elevation angle [deg]		$10° - 90°$
Distance between satellite and vessel	Altitude distance	
Antenna gain	$36.5\ dBi$	$43.4\ dBi$

4.2 Minimum Number of Satellites

The general aim of the satellite constellation design is to have as few satellites as possible and thus to satisfy a given geometrical coverage criterion. In particular, the aim is to design a constellation for continuous connectivity in the Arctic region.

For the constellation design, the following assumptions have been made in the search for simplification:

1. All LEO orbits in the constellation are of common size and of $90°$ inclination.
2. All LEO orbits are circular and evenly distributed around the Earth.
3. LEO satellites are evenly distributed in LEO planes.

A circular instantaneous footprint of the satellite determines the satellite coverage, called the field of view (FoV) of the satellite. The footprint size is determined by the orbital height of the satellite and the minimum elevation angle ε_{min} under which the satellite cannot be seen from the ground.

The traditional approach of constellation design is the symmetrical distribution of the orbits and satellites. This approach is often referred to as the Walker constellation, based on the contributions by J.G. Walker [116]. In order to have symmetric arrangement, the *S* satellites are equally spaced in a given orbital plane and the *P* orbital planes are evenly distributed around the globe. Using this method, the number of satellites can be calculated for a desired latitude band. The coverage of the LEO polar orbit constellation is dense in high latitude areas and sparse in the equatorial area. Therefore, the required number of satellites needs to be calculated for equatorial areas, as this number of satellites will be sufficient for Polar regions.

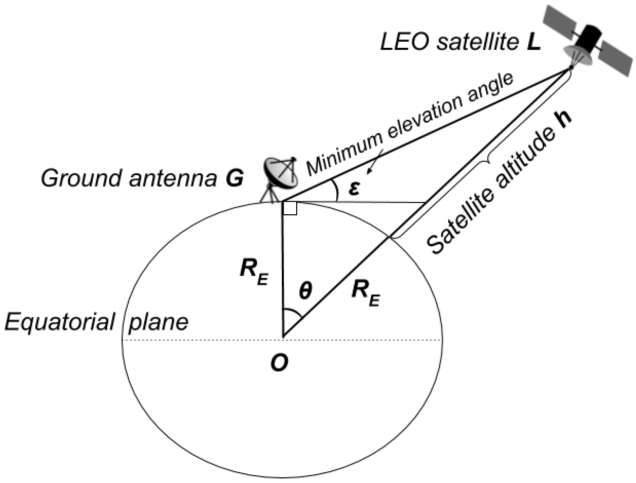


Figure 4.3. *Satellite sensor geometry.*

As is shown in Figure 4.3, the longitudinal range of an LEO satellite's coverage area can be obtained by calculating the coverage semi-angle θ. Given that $OG = R_e$, $OL = h + R_e$, where $R_e = 6378$ is the radius of the Earth, the required number of LEO orbital planes for full coverage of the equatorial region can hence be calculated according to the formula [110]:

$$OL^2 = OG^2 + GL^2 - 2OG \cdot GL \cdot cos\angle OGL, \tag{4.4}$$

where ε in $\angle OGL$ (Figure 4.3) is the minimum elevation angle $(10°)$. When GL is known, the coverage semi-angle θ is obtained by the law of sines:

$$\frac{GL}{sin(\theta)} = \frac{OL}{sin\angle OGL}. \tag{4.5}$$

After substituting GL, OL, $\angle OGL$ in Eq. 4.5, θ can be obtained by omitting an obtuse angle solution. As an example, for an altitude of $500\ km$, the distance between the vessel and the satellite in the equatorial area using the minimum elevation angle of $10°$ is $1\ 695.2\ km$. The coverage semi-angle, in this case, is $\theta = 13.9°$. Finally, an LEO satellite can cover twice the θ longitudinal range of an equatorial area. This means that $\lceil 360°/2\theta \rceil = 13$ LEO satellites are needed to cover the entire equatorial plane. The number of orbital planes P in this case would be $\lceil 360°/4\theta \rceil = 7$.

Table 4.2 provides the results for the calculated number of satellites in the constellation for different altitudes (top part).

4.2.1 Simulation Verification

In order to confirm that the calculated number of satellites is satisfactory, the Figure of Merit was constructed in the defined area in order to define the performance of the satellite system. In total 10 vessels were distributed across the Arctic main routes, as shown in Figure 4.4, in such a way that at least one vessel is fully or partially covering the Arctic routes. The current distribution helps to analyse all the main Arctic routes simultaneously. All vessels had access to at least one (1) satellite over the entire route of the vessel. The simulation period was chosen to be 24 hours, as this long period is sufficient for the constellation to complete the entire running cycle of the satellites and to return to the initial position.

The coverage analysis was carried out in terms of the percentage of coverage. In the simulations, the BER value of the communication link vessel-satellite was limited to a maximum fixed value of 10^{-6} for all simulations, in order to ensure the reliable operation of most of the applications, according to Table 2.7.

The simulated constellation is presented in Figure 4.5. The simulations showed that the Walker calculation method provides continuous coverage for the area above $70°$N. Although the coverage percentage was almost 100%, there was constant interruption at some altitudes in the latitudinal bands between $65°$N and $70°$N (Table 4.2). An example of link interruptions can be seen in Figure 4.6, where the vertical lines represent the link disconnection. The length of interruptions presented in the figure is from a few seconds

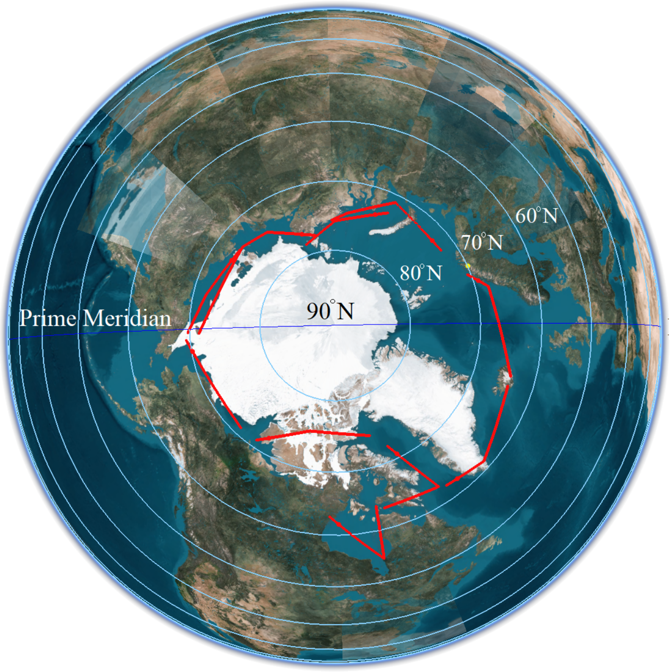


Figure 4.4. *Distribution of ships in the Arctic region.*

up to $1\ min$. It should be noted that in real life situations the interrupted time could be greater due to procedures for re-establishment of connection.

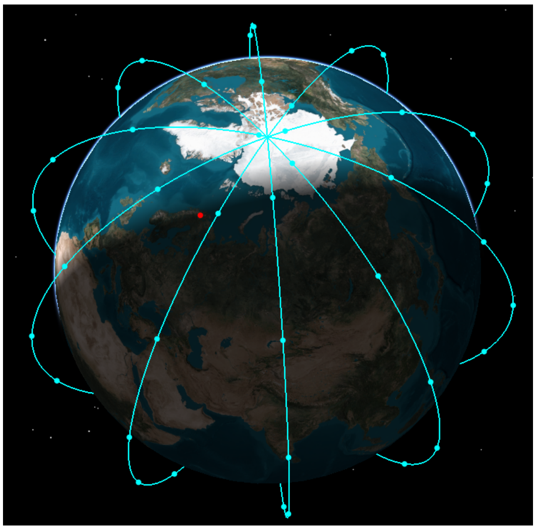


Figure 4.5. *Simulated constellation of $90°$ (blue lines). The red dot represents GW.*

Table 4.2. *Number of satellites in a constellation depending on the altitude.*

Calculated minimum number of satellites						
Altitude [km]	1 000	900	800	700	600	500
$\mathbf{P}$	5	5	5	6	6	7
$\mathbf{S}$	9	9	10	11	12	13
$\mathbf{T}$	45	45	50	66	72	91
Coverage %	100	99.99	99.98	100	99.98	99.97
Simulated minimum number for 100% coverage						
$\mathbf{P}$	5	5	5	6	6	7
$\mathbf{S}$	9	10	11	11	13	14
$\mathbf{T}$	45	50	55	66	78	98

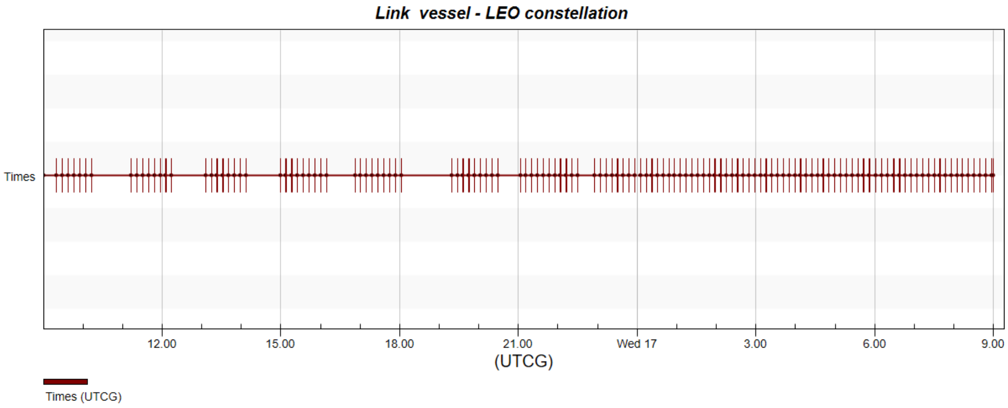


Figure 4.6. *Interruptions to the link vessel - LEO satellite constellation from a single vessel communicating with a satellite at 600 km altitude.*

In order to reach 100% coverage in the Arctic region, one more satellite per plane was

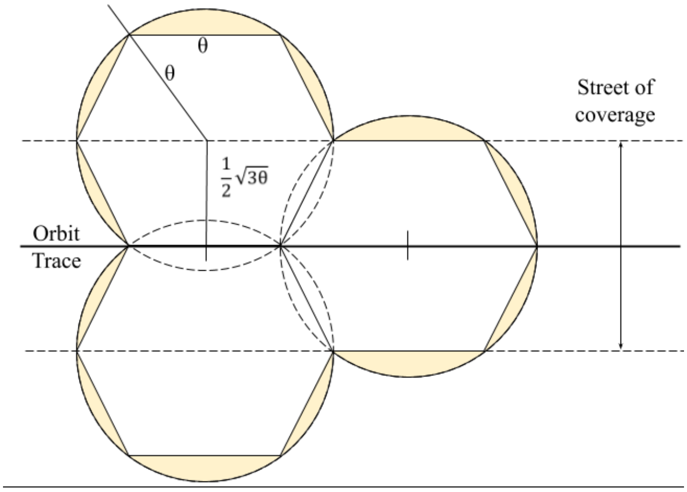


Figure 4.7. *Satellite footprint geometry.*

added. Results with 100% coverage provided by a larger constellation are presented in the lower part of Table 4.2. Based on the results, it can be concluded that this method cannot be used as a single model for all altitudes, as for this method in order to reach the desired coverage, multiple simulations are needed due to the method's inaccuracy. However, the method allows a rapid estimation of the minimum number of satellites in the constellation.

4.3 Optimal Number of Satellites

The aim of the optimal satellite constellation design is to be able to use the minimal number of satellites required at a certain altitude while providing the required percentage of coverage. The necessary number of satellites for continuous connectivity can be calculated based on the Streets-of-Coverage (SOC) approach, described by Thomas J. Lang [117]. The most important parameters are the orbital height h and minimum elevation angle ε_{min}. For complete coverage of the defined area, it is essential that the footprints overlap, as is shown in Figure 4.7. The coverage semi-angle θ of the footprint is given by [117]:

$$\theta = \frac{\pi}{2} - \varepsilon_{min} - arcsin(\frac{R_e}{R_e + h} \cdot cos\ \varepsilon_{min}). \tag{4.6}$$

The largest possible effective footprint of a single satellite is then equivalent to the largest hexagon inscribed into the footprint. The hexagon consist of six isosceles spherical triangles with $60°$ at the centre of the footprint and two identical angles α at the periphery of the footprint, that are equal to

$$\alpha = arctan(\frac{\sqrt{3}}{cos\theta}). \tag{4.7}$$

As the spherical excess of the triangles is

$$\epsilon = 2\alpha(\frac{2\pi}{3}), \tag{4.8}$$

the area of the hexagon is calculated as

$$S = 6R^2\epsilon, \tag{4.9}$$

and thus, to cover the entire Earth,

$$N = \frac{4\pi R^2}{S} = \frac{\pi}{3\alpha - \pi} \tag{4.10}$$

satellites are required.

4.3.1 Simulation Verification

Based on mathematical analysis for different altitudes, an optimal constellation providing continuous coverage was derived. The pattern of the constellation, providing continuous "streets" of coverage, is presented in Figure 4.8. The calculated constellation was verified with the simulations. The measurements are based on the constraints of a fixed BER value of 10^{-6} of the link from vessels to any of the satellites in the constellation. The constellation results are provided in Table 4.3.

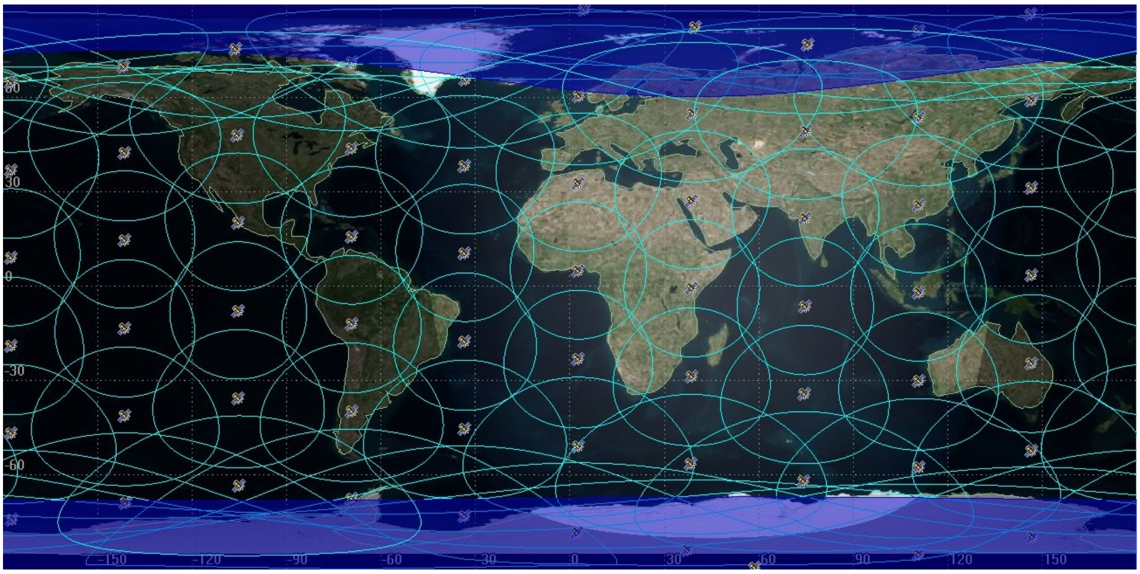


Figure 4.8. *2D LEO optimal constellation pattern at 1000 km (6×10). Dark blue colour represents the coverage of Polar regions.*

According to the simulation results, the constellation calculated by the SOC method provides 100% coverage for the minimal elevation angle $\varepsilon_{min} = 10^\circ$ in the area below 70°N and with $\varepsilon_{min} = 20^\circ$ at higher longitudes (above 70°N). However, if the minimum elevation

Table 4.3. *Optimal number of satellites in a constellation in a defined area for* $\varepsilon = 10°$ *based on the SOC method with 100% coverage at all altitudes.*

Optimal number of satellites for the Arctic region						
Altitude [km]	1 000	900	800	700	600	500
$\mathbf{P}$	6	6	7	7	8	9
$\mathbf{S}$	10	11	11	12	14	15
$\mathbf{T}$	60	66	77	84	112	135

angle of the antenna of the vessel is installed for more than $10°$ at lower longitudes, the constellation must be redesigned with a higher number of satellites for continuous satellite access. Although this method might be applied for global coverage provision, it has been verified only for the Arctic region.

4.4 Simulation Analysis of Constellations

In this section more detailed analysis of the constellations is provided.

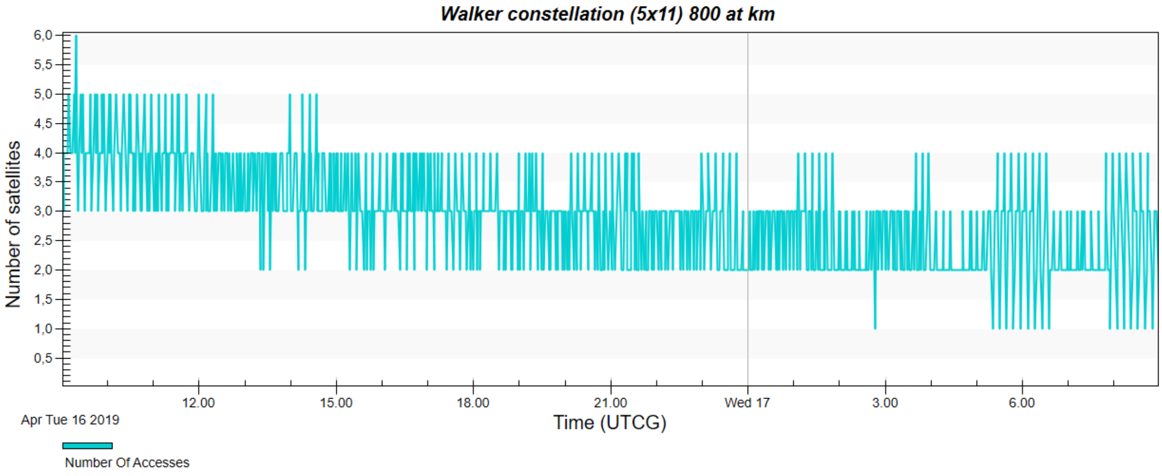
4.4.1 Constellation Redundancy Analysis

Two types of constellations, the optimal constellation, constructed by the SOC method and the minimal satellite constellation, constructed by the Walker method were compared in terms of the number of satellites covering the vessels. The simulation results are presented in Table 4.4. The constellation size is described as the number of orbital planes ($\mathbf{P}$) times the number of satellites in each plane ($\mathbf{S}$). The measurements were averaged for all vessels distributed across Arctic routes.

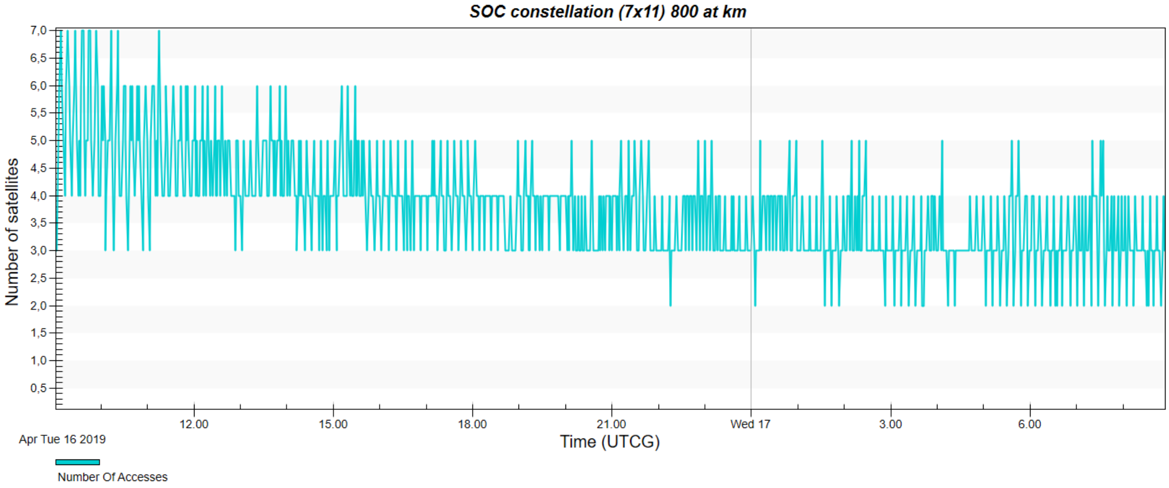
Table 4.4. *Number of simultaneous accesses to the constellation comparison for constellations constructed by two methods.*

Altitude [km]	**Constellation** $(\mathbf{P} \times \mathbf{S})$	**Minimum**	**Maximum**	**Average**
1000	Walker (5×9)	2	5	3
	SOC (6×10)	4	8	5
800	Walker (5×11)	2	5	3
	SOC (7×11)	3	8	6
600	Walker (6×13)	2	5	4
	SOC (8×14)	3	8	6

According to Table 4.4, the simulation results for constellation (6×10) at an altitude of $1000\ km$ show that on average the vessels passing through the Arctic routes are covered by at least 4 satellites, while the maximum number reaches 8 LEO satellites during the simulation period. For the constellation (5×9) at the same altitude on average, the routes



(a) *Constellation* (5×11) *constructed by the Walker method.*



(b) *Constellation* (7×11) *constructed by the SOC method.*

Figure 4.9. *Comparison of two constellations for 800 km altitude constructed using different methods. The comparison was made from a single place for a single vessel.*

are covered by at least 2 satellites and the maximum averaged number of satellites is 5.

For constellation (7×11) at $800\ km$ on average at least 3 LEO satellites on average cover the vessels along the Arctic routes, and the averaged maximum number of satellites is 8, compared to at least 2 LEO satellites for (5×11) and a maximum averaged number of 5.

For a constellation (8×14) at $600\ km$ at least 3 LEO satellites on average cover the vessels along the Arctic routes, and the maximum averaged number is 8, compared to at least 2 LEO satellites for (6×13) and a maximum averaged number of 5.

A comparison of the two graphs is presented in Figure 4.9. These graphs present the number of accesses to the constellations for a single ship from a single place. The blue vertical lines represent the number of connected satellites to the vessel at a moment in time.

In general, it can be concluded that the constellation designed by the "streets-of-coverage" approach increases the average number of simultaneous satellite accessions. This method can be used for redundant satellite constellation definition for local and global coverage.

4.4.2 Delay Analysis

Elevation angle impact on link duration. In comparison to other constellations, LEO satellites provide lower propagation delays due to closer positioning to the Earth. However, with lower altitude, a larger constellation is needed in order to provide global coverage. At the same time, it is more challenging to maintain the desired quality of communication link for LEO constellations due to the higher delay variations caused by frequent antenna handovers. High delay variations are adverse for both real-time and non-real-time applications [106].

Higher altitude constellations require fewer satellites employed, and thus the delay on the path vessel-satellite-GW will be reduced due to fewer handover procedures. However, on other hand, there is an increased propagation delay for uplink and downlink transmissions.

The least continuous coverage time of LEO-layered satellites for vessels is $8\ min$ for $600\ km$ (8×14), $10\ min$ for $800\ km$ (7×11) and $12\ min$ for $1000\ km$ (6×13), as is shown in Table 4.5. The elevation angle is $0°$ in the theoretical passing time calculations, whereas in practical situations the minimal elevation angle reduces the connection time, as is shown in Table 4.5. It can be noticed that the difference is quite significant: with $800\ km$ altitude the simulated link duration is 5 minutes shorter than the theoretical time, calculated from horizon to horizon.

Table 4.5. *Link duration and running cycle of the satellite.*

Orbital height	1000 km	800 km	600 km
Passing time	17 min	15 min	13 min
Link duration (simulations)	12 min	10 min	8 min
Running cycle	1.7 h	1.7 h	1.6 h

The results of one-way delay for different altitude height and elevation angles are presented in Figure 4.10. It can be noticed that the lower elevation angle corresponds to a higher propagation delay. Thus, the elevation angle plays an important role in constellation design.

Round-Trip Time. In order to calculate the round-trip time (RTT), the distance from the vessel to the satellite (d_{V-S}) and the distance from the satellite to the GW gNB (d_{S-GW}) must be taken into account. Very often a path between GW gNB and the actual ROC position can also be defined, but in current simulations, GW and ROC are considered as a single position. If we assume a fibre connection between the GW and the actual position of the ROC with a distance that does not exceed $200\ km$, the transmission delay can be neglected, as it is not significant in the applications of current scenarios. However, the position of the GW is important as it is one of the main factors that impacts the coverage,

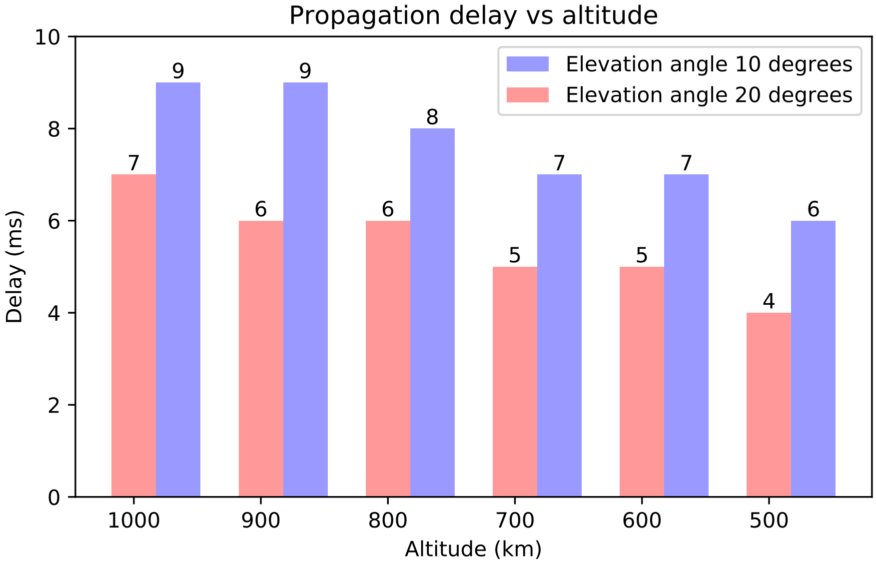


Figure 4.10. *Propagation delay vs altitude and elevation angle.*

as was demonstrated by the authors in [118].

The RTT is calculated according to the following equation [119]:

$$RTT = 2 \times \frac{d_{V-S} + d_{S-GW}}{c}, \tag{4.11}$$

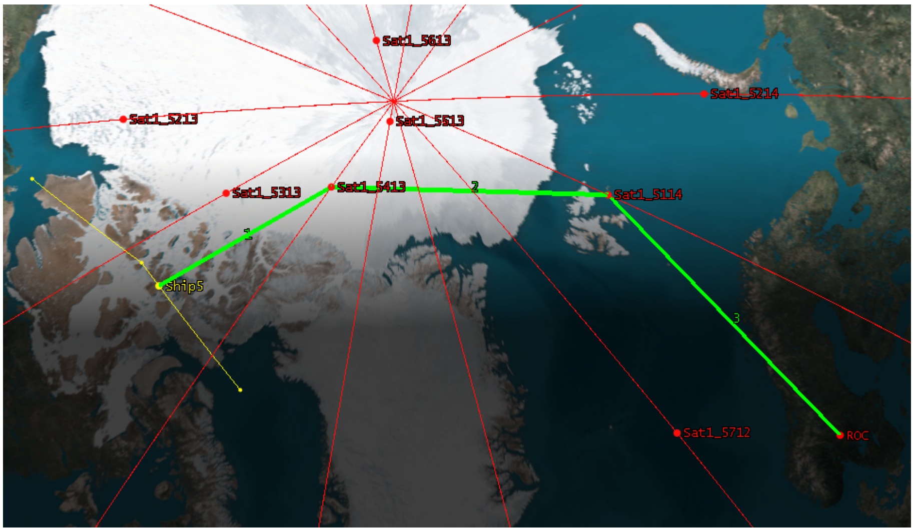
where c is the speed of light. According to the simulation results, for $h = 1000\ km$ the RTT time varies in different scenarios from $16\ ms$ up to $36\ ms$. This value is within the range of approved target key performance indicators for 5G, which is $50\ ms$ of RTT [119].

Delay Analysis for ISL. The constellation might employ inter-satellite links (ISL). Constellation with ISL might employ longer delays than without ISL due to inter-orbit link distance variation. Accordingly, the delay propagation with ISL at $1000\ km$ altitude might be smaller, than in the constellation with ISL at $500\ km$ altitude. As can be seen in Figure 4.11a, the path goes through two satellites, which gives $6\ ms + 13\ ms + 5\ ms = 24\ ms$ one-way of propagation delay. The path (b) consists only of a single satellite and has a propagation delay of $9\ ms + 12\ ms = 21\ ms$. Additional delays might include processing delays by satellites. In order to mitigate these delays, an appropriate routing algorithm should be employed [120].

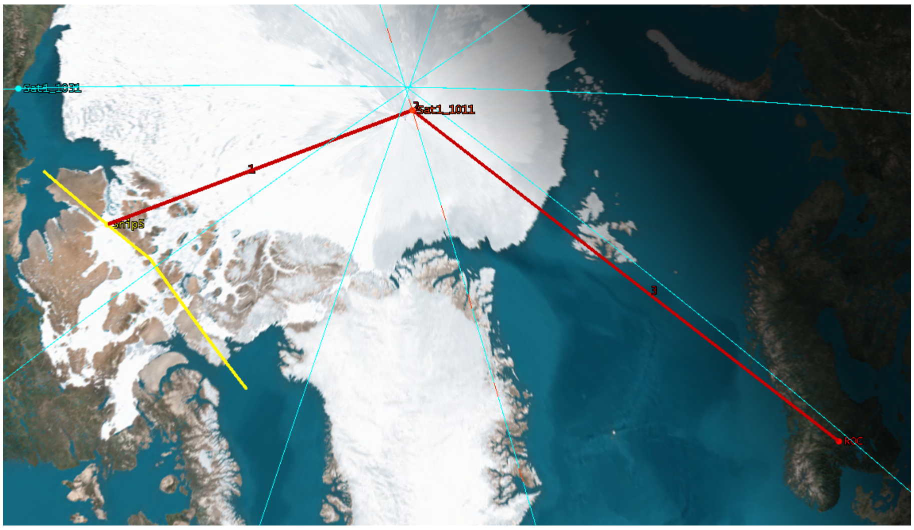
4.4.3 Doppler Shift Analysis

Doppler shift is determined as a shift of the signal frequency caused by the motion of the receiver, the transmitter or both [121]. The maximum Doppler frequency is given by:

$$\Delta F = \frac{F_c \times \vartheta \times cos(\beta)}{c}, \tag{4.12}$$



(a) *Multi-hop link at 500 km altitude vessel-GW with ISL and one-way delay of* $24\ ms$.



(b) *Multi-hop link at 1000 km altitude vessel-GW without ISL and one-way delay of* $21\ ms$.

Figure 4.11. *Comparison of systems with and without ISL.*

where c is the speed of light, F_c is the nominal carrier frequency, ϑ is the velocity of the vessel, and β is the angle between the velocity vector ϑ of the mobile transmitter and the direction of propagation of the signal between the vessel and the satellite.

In Figure 4.12, comparison of constellations for different altitudes over time for an uplink is presented. The results are in the range of the worst-case scenario specified by the 3GPP in the specification [121]. The Doppler effect is one of the challenges in LEO systems. As illustrated in Figure 4.12, at a height of $600\ km$ the LEO satellite moving at a speed of $7.56\ km/s$ results in a Doppler shift value of $600\ kHz$ at a carrier frequency of $27.5\ GHz$.

The Doppler shift mitigation remains one of the main challenges for non-geostationary (NGO) satellite systems. The Doppler shift value varies rapidly over time, and the rate of such variation is referred to as the Doppler variation rate. To cope with heavy Doppler effects, appropriate Doppler compensation techniques must be implemented. In [122], as well as in [123] and in [32] the authors suggested a methodology of Doppler shift

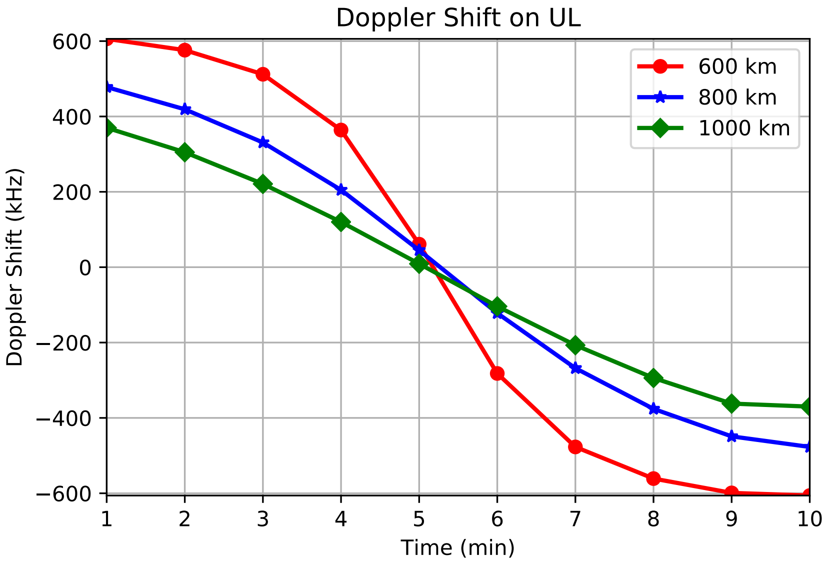


Figure 4.12. *Doppler shift results on uplink (UL) for different altitudes.*

compensation in LEO satellite systems by estimating the satellite position (GNSS based technique) and predicting the point at which the Doppler shift is zero. Furthermore, a resource allocation approach both in time and in the frequency domain in order to reduce Doppler values was proposed in [124], and in [125] the authors proposed an uplink scheduling technique for the LEO satellite system that is able to mitigate the level of the differential Doppler. To deal with high Doppler values, integrated large sub-carrier spacing will result in increased robustness to the Doppler shift, which will be provided by 5G technology. 5G NR waveform will provide flexibility, which should allow to scale sub-carrier spacing at least from $15\ kHz$ to $480\ kHz$ [32].

4.5 Simulation Summary

It can be concluded that for any specific purpose, a certain type of satellite constellation should be defined. No unique satellite constellation design exists, and the constellation depends highly on specific application requirements for provided coverage, satellite revisit times, link duration, antenna characteristics, area of interest, etc.

In the current chapter, we designed the optimal satellite constellation for the use cases, as specified in Chapter 3. The final designed constellation proved to meet the requirements, described in the beginning of the current chapter:

1. The constellation is able to provide 100% coverage for the minimum elevation angle $\varepsilon_{min} = 10°$ in the Arctic area from $60°$N.
2. There are no interruptions to the link *vessel - LEO satellite constellation - GW* while maintaining a constrained BER value for the continuous connectivity use case. In the simulations, the BER value was restricted to a maximum value of 10^{-6}.
3. The minimum satellite link duration time to any vessel corresponds to the time pe-

riod specified in Table 2.6 for the discontinuous use case. The minimum satellite link duration time to any vessel and the GW (connectivity without handovers) is $8\ min$ at an altitude of $600\ km$, $10\ min$ at an altitude of $800\ km$, and $12\ min$ at an altitude of $1000\ km$.

4. The number of satellites and orbits is minimal and optimal for specified system parameters. In general, it can be concluded that by selecting higher orbital altitudes, the number of satellites may be reduced but this will increase propagation delay and required transmitted power.

In general, the following aspects of the constellation design can be highlighted:

- *Latency.*

  The latency parameter was analysed in terms of different orbital heights, elevation angles, and ISL implementation. In conclusion, when designing the satellite system it is important to find a compromise between altitude and elevation angle selection, as higher elevation angle leads to lower propagation delay, although when selecting lower altitude, more satellites might be needed to meet the requirements. In case of ISL implementation, appropriate routing algorithms must be considered in order not to contribute to the delay due to inter-orbit link distance variation. Otherwise, constellation without ISL might be a better choice for delay-tolerant applications.

  The calculated RTT value corresponds to the approved target requirements specified by the 3GPP for communication that involves satellite systems. In order to decrease the RTT value in addition to compromised selection between satellite altitude and minimum elevation angle, appropriate routing algorithms for ISL must be implemented.

- *Doppler shift.*

  Based on simulation results, the Doppler shift values for different altitudes for the system parameters presented in Table 2.7 were obtained. The Doppler values are high, although in the range of the worst-case scenario, defined by the 3GPP. Obviously, these large Doppler shifts will introduce significant limitations on the way to seamless and robust connectivity deployment. The mitigation techniques for large Doppler shift values need to be investigated in greater depth. In general, 5G introduces more flexible NR waveforms. Its flexibility is exemplified by its ability to support wider sub-carrier spacing (SCS), which will lead to increased robustness to Doppler shifts. Another solution to mitigate large Doppler shifts is the method of estimation of satellite position, and thus prediction of where the Doppler shift can be compensated. It is important to note that the highest Doppler shift is experienced at $\varepsilon = 90°$.

- *Satellite handover.*

  As was shown, LEO satellites move at high speeds above the ground, providing different link durations to the vessel. With closer positioning to the Earth, the link

> duration will be lower, and accordingly, the vessel antenna will have to pass through the handover process more often. The random access (RA) procedure must be executed in order to find a new satellite and establish a communication link with it. Often RA procedures are very time-consuming. Besides increased delays and possible connectivity interruptions, there might be significant reductions in throughput [31]. In this regard, selection of higher altitudes might be a better option.

The satellite constellation was designed using two mathematical methods. These methods, Walker and SOC, yielded different results. In order to identify the more reliable method, a comparison was made in terms of the reliability of the methods and redundancy of the constellation provided by these methods.

Reliability of the methods.

Based on the described two methods, the following conclusions can be drawn. The Walker method cannot be used as a single model for all altitudes, as for this method in order to reach the desired coverage, multiple simulations are needed due to the method's inaccuracy. In the current work, in order to reach 100% coverage of the Arctic region at specific altitudes, one more satellite per plane was added. This method allows a rapid estimation of the minimum satellite number in the constellation. On the other hand, the SOC method provided reliable calculation results for all altitudes studied in the current work and provided continuous coverage for the entire Arctic region. This method can be used for global coverage, although only coverage for the Arctic area was analysed in this work.

Redundancy.

Compared to the minimum set of satellites, the analysis of the optimal constellation calculated by the SOC method showed the improvement in system redundancy by means of an increased number of satellites visible from a single vessel. This directly influences the system performance and increases the chances of maintaining the required link QoS.

5 CONCLUSIONS

This MSc thesis reported research work on satellite-terrestrial connectivity for enabling the autonomous vessel concept. As a summary, the current work includes:

- Review and analysis of current satellite systems and proposed future satellite mega-constellations;
- State of the art of the Arctic region with regard to marine operations, communication capabilities and maritime operational challenges in this region;
- Description of satellite-terrestrial architecture for autonomous vessel operation as well as a description of link requirements;
- Development and description of use cases for drone-assisted autonomous vessel system;
- Design and analysis of a satellite constellation for defined use cases.

5.1 Highlights and Summary of the Work

The main goal of this thesis was to design a satellite constellation for the use cases of autonomous vessel applications and to answer the following research questions: what kind of satellite communication system is needed for reliable operations in the defined area when the main application is a drone-assisted situational awareness system for autonomous vessels? What is the optimal satellite constellation configuration that meets the required communication gap intervals, link bit error rate (BER) values, and communication delay?

As a main result, the reliable satellite constellation was designed for defined own use cases on autonomous vessel operation in the Arctic region. The designed constellation consists of minimum and optimal numbers of satellites for defined scenarios and proved to meet the requirements of continuous satellite access for defined BER, communication gap interval, coverage and communication delay that were described in Chapter 3.

As a significant contribution, a methodology of satellite constellation design for a specific application was developed, which illustrates the main steps in the satellite constellation design process. Current constellation design methodology can help in developing future missions. The proposed design is a first step towards the development of practical systems.

As a secondary significant contribution, novel use cases for autonomous vessels with drone-assisted situational awareness system were created and described in detail with proposed technologies for utilization. The use cases describe the interaction procedure between autonomous vessel, UAV and the Remote Operations Centre and help to understand how the system should behave. The described use cases will help to understand future aspects of developing the autonomous system and analysing the system requirements.

During the constellation design, two mathematical methods were studied: the Walker method and the streets-of-coverage (SOC) method. The mathematical calculations based on these methods were verified with an extensive set of simulation modelling, which allowed revealing of an efficient method of the satellite constellation design and verified that the developed constellation provides 100% coverage of the defined area.

Based on the simulations, the Walker method was able to provide the minimum number of satellites in the constellation for the defined area, although the final optimal constellation was obtained on the basis of the SOC method. The SOC method appeared to be more efficient than the Walker method, and to provide faster and more accurate means to achieve the desired constellation design. When using the Walker method, several simulations were required in order to achieve the desired coverage level. However, it might lead to a smaller number of satellites. In addition, the number of simultaneous accesses to satellites in the constellation-based SOC method was increased, which was one criterion of a reliable constellation.

The conducted research illustrates the importance of the thesis topic, based on the literature review provided in Chapter 2. The results obtained during the study can be used as a reference for other constellation design and future system parameters definition, especially for the Arctic region.

5.2 Future Directions

This study may point to many future research directions. Regarding the satellite constellation design, more detailed comparative studies between traditional, such as the Walker method, and non-traditional, such as the SOC or other methods, for the constellation mathematical analysis are needed, as different methods might lead to a higher or lower number of satellites, which would directly influence the economical factor.

The proposed constellation development can be continued in the future for example by including the network-level aspects and routing procedures. This would provide deeper understanding of the required architecture including how to integrate terrestrial systems to the megaconstellation and provide a basis for the standardization of communication link parameters for autonomous vessel operation.

Some other directions may include:

- Detailed study of handover delay and interference from other systems.

- Investigation of different constellation parameter aspects to mitigate the Doppler effect.
- Investigation of optimal positioning of GW stations in order to reduce the communication link delay between autonomous vessels and the Remote Operations Centre.

REFERENCES

[1] C. S. Ruf, S. Gleason, Z. Jelenak, S. Katzberg, A. Ridley, R. Rose, J. Scherrer, and V. Zavorotny. The CYGNSS nanosatellite constellation hurricane mission. In: *2012 IEEE International Geoscience and Remote Sensing Symposium*. IEEE. 2012, 214–216.

[2] M. Deckett. The ORBCOMM system. In: *Small Satellites Systems and Services* (1993).

[3] ESA. *GLONASS Space Segment*. 2018. URL: `https://gssc.esa.int/navipedia/index.php/GLONASS_Space_Segment` (visited on 06/22/2019).

[4] M. Höyhtyä, A. Mämmelä, X. Chen, A. Hulkkonen, J. Janhunen, J.-C. Dunat, and J. Gardey. Database-assisted spectrum sharing in satellite communications: A survey. In: *IEEE Access* 5 (2017), 25322–25341.

[5] J. Christensen. ITU regulations for Ka-band satellite networks. In: *30th AIAA International Communications Satellite System Conference (ICSSC)*. 2012, 15179.

[6] J. Radtke, C. Kebschull, and E. Stoll. Interactions of the space debris environment with mega constellations—Using the example of the OneWeb constellation. In: *Acta Astronautica* 131 (2017), 55–68.

[7] R. Radhakrishnan, W. W. Edmonson, F. Afghah, R. M. Rodriguez-Osorio, F. Pinto, and S. C. Burleigh. Survey of inter-satellite communication for small satellite systems: Physical layer to network layer view. In: *IEEE Communications Surveys & Tutorials* 18.4 (2016), 2442–2473.

[8] S. Cakaj, B. Kamo, A. Lala, and A. Rakipi. The coverage analysis for low earth orbiting satellites at low elevation. In: *Int. J. Adv. Comput. Sci. Appl.(ijacsa)* 5.6 (2014).

[9] D. Roddy. *Satellite Communications, (Professional Engineering)*. McGraw-Hill Professional: New York, 2006.

[10] T. G. Reid, A. M. Neish, T. F. Walter, and P. K. Enge. Leveraging commercial broadband LEO constellations for navigation. In: *Proceedings of the ION GNSS*. 2016, 2300–2314.

[11] O. L. De Weck, U. Scialom, and A. Siddiqi. Optimal reconfiguration of satellite constellations with the auction algorithm. In: *Acta Astronautica* 62.2-3 (2008), 112–130.

[12] S. Plass, F. Clazzer, and F. Bekkadal. Current situation and future innovations in Arctic communications. In: *2015 IEEE 82nd Vehicular Technology Conference (VTC2015-Fall)*. IEEE. 2015, 1–7.

[13] R. Birkeland. An overview of existing and future satellite systems for arctic communication. In: *Proceedings of ESA small satellites systems and services* 2014 (2014).

[14] O. Gupta and C. Fish. Iridium NEXT: A Global access for your sensor needs. In: *AGU Fall Meeting Abstracts*. 2010.

[15] O. Gupta. Iridium NEXT SensorPODs: Global access for your scientific payloads. In: *25th Annual AIAA/USU Conference of Small Satellites*. 2011.

[16] Iridium. *Iridium Pilot - Brochure*. 2019. URL: `https://www.iridium.com/download/?dlm-dp-dl=24045` (visited on 03/09/2019).

[17] M. M. McMahon and R. Rathburn. *Measuring latency in Iridium satellite constellation data services*. Tech. rep. Naval Academy Annapolis MD, Dept of Computer Science, 2005.

[18] Iridium. *Iridium Certus - Maritime Fact Sheet*. 2018. URL: `https://www.iridium.com/download/?dlm-dp-dl=213467` (visited on 03/10/2019).

[19] *Intelsat EpicNG High -Throughput Satellite Platform*. URL: `https://www.intelsatgeneral.com/intelsat-epicng/` (visited on 03/09/2019).

[20] Intelsat. *Intelsat EpicNG: Realizing Resilient Tactical Networks with Maximum Government Control on an Open Architecture High-Throughput Satellite*. 2019. URL: `https://www.intelsatgeneral.com/wp-content/uploads/2018/05/8039-HTS_IGC_whitepaper_2019-1.pdf` (visited on 05/26/2019).

[21] Viasat. *High-Capacity Satellite System. Transforming Satellite Communications*. 2019. URL: `https://www.viasat.com/products/high-capacity-satellites`.

[22] Y. Koulikova and L. Roberti. Global Xpress: Global Mobile Broadband. In: *Almaty, Kazakhstan, sep. de* (2012).

[23] S. H. Blumenthal. Medium earth orbit Ka-band satellite communications system. In: *MILCOM 2013-2013 IEEE Military Communications Conference*. IEEE. 2013, 273–277.

[24] G. Giambene, S. Kota, and P. Pillai. Satellite-5G Integration: A Network Perspective. In: *IEEE Network* 32.5 (2018), 25–31.

[25] Viasat. *SOYUZ Flight VS21 with OneWeb F6*. 2019. URL: `http://www.arianespace.com/mission/ariane-flight-vs21/`.

[26] Telesat. *OmniAccess to Begin Testing and Trials on Telesats Recently Launched Phase 1 LEO Satellite*. 2018. URL: `https://www.telesat.com/news-events/omniaccess-begin-testing-and-trials-telesats-recently-launched-phase-1-leo-satellite`.

[27] FCC. *IBFS Internet Reports*. 2018. URL: `https://bit.ly/2lzqtsw` (visited on 08/05/2019).

[28] B. G. C. Inigo del Portillo. A Technical Comparison of Three Low Earth Orbit Satellite Constellation Systems to Provide Global Broadband. In: (2018), 1–15.

[29] LeoSat. *LeoSat Non-Geostationary Satellite System Attachment A: Technical Annex to Supplement Schedule S*. 2018.

[30] C. Henry. *OneWeb asks FCC to authorize 1,200 more satellites*. 2018. URL: `https://spacenews.com/oneweb-asks-fcc-to-authorize-1200-more-satellites/` (visited on 03/20/2019).

[31] A. Guidotti, A. Vanelli-Coralli, M. Caus, J. Bas, G. Colavolpe, T. Foggi, S. Cioni, A. Modenini, and D. Tarchi. Satellite-enabled LTE systems in LEO constellations. In: *2017 IEEE International Conference on Communications Workshops (ICC Workshops)*. IEEE. 2017, 876–881.

[32] O. Kodheli, A. Guidotti, and A. Vanelli-Coralli. Integration of Satellites in 5G through LEO Constellations. In: *GLOBECOM 2017-2017 IEEE Global Communications Conference*. IEEE. 2017, 1–6.

[33] P. Jakob, K. Ho, S. Shimizu, and S. Yoshikawa. Optimal Satellite Constellation Spare Strategy Using Multi-Echelon Inventory Control. In: *preprint arXiv:1807.02685* (2018).

[34] G. Ziaragkas, G. Poziopoulou, J. Nunez-Martinez, J. Baranda, I. Moreno, C. Tsinos, S. Maleki, S. K. Sharma, M. Alodeh, and S. Chatzinotas. SANSA—hybrid terrestrial–satellite backhaul network: scenarios, use cases, KPIs, architecture, network and physical layer techniques. In: *International Journal of Satellite Communications and Networking* 35.5 (2017), 379–405.

[35] K. Liolis, A. Geurtz, R. Sperber, D. Schulz, S. Watts, G. Poziopoulou, B. Evans, N. Wang, O. Vidal, B. Tiomela Jou, et al. Use cases and scenarios of 5G integrated satellite-terrestrial networks for enhanced mobile broadband: The SaT5G approach. In: *International Journal of Satellite Communications and Networking* 37.2 (2019), 91–112.

[36] X. Artiga, J. Nunez-Martinez, A. Perez-Neira, G. J. L. Vela, J. M. F. Garcia, and G. Ziaragkas. Terrestrial-satellite integration in dynamic 5G backhaul networks. In: *2016 8th Advanced Satellite Multimedia Systems Conference and the 14th Signal Processing for Space Communications Workshop (ASMS/SPSC)*. IEEE. 2016, 1–6.

[37] N. Courville, H. Bischl, E. Lutz, A. Svigelj, P. M. Chan, E. Papapetrou, and R. Asorey-Cacheda. Hybrid satellite/terrestrial networks: State of the art and future perspectives. In: *QShine 2007 Workshop: Satellite/Terrestrial Interworking*. ACM. 2007, 1–7.

[38] M. Bever, J. Freitag, S. Linsky, J. M. Myers, R. M. Nuber, J. L. Prieto Jr, and E. R. Wiswell. Fast-packet vs circuit switch and bent pipe satellite network architectures. In: *International journal of satellite communications* 17.2-3 (1999), 83–105.

[39] M. Höyhtyä, T. Ojanperä, J. Mäkelä, S. Ruponen, and P. Järvensivu. Integrated 5G satellite-terrestrial systems: Use cases for road safety and autonomous ships. In: *Proceedings of the 23rd Ka and Broadband Communications Conference, Trieste, Italy*. 2017, 16–19.

[40] 3GPP. *Technical Specification Group Services and System Aspects; System Architecture for the 5G System; Stage 2 (Release 15)*. Tech. rep. 3GPP, 2018.

[41] 3GPP. *Technical Specification Group Services and System Aspects; Study on using Satellite Access in 5G; Stage 1 (Release 16)*. Tech. rep. 3GPP, 2018.

[42] *The Maritime Executive. IMO Takes First Steps to Address Autonomous Ships*. 2018. URL: `https://www.maritime-executive.com/article/imo-takes-first-steps-to-address-autonomous-ships` (visited on 07/14/2019).

[43] Cefor. *Maritime autonomous surface ships – Zooming in on civil liability and insurance*. 2018. URL: `https://cefor.no/globalassets/documents/industrypolicy/news/mass---zooming-in-on-civil-liability-and-insurance---10-december-2018.pdf`.

[44] Ø. J. Rødseth and H. Nordahl. Definitions for autonomous merchant ships. In: *Norwegian Forum for Unmanned Ships, Version*. Vol. 1. 2017, 2017–10.

[45] K. J. Casola. *System architecture and operational analysis of Medium Displacement Unmanned Surface Vehicle Sea Hunter as a surface warfare component of distributed lethality*. Tech. rep. Naval Postgraduate School Monterey United States, 2017.

[46] S. Electronics. *VENUS Unmanned Surface Vehicle*. 2018. URL: `https://www.stengg.com/en/electronics/companies-affiliates/st-electronics-large-scale-systems-group/venus-unmanned-surface-vehicle/`.

[47] Rolls-Royce. *Rolls-Royce and Finferries demonstrate world's first Fully Autonomous Ferry*. 2018. URL: `https://www.rolls-royce.com/media/press-releases/2018/03-12-2018-rr-and-finferries-demonstrate-worlds-first-fully-autonomous-ferry.aspx`.

[48] Y. International. *ABB enables groundbreaking trial of remotely operated passenger ferry*. 2018. URL: `https://new.abb.com/news/detail/11632/abb-enables-groundbreaking-trial-of-remotely-operated-passenger-ferry`.

[49] Y. International. *Yara Birkeland press kit*. 2017. URL: `https://www.yara.com/news-and-media/press-kits/yara-birkeland-press-kit/`.

[50] D. GL. *The ReVolt. A new inspirational ship concept*. 2014. URL: `https://www.dnvgl.com/technology-innovation/revolt/index.html`.

[51] M. Höyhtyä, J. Huusko, M. Kiviranta, K. Solberg, and J. Rokka. Connectivity for autonomous ships: Architecture, use cases, and research challenges. In: *2017 International Conference on Information and Communication Technology Convergence (ICTC)*. IEEE. 2017, 345–350.

[52] H. Kdouh, G. Zaharia, C. Brousseau, G. Grunfelder, H. Farhat, and G. El Zein. Wireless sensor network on board vessels. In: *2012 19th international conference on telecommunications (ICT)*. IEEE. 2012, 1–6.

[53] F. Bekkadal. Future maritime communications technologies. In: *OCEANS 2009-EUROPE*. IEEE. 2009, 1–6.

[54] F. Lazaro, R. Raulefs, W. Wang, F. Clazzer, and S. Plass. VHF Data Exchange System (VDES): an enabling technology for maritime communications. In: *CEAS Space Journal* (2018), 1–9.

[55] T. Eriksen, G. Høye, B. Narheim, and B. J. Meland. Maritime traffic monitoring using a space-based AIS receiver. In: *Acta Astronautica* 58.10 (2006), 537–549.

[56] T. Eriksen, A. N. Skauen, B. Narheim, Ø. Helleren, Ø. Olsen, and R. B. Olsen. Tracking ship traffic with space-based AIS: experience gained in first months of operations. In: *2010 International WaterSide Security Conference*. IEEE. 2010, 1–8.

[57] Ø. J. Rødseth, B. Kvamstad, T. Porathe, and H.-C. Burmeister. Communication architecture for an unmanned merchant ship. In: *2013 MTS/IEEE OCEANS-Bergen*. IEEE. 2013, 1–9.

[58] M. Radovic, O. Adarkwa, and Q. Wang. Object recognition in aerial images using convolutional neural networks. In: *Journal of Imaging* 3.2 (2017), 21.

[59] A. Zolich, D. Palma, K. Kansanen, K. Fjørtoft, J. Sousa, K. H. Johansson, Y. Jiang, H. Dong, and T. A. Johansen. Survey on communication and networks for autonomous marine systems. In: *Journal of Intelligent & Robotic Systems* (2018), 1–25.

[60] G. Yang, X. Lin, Y. Li, H. Cui, M. Xu, D. Wu, H. Ryden, and S. B. Redhwan. A Telecom Perspective on the Internet of Drones: From LTE-Advanced to 5G. In: *arXiv preprint arXiv:1803.11048* (2018).

[61] A. A. Atayero, O. I. Sheluhin, and Y. A. Ivanov. Modeling, simulation and analysis of video streaming errors in wireless wideband access networks. In: *IAENG Transactions on Engineering Technologies*. Springer, 2013, 15–28.

[62] Huawei. *Cross-Industry Whitepaper Series: Empowering Our Connected World. Empowering Consumer-Focused Immersive VR and AR Experiences with Mobile Broadband*. 2016. URL: `https://www.huawei.com/minisite/hwmbbf16/insights/HUAWEI-WHITEPAPER-VR-AR-Final.pdf`.

[63] W. Xu, H. Zhou, N. Cheng, F. Lyu, W. Shi, J. Chen, and X. Shen. Internet of vehicles in big data era. In: *IEEE/CAA Journal of Automatica Sinica* 5.1 (2018), 19–35.

[64] A. Biernacki and K. Tutschku. Performance of HTTP video streaming under different network conditions. In: *Multimedia Tools and Applications* 72.2 (2014), 1143–1166.

[65] ITU-R. Revised technical and operational parameters for typical IMT-2000 terrestrial systems using high altitude platform stations and CDMA radio transmission technologies. In: *International Telecommunications Union Document*. ITU. 1999.

[66] A. K. Widiawan and R. Tafazolli. High altitude platform station (HAPS): A review of new infrastructure development for future wireless communications. In: *Wireless Personal Communications* 42.3 (2007), 387–404.

[67] Comtech. *Very-Small-Aperture Terminal*. 2019. URL: `https://www.comtech-cct.com/products/cct/very-small-aperture-terminal`.

[68] Thuraya. *Thuraya Orion IP*. URL: `https://www.thuraya.com/orion-ip` (visited on 06/20/2019).

[69] Cobham. *Sailor 600 VSAT KA. Product Sheet*. URL: `https://bit.ly/2nuaVaT` (visited on 06/20/2019).

[70] I. KVH Industries. *Connectivity at sea: a guide to advances in maritime VSAT*. 2012. URL: `http://www.pronav.fi/pdf/miniVSAT_Guide_0812.pdf` (visited on 06/22/2019).

[71] Marlink. *Maritime connectivity. Sealink Premium*. URL: `https://marlink.com/products/sealink-premium/` (visited on 06/22/2019).

[72] N. R. Hart, C. B. Meulman, and P. J. Clifford. *Satellite system for vessel identification*. US Patent 7,483,672. 2009.

[73] F. Lasserre and P.-L. Tetu. The cruise tourism industry in the Canadian Arctic: Analysis of activities and perceptions of cruise ship operators. In: *Polar Record* 51.1 (2015), 24–38.

[74] T. Nilsen. *The Barents Observer: Arctic cruise ship boom*. 2018. URL: `https://thebarentsobserver.com/en/travel/2018/05/arctic-cruise-ship-boom`.

[75] OCIMF. *Offshore Vessel Operations in Ice and/or Severe Sub-Zero Temperatures In Arctic and Sub-Arctic Regions*. Tech. rep. Oil Companies International Marine Forum (OCIMF), 2014.

[76] K. E. Fjørtoft, F. Bekkadal, and P. Kabacik. Maritime operations in arctic waters. In: *2013 MTS/IEEE OCEANS-Bergen*. IEEE. 2013, 1–8.

[77] K. M. Eger. Marine Traffic in the Arctic: A Report Commissioned by the Norwegian Mapping Authority. In: *Analyse and Strategy* (2011).

[78] Z. Liu, Y. Zhang, X. Yu, and C. Yuan. Unmanned surface vehicles: An overview of developments and challenges. In: *Annual Reviews in Control* 41 (2016), 71–93.

[79] CyberKeel. *Maritime cyber-risks. Virtual pirates at large on the cyber seas*. 2014. URL: `https://maritimecyprus.files.wordpress.com/2015/06/maritime-cyber-risks.pdf`.

[80] Z. Liu, Z. Li, B. Liu, X. Fu, I. Raptis, and K. Ren. Rise of mini-drones: Applications and issues. In: *Proceedings of the 2015 Workshop on Privacy-Aware Mobile Computing*. ACM. 2015, 7–12.

[81] K. Choi and I. Lee. A UAV-based close-range rapid aerial monitoring system for emergency responses. In: *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci* 38 (2011), 247–252.

[82] M. Ader and D. Axelsson. *Drones in Arctic environments*. 2017.

[83] H. Runge, W. Rack, A. Ruiz-Leon, and M. Hepperle. A solar powered hale-UAV for Arctic research. In: *1st CEAS European Air and Space Conference*. 2007.

[84] R. A. Shuchman and D. G. Flett. SAR measurement of sea ice parameters: sea ice session overview paper. In: *Proceedings of 2nd Workshop on Coastal and Marine Applications of SAR (CMASAR), Svalbard, Norway, September 8*. Vol. 12. 2003.

[85] J. Light, S. Parthasarathy, and W. McIver. Monitoring winter ice conditions using thermal imaging cameras equipped with infrared microbolometer sensors. In: *Procedia Computer Science* 10 (2012), 1158–1165.

[86] J. Linchant, J. Lisein, J. Semeki, P. Lejeune, and C. Vermeulen. Are unmanned aircraft systems (UASs) the future of wildlife monitoring? A review of accomplishments and challenges. In: *Mammal Review* 45.4 (2015), 239–252.

[87] S. Domaille and D. Campion. *Droning On: A review of UAV use in recent spills attended by ITOPF and considerations for the future*. 2018.

[88] A. Polak, S. Marshall, J. Ren, B. P. Hwang, B. Hagan, and D. J. Stothard. Remote oil spill detection and monitoring beneath sea ice. In: *The 2016 European Space Agency Living Planet Symposium*. 2016.

[89] M. Board, N. R. Council, et al. *Polar icebreakers in a changing world: An assessment of U.S. Needs*. National Academies Press, 2007.

[90] M. Humpert. *Canadian Arctic shipping traffic nearly tripled over 25 years*. 2018. URL: `https://www.arctictoday.com/canadian-arctic-shipping-traffic-nearly-tripled-25-years`.

[91] G. Timco. *Grand Banks iceberg management*. Tech. rep. National Research Council Canada, 2007.

[92] Z. Qu, G. Zhang, H. Cao, and J. Xie. LEO satellite constellation for Internet of Things. In: *IEEE Access* 5 (2017), 18391–18401.

[93] Z. Jin, M. Ding, and S. Li. An energy-efficient and obstacle-avoiding routing protocol for underwater acoustic sensor networks. In: *Sensors* 18.12 (2018), 4168.

[94] P. Chhabra, A. Maccarone, A. McCarthy, G. Buller, and A. Wallace. Discriminating underwater lidar target signatures using sparse multi-spectral depth codes. In: *2016 Sensor Signal Processing for Defence (SSPD)*. IEEE. 2016, 1–5.

[95] C. Galarza, I. Masmitja, J. Prat, and S. Gomariz. Design of obstacle detection and avoidance system for Guanay II AUV. In: *2016 24th Mediterranean Conference on Control and Automation (MED)*. IEEE. 2016, 410–414.

[96] A. Wada, T. Yamashita, M. Maruyama, T. Arai, H. Adachi, and H. Tsuji. A surveillance system using small unmanned aerial vehicle (UAV) related technologies. In: *NEC Technical Journal* 8.1 (2015), 68–72.

[97] GIC. *Hyperspectral Remote Sensing Scenes*. 2014. URL: `http://www.ehu.eus/ccwintco/index.php?title=Hyperspectral_Remote_Sensing_Scenes`.

[98] F. Bekkadal. Emerging maritime communications technologies. In: *2009 9th International Conference on Intelligent Transport Systems Telecommunications, (ITST)*. IEEE. 2009, 358–363.

[99] T. Braud, F. H. Bijarbooneh, D. Chatzopoulos, and P. Hui. Future networking challenges: The case of mobile augmented reality. In: *2017 IEEE 37th International Conference on Distributed Computing Systems (ICDCS)*. IEEE. 2017, 1796–1807.

[100] C. Benton, R. Nitzel, and T. Zysk. Merging ocean/maritime models and Arctic operations using mission planning toolkits and augmented reality. In: *OCEANS 2008*. IEEE. 2008, 1–6.

[101] C. Brekke and A. H. Solberg. Oil spill detection by satellite remote sensing. In: *Remote sensing of environment* 95.1 (2005), 1–13.

[102] V. Broje and A. A. Keller. Improved mechanical oil spill recovery using an optimized geometry for the skimmer surface. In: *Environmental science & technology* 40.24 (2006), 7914–7918.

[103] ITU-R. *Recommendation ITU-R M.828-1. Definition of Availability for communication circuits in the mobile-satellite service (MSS)*. Tech. rep. ITU, 1994.

[104] G. Maral, J.-J. de Ridder, B. G. Evans, and M. Richharia. Low earth orbit satellite systems for communications. In: *International Journal of satellite communications* 9.4 (1991), 209–225.

[105] 3GPP. *Technical Specification Group Services and System Aspects; Feasibility Study on New Services and Markets Technology Enablers; Stage 1 (Release 14)*. Tech. rep. 3GPP, 2016.

[106] R. Goyal, S. Kota, R. Jain, S. Fahmy, B. Vandalore, and J. Kallaus. Analysis and simulation of delay and buffer requirements of satellite-ATM networks for TCP/IP traffic. In: *arXiv preprint cs/9809052* (1998).

[107] AGI. *STK and ODTK*. URL: `https://agi.com/products`.

[108] S. Knowles, J. Picone, S. Thonnard, and A. Nicholas. The effect of atmospheric drag on satellite orbits during the Bastille Day event. In: *Solar Physics* 204.1-2 (2001), 387–397.

[109] N. Y. Ganushkina, I. Dandouras, Y. Shprits, and J. Cao. Locations of boundaries of outer and inner radiation belts as observed by Cluster and Double Star. In: *Journal of Geophysical Research: Space Physics* 116.A9 (2011).

[110] F. Long. *Satellite network robust QoS-aware routing*. Springer, 2014.

[111] M. Höyhtyä, J. Ylitalo, X. Chen, and A. Mämmelä. Use of databases for dynamic spectrum management in cognitive satellite systems. In: *Cooperative and Cognitive Satellite Systems*. Elsevier, 2015, 453–480.

[112] S. Ilcev. 18. Shipborne Satellite Antenna Mount and Tracking Systems. In: *International Recent Issues about ECDIS, e-Navigation and Safety at Sea: Marine Navigation and Safety of Sea Transportation* (2011), 139.

[113] A. D. Panagopoulos, P.-D. M. Arapoglou, and P. G. Cottis. Satellite communications at Ku, Ka, and V bands: Propagation impairments and mitigation techniques. In: *IEEE Communications Surveys & Tutorials* 6.3 (2004), 2–14.

[114] S. Cakaj, B. Kamo, I. Enesi, and O. Shurdi. Antenna noise temperature for low earth orbiting satellite ground stations at l and s band. In: *Europe* 5 (2011), 6.

[115] Telesat. *Petition for Declaratory Ruling to Grant Access to the U.S. Market for Telesat's NGSO Constellation*. Tech. rep. Telesat, 2016.

[116] T. W. Beech, S. Cornara, M. B. Mora, and G. Lecohier. A study of three satellite constellation design algorithms. In: *14th international symposium on space flight dynamics*. 1999.

[117] M. Werner, A. Jahn, E. Lutz, and A. Bottcher. Analysis of system parameters for LEO/ICO-satellite communication networks. In: *IEEE Journal on Selected areas in Communications* 13.2 (1995), 371–381.

[118] M. Luglio, C. Roseti, E. Russo, and F. Zampognaro. Ka-band High Throughput Satellites for 5G Based Applications: The Athena-Fidus Case Study. In: *International Conference on E-Business and Telecommunications*. Springer. 2017, 16–37.

[119] ETSI. *Study on Scenarios and Requirements for Next Generation Access Technologies in 5G (3GPP TR 38.913 version 14.2.0 Release 14)*. Tech. rep. ETSI, 2017.

[120] M. Mohorcic, M. Werner, A. Svigelj, and G. Kandus. Adaptive routing for packet-oriented intersatellite link networks: performance in various traffic scenarios. In: *IEEE Transactions on Wireless Communications* 1.4 (2002), 808–818.

[121] 3GPP. *Technical Specification Group Radio Access Network; Study on New Radio (NR) to support non terrestrial networks (Release 15)*. Tech. rep. 3GPP, 2018.

[122] A. Guidotti, A. Vanelli-Coralli, T. Foggi, G. Colavolpe, M. Caus, J. Bas, S. Cioni, and A. Modenini. LTE-based satellite communications in LEO mega-constellations. In: *International Journal of Satellite Communications and Networking* 37.4 (2019), 316–330.

[123] X. Lin, B. Hofström, E. Wang, G. Masini, H.-L. Maattanen, H. Rydén, J. Sedin, M. Stattin, O. Liberg, S. Euler, et al. 5G New Radio Evolution Meets Satellite Communications: Opportunities, Challenges, and Solutions. In: *arXiv preprint 1903.11219* (2019).

[124] O. Kodheli, S. Andrenacci, N. Maturo, S. Chatzinotas, and F. Zimmer. Resource Allocation Approach for Differential Doppler Reduction in NB-IoT over LEO Satellite. In: *2018 9th Advanced Satellite Multimedia Systems Conference and the 15th Signal Processing for Space Communications Workshop (ASMS/SPSC)*. IEEE. 2018, 1–8.

[125] O. Kodheli, S. Andrenacci, N. Maturo, S. Chatzinotas, and F. Zimmer. An uplink UE group-based scheduling technique for 5G mMTC systems over LEO satellite. In: *IEEE Access* (2019).