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Executive summary

Shipping is increasingly relying on digital communication between ship and shore for operational, safety and infotainment purposes. However, there is a lack of knowledge of limitations and benefits of the different communication carriers with respect to different applications' requirements. This report has analyzed communication requirements for various application classes, investigated current and emerging data carriers and compared the carriers' capabilities to the application requirements.

The discussion is mostly based on cargo ships in international trade and general conclusions will normally be most applicable to this class of ships. Special ships like passenger, scientific, military or offshore service vessels as well as ships in special trades may have different overall requirements. However, the more general observations will still be valid.

Accumulated bandwidth requirements for normal operation are not very high. A mean bandwidth of 1.2 kbps is the estimate for a typical merchant ship (Table 9 at page 26). Thus, Inmarsat C with an offered bandwidth of 9.6 kbps should be sufficient. However, other important drivers behind bandwidth requirements today is crew welfare and possibly more advanced interactive services between ship and shore. This can easily drive demands to significantly higher levels so that other and higher capacity carriers need to be considered.

An important result of the study is that satellite systems, although indispensable in deep sea shipping, is not always the best carrier, e.g., near the coast. Shadowing and fading effects should be taken into consideration and alternatives checked, at least for applications with some criticality. This is particularly important for exchanges of legislative or commercial importance, such as port arrival notifications and other messages to the port state. One can also argue that these services should be made available on a publicly supported carrier, in which case satellite may not be the best option.

Another conclusion is that there are too many factors involved in selecting an appropriate carrier for a given ship to provide very simple guidance on these issues. Thus, a more detailed analysis needs to be done for each ship. Some of the relevant factors are:

- *Geographic coverage* as summarized in Table 14 at page 38. Different carriers have different quality of service in different areas.
- *Suitability for selected applications* as summarized in Table 16 at page 46. Due to different capabilities and different application requirements, carriers will be more or less suited.
- *Security issues* as discussed in section 4.5.
- *Cost* as discussed in section 4.6. Although this is a very rough overview it gives an idea of the wide range of options that exist.

In general, one will need more than one carrier to satisfy different application requirements in different trading regions. Redundancy in carriers will also provide more reliable communication services in the case where one system fails. Note also that the analysis only cover a limited selection of carriers. Refer to section 3.6 for a brief overview of other possibilities.

The report provides a fairly detailed overview of the communication requirements one can expect in future shipping. Also, it is pointed out that crew welfare is a significant issue in selecting a higher capacity carrier over a lower cost lower capacity solution. Higher capacities may also allow types of ship shore communication that makes better use of video and other forms of cooperation between ship and shore crew.

List of abbreviations

3G, 4G	More advanced variants of mobile telecommunication systems. LTE is normally considered a 3G variant.
AIS	Automatic Identification System
AMVER	Automated Mutual-Assistance Vessel Rescue System (reporting system)
AtoN	Aids to Navigation
BER	Bit Error Rate
C-band	4 to 8 GHz range
DSC	Digital Selective Calling.
EGNOS	European Geostationary Navigation Overlay Service
ECDIS	Electronic Chart Display and Information System
EDI	Electronic Data Interchange
ENC	Electronic Chart System (ECDIS is reserved for approved ECS).
EPIRB	Emergency Position Indicator Radio Beacon
FAL	Reference to Facilitation Committee in IMO or FAL Convention from same. Related to ship clearance in and out of port.
GEO	Geostationary Earth Orbit (identical to GSO)
GMDSS	Global Maritime Distress Safety System
GSO	Geo-Synchronous Orbit (identical to GEO).
HEO	Highly Elliptic Orbit
HF	High Frequency, Short Wave (3 MHz to 30 MHz)
IP	Internet Protocol (e.g., TCP/IP or UDP)
IEC	International Electrotechnical Commission
IMO	International Maritime Organization
ISDN	Integrated Services Digital Network
ISO	International Standards Organization
ITU	International Telecommunication Union
K_a-band	26.5 to 40 GHz range (K-above)
K_u-band	12 to 18 GHz range (K-under)
kbps	Kilo-bit per second
km	Kilometre (1000m)
L-band	1 to 2 GHz range
LEO	Low Earth Orbit
LNG	Liquid Natural Gas
LOS	Line of sight
LRIT	Long Range Identification and Tracking
LTE	Long Term Evolution (Mobile telephone)
MF	Medium Frequency, Medium Wave (300 kHz to 3 MHz)
MIO	Maritime Information Object (to be plotted in ECDIS)
MMSI	Maritime Mobile Service Identity (Assigned to ship by national authority)
MSI	Maritime Safety Information
NAVTEX	Navigational telex

nm	Nautical mile (1852m)
QoS	Quality of Service
RT	Real Time (Response time – on order of milliseconds)
S-band	2 to 4 GHz range
SAR	Search and Rescue (Centre)
SatCom	Satellite communication
SGEO	GEO satellite system that provides spot beam coverage
SHF	Super High Frequency
SSAS	Ship Security Alert System
SLOS	Shore based Line of Sight
S/N	Signal to Noise ratio (Higher is better)
TCP/IP	Transmission Control protocol / Internet Protocol: Most common protocol for point to point streaming and reliable digital data transmission.
UDP	User Datagram Protocol, a variant of IP only supporting unreliable messages.
UHF	Ultra High Frequency (300 MHz to 3 GHz)
VHF	Very High Frequency (30MHz to 300 MHz)
VoIP	Voice over Internet Protocol
VSAT	Very Small Aperture Terminal
VTS	Vessel Traffic Services ("Maritime traffic central ").
WiMAX	Worldwide Interoperability for Microwave Access

Table of contents

1. Introduction

As new information and communication technologies emerge, so does the wish for being able to use these technologies anywhere; on sea as well as on land. The ability to connect and communicate with the rest of the world wherever one wants to, is often taken for granted, both for personal and business communications. Digital communications is increasingly important in maritime businesses; both for operational purposes, crew and passenger infotainment as well as for safety and emergency communications.

On land, the necessary infrastructure to satisfy communication needs is often relatively straightforward to construct. On ships, however, the same infrastructure possibilities are not readily available. Along the coast, terrestrial services like digital VHF or even high capacity wireless services like WiMAX may be available, but far from the coast, terrestrial high-bandwidth digital services cannot be used. Here, satellite communication will be necessary. Satellite communication is often based on geostationary satellite systems; these are however unusable in arctic waters, where the geostationary satellites are below the horizon. Satellite systems will often rely on complex stabilized antennas that may be susceptible to mechanical problems and excessive ship movements.

Wireless communication is in general subject to phenomena like interference, unintended reflections, and atmospheric effects which may deteriorate the signal quality, leading to lower possible bandwidth and errors in the transferred signal. Also, antennas and other equipment may be subject to failures that may disrupt communications.

Analysis and comparison of the communication carriers that are used for ship-shore communication is necessary to expose strengths and weaknesses, the geographical areas where the carriers may be used, how they fulfil different communication needs, the cost of using the carriers, and so on.

1.1 Scope

The scope of this report is to present a comparison of different general purpose communication carriers proposed for digital “broadband” ship-shore communications. The basis for comparison is a set of application groups as well as some general properties of the carriers, such as geographic coverage, quality of service and security.

General purpose means data carriers that can be used for commercial, infotainment and operational data exchanges as well as for safety and security related messaging. The report will not consider the use of dedicated systems such as NAVTEX or EPIRB and it will only include carriers with digital data transmission capabilities and carriers that are useful for general ship use. Although both short and medium wave systems can carry digital data, these have not been included here as they have very limited capacity in their respective coverage areas and cannot be considered general purpose communication systems.

The communication carriers included in this report are the satellite systems Inmarsat C and Fleet 77, VSAT (generally covering commercial K_u and C band services), and Iridium, as well as terrestrial carriers like Digital VHF and high capacity long range digital technologies (using WiMAX as an example). These are widely used carriers that provide digital services with a relatively high bandwidth. Future and non-widespread systems, like satellites in highly elliptical polar orbits (e.g., Molniya for Arctic coverage), will not be covered.

Bandwidth requirements listed are based on estimates related to emerging e-Navigation services and does not necessarily reflect current minimum usage scenarios.

An analysis of the geographic availability, quality of service and technical availability for the carrier and subsystems necessary for using the carrier is presented, as well as an analysis of the requirements of different types of communications.

The results of the analysis are used to show how the different carriers suit the different types of communication requirements.

1.2 Report structure

The rest of this report is structured as following:

- Section two defines terms and concepts used in the report.
- Section three describes the approach used in the analysis.
- Section four contains the technical results of the analysis.
- Section five contains the conclusions and a summary from the analysis.
- Section six contains references.
- Section seven contains annexes giving more background to some of the analysis and methodology work.

2. Definitions

2.1 Application

The term application is used in this report to denote a certain onboard or shore function that relies on communication to be performed. A synonym might be “service”.

2.2 Bent pipe

Bent pipe is a satellite communication system where the satellite acts as a real time relay between the ship and the ground station. This means that communication is only possible when both the ship and the earth station are visible from the satellite. GEO satellites are by definition of the “bent pipe” category and as these are stationary relative to the Earth surface they always gives a well defined coverage area (spot beam or global beam).

2.3 Bit Error Rate - BER

This is a measure of the probability that a transmitted bit (zero or one) is not received as the same. BER will often be handled by error correction techniques, including retransmissions or forward error coding. However, extensive use of such methods will obviously impact the available bandwidth.

2.4 Carrier

The term Carrier is in this report used to describe a system used for establishing communication links. Some examples of carriers are Inmarsat C, VSAT, and digital VHF.

2.5 Cumulative bandwidth

This report mainly discusses the bandwidth needs as seen from the ship. However, all carriers will in general have to cater for a number of ships that are located into the area covered by the carrier. For a shore based system, this will correspond to the “cell” formed by the range of the signal from the base station. For satellite systems it will correspond to the footprint of the beam used (see spot beam and global beam below). In both cases, it is possible to reserve part of or the full bandwidth of the carrier, but this will be at a cost.

Within this area, the system may use different techniques to service multiple clients, such as TDMA (Time Division Multiple Access), FDMA (frequency division multiple access) or any other of a wide range of different technologies.

The total bandwidth available for all users in an area is termed “cumulative bandwidth”. This report operates with mean bandwidth requirements over a 24 hour period, so in general the cumulative bandwidth should be the mean requirement multiplied with the number of ships in the area. However, as much of the information is sent as broadcast to all ships in the area (e.g., nautical warnings and information), the actual cumulative bandwidth requirement will normally be much smaller than this [Rød09].

2.6 Elevation angle

The elevation angle is the angle between the line from the ship antenna to the satellite and the local horizontal plane

2.7 e-Navigation and e-Maritime

e-Navigation is an ongoing initiative by International Maritime Organisation (IMO) to implement next generation navigation and safety systems for shipping. This entails increased ship/shore information exchange and new nautical applications to make better use of the information that is available. IMO approved its e-Navigation strategy in December 2008 [MSC85] and at time of writing an IMO correspondence group is working on the implementation plan.

e-Navigation is closely related to e-Maritime which is a corresponding initiative by DG TREN (Directorate General Transport and Energy) in EU which has been described as:

> *"e-Maritime capabilities will encompass legal, organizational and technical frameworks to enable maritime transport operators, shippers/ freight forwarders, and maritime administrations to seamlessly and effortlessly exchange information in order to improve the efficiency and quality of their services"* [Chr09].

The application set discussed in section 4.1 includes several future e-Navigation/e-Maritime services.

2.8 Geographic availability

Geographic availability is the dependence on geographic area (see section 3.6) for a communication carrier's availability. Many carriers are unavailable in certain regions, e.g. carriers based on geostationary satellites will be unavailable in arctic regions, and most terrestrial systems will only be available near the coast.

2.9 Global beam

Some GEO satellites have transponders or transponder systems that cover the full earth surface that is visible from the satellite. The size of a *spot beam* may vary as illustrated in Figure 1. Thus, even if a VSAT system in theory can provide near global service, many systems will only provide spot beam coverage in selected areas. The below figure illustrates global beam coverage (green), global coverage through a system of spot beams (yellow) and selective spot beam coverage (orange).

Global beam coverage area is the footprint of one global beam antenna (horn or reflector) at a satellite. This area is typically large (covering up to one third of the Earth's surface) and with lower signal-to-noise ratio (S/N) and capacity than the other beam areas.

Regional coverage area is composed by a number of scanning or hopping satellite antenna beams. A phased array antenna is used to create many narrow beams which can be clustered to create a specific pattern on the coverage zone of a satellite. This coverage pattern is optimized for areas with high traffic density. This area can be as large as the global beam area, but has higher S/N and higher capacity.

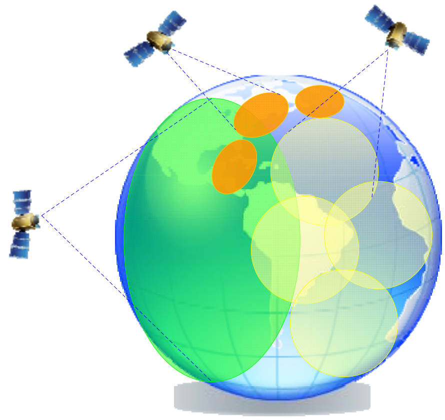

Figure 1 – Global beam and spot beam

Narrow spot beam coverage area is also offered in areas with high traffic density, that is, in typical sea routes and along the coast lines. The beams are narrower than the other two defined areas and hence offer higher S/N and higher capacity links (broadband connections).

2.10 Multi-path

When signals are reflected by obstructions, multiple "copies" of the signal, slightly skewed in time, will often be received at the receiver terminal. This causes interference between signal components and may lower signal to noise ratio. On the other hand, multi-path may also extend coverage for LOS signals by providing alternative routes around obstacles.

2.11 Quality of service - QoS

Quality of Service (QoS) is a measurement of a communication system's performance. Typical QoS measurements are Bit Error Rate (BER), signal to noise ratio (S/N or E_b/N_o) as well as minimum bandwidth and maximum latency. Communication service providers normally guarantee a certain QoS under certain given conditions. They make reservations on the QoS when the conditions are outside the given boundaries. The coverage area for a carrier is defined as the area within specified geographic boundaries where minimum QoS can be guaranteed.

2.12 Rain fade

In this report the term rain fade is used for severe signal degradation due to fading of the carrier signal in rain or snow. Carrier frequencies above 11 GHz are particularly vulnerable to this phenomenon and more at high latitudes than lower. This is due to the lower elevation angle on the antenna and a longer travel through the atmosphere for the signal.

For practical purposes, K_u and K_a band transmissions from and to geostationary satellites are most vulnerable to this phenomenon.

2.13 Signal shadow

Signal shadow is an area within the normal coverage area of a communication solution with no availability of the signal. This may because the signal has been stopped by surrounding obstructions such as e.g. a building or a mountain. However, multi-path propagation will in some cases overcome the shadow effect.

2.14 Signal to noise ratio – S/N

This is a measure of the relative signal strength at the receiver side and determines the bit error rate as well as the bandwidth one can expect. Lower S/N increases BER and/or decrease bandwidth.

2.15 Spot beam

See section 2.9 on Global beam.

2.16 Technical reliability

The reliability of a system is the ability of the system to perform its required function. *Technical reliability* will in this report be used to describe the reliability of the technical parts of the system (e.g. antennas, cables and electronics) and how the failures of these parts affect the use of a given communication carrier. This excludes failure of communication due to interference, weather or geographical region.

2.17 VSAT

VSAT is an abbreviation for “Very Small Aperture Terminal” and is used for satellite terminals, e.g., on ships. “Very small aperture” generally means an opening angle of less then one degree in which the terminal has to transmit and receive signals. Gyro stabilized antennas are used for moving units like vessels and floating offshore installations.

In this report, VSAT is used as a generic term for commercial satellite systems that typically have coverage in relatively high traffic density areas.

3. Methodology

The overall purpose of the report is to present a relatively high level overview of the possibilities and limitations of different digital data carriers in shipping. This section will present the general methodology while the next section contains the analysis.

3.1 General quality criteria

Quality criteria in this report are normally organized in four levels as described below.

Table 1 – Quality criteria codes

Level	Code	Explanation
High		The service will normally be continuously available unless unexpected conditions, e.g., a complete system failure, make it unavailable.
Acceptable		Due to the nature of the service and the context it is operating in, one should expect occasional disruption of the service.
Not recommended		One must expect regular disruption of the service and it should not be relied on for applications that require continuous availability.
None		The service is not available with any useful level of quality.

The reader should keep in mind that the criteria in many cases represent the authors' somewhat subjective view in a specific context. The scoring may very well be different when done by others and in other contexts.

3.2 Application classes

The analysis will use the application types listed in Table 2 as baseline. These are derived from the traffic categories defined in [Rød09] as discussed in more detail in section 4.1. Refer to that section for a detailed description of the services included in each category and the estimates for bandwidth requirements.

Table 2 – Application classes

Type	Description
Distress signalling	DSC emergency signals, EPIRB, SSAS. Highly critical information, but not necessarily with very real time performance.
Emergency operations	Ship-ship or ship-shore emergency operations. Critical, real time data.
Nautical reporting	Various longer latency message exchanges related to nautical operations, e.g., VTS reporting.
AIS operations	AIS reporting requirements, position reports and AtoN reports.
Nautical operations	Operational VTS-Ship communication, ship-ship, pilot-ship, port/lock-ship etc. This is critical real time communication with low latency requirements.
Voyage reporting	Mandatory and operational voyage reporting, port call logistics. Larger messages typically sent as e-mail.
Cargo reporting	Cargo related information directly to cargo owner. Typically daily reporting on, e.g., temperatures or other parameters.
Cargo operations	Real time coordination between port and ship during loading and

	discharge. May, e.g., be emergency shut-down signals.
Technical reporting	Technical reports, maintenance related exchanges, spare parts orders.
Technical operations	Interactive technical operations related to maintenance, fault findings and repair.
Crew infotainment	Family and relatives communication, web browsing, entertainment.
Passenger infotainment	Passengers' use of Internet services, typically by payment.
Billing	Transactions related to passengers' payment for services. May include money transactions as well as information for supply logistics.

3.3 Application requirements

Different kinds of application classes will have different requirements that are satisfied in varying degree by the different carriers. These may be requirements that a carrier provides a minimum bandwidth or the possibility to run an interactive service, or that the carrier can be used for critical applications like emergency management. The table lists the main requirements groups and a more detailed description can be found in the following subsections.

Table 3 – Overview of requirements and corresponding parameters

kbps	Regulations	Criticality	Latency
Bandwidth in kbps, mean over 24h	Examples or empty	Very high, high, medium	RT, IP, Low, Medium

Note that the analysis does not look at integrity requirements (e.g., as maximum error rates) explicitly. This issue is quantitatively included in criticality. Also, only digital exchanges are covered. For special data transmissions such as voice over a digital channel (e.g., VoIP), more specific requirements on latency, error rates etc. will apply.

3.3.1 Bandwidth – kbps

The bandwidth describes the amount of data that can be sent or received in a given time interval, and is measured in kilobits per second (kbps). The figure is given as a mean value over 24 hours in a "worst case" situation when the ship is approaching port.

3.3.2 Regulations

Regulations will provide some constraints for what communication systems can be used for what applications. Of main interest in this context are the following main types:

- *GMDSS:* Global Maritime Distress and Safety System compliant equipment is required according to SOLAS for a range of safety and security services [SOLAS]. The requirements will normally be fulfilled by various dedicated communication equipment such as VHF radio, emergency beacon transmitters etc. However, GMDSS will for many ships mean that they have to invest in an Inmarsat C or Inmarsat Fleet 77 terminal to cover emergency communication. This means that this system either can be used for general digital communication or as a backup to a VSAT or other type of system.
- *LRIT:* Long Range Identification and Tracking is also mandated by SOLAS and will in many cases require satellite systems. In this case, one may also use VSAT or Iridium solutions, but if Inmarsat is installed, it may be more cost effective to use this.

- *SSAS:* Ship Security Alert System is also mandated by SOLAS and is covered by similar requirements as LRIT.
- *FAL:* There are requirements to messages being sent to ports and port state authorities to request clearance for ships. This is to some degree covered in SOLAS, but mostly in national legislation that is more or less aligned with the FAL Convention [FAL].
- *SOLAS:* Various instruments, including SOLAS itself, have provisions that mandate exchange of information between ship and shore entities. One example is the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk that has certain requirements for communication between ship and shore facilities during loading and offloading of gas carriers. This is normally implemented with the help of fixed land lines between ship and shore facilities [IGC]. Note that also the Bulk loading and unloading code [BLU] has requirements for communication between port and ship. However, the BLU code will normally be implemented in the form of pre-arrival reports.

For the purpose of this report, regulatory requirements may not be a determining factor for the selection of communication carrier. However, as it represents "minimum requirements" it may determine which of a range of possible systems one selects.

3.3.3 Criticality

The criticality of a communication service can be defined as the cost of unavailability when service is needed, or the importance of service availability. For instance, the lack of communications during an emergency may greatly increase the threat to human lives, thus emergency communications are considered highly critical. A carrier used for critical messaging should be able to prioritize these messages above other messages, for instance by providing a separate channel reserved for critical messages.

Criticality can be more quantitatively classified as shown below. It relates to how much of the time a carrier may be out of service and for how long. The table indicates criteria for determining criticality. The table will not be used directly in the analysis, but is included here to illustrate how criticality can be mapped to availability requirements. The analysis section will use qualitative criteria only.

Table 4 – Example criticality criteria

Criticality	Duration of loss	Service unavailable
Very high	< 10 second	< 1%
High	< 1 minute	< 1%
Medium	< 1 hour	< 10 %

Very high means that availability must be close to continuous and that messages are guaranteed to be passed through within the latency periods specified. One may need multiple transmissions, but the time frame should be kept. High criticality requires very high availability. Some loss of carrier is allowed, but not for extended periods, e.g., a minute loss may be acceptable. Medium criticality will allow loss of a carrier for some hours. Criticality will have an impact on the suitability for a given carrier, given operational limitations, to provide the communication service for a given application.

3.3.4 Latency

Different services may have different needs in relation to how the messages are transmitted on the communication carrier. Typically, services can be divided into message based services and continuous streaming services. In addition to that, there are typically some latency requirements related to the transport. Carrier capabilities will be discussed in more detail in section 3.5.5, but for applications the classification is limited to the following classes:

- *RT (Real Time):* Latency on the order of milliseconds is required. This is only possible for communication directly between ships or between ship and shore. Satellite communication will generally not be able to supply RT class latency.
- *IP (Internet):* This indicates a requirement to provide Internet (TCP/IP) connectivity in near “real time”. This will typically be a latency of on the order of less than one second. For general ship-shore communication via satellite this is as close to real time one can come.
- *Low:* Messages is allowed to use a few seconds up to a minute to reach the destination. This is typical for most short messaging services, e.g., for distress signalling.
- *Medium:* Messages is allowed to use several minutes up to an hour to reach the destination. This is typical for reporting type applications where sender does not require immediate replies and is a typical characteristic of e-mail applications.

Note that latency is different from the criticality criterion relating to service unavailability duration.

3.4 Carrier classes

For the purpose of this analysis, the number of carriers has been limited to those normally in use on ships and which have typical properties that often can be generalized for a larger class of carriers. The table briefly describes the carrier classes considered.

Table 5 – Carrier classes

Type	Description
Inmarsat C	Unidirectional antenna, GEO system. Part of GMDSS.
Fleet 77	Stabilized antenna, higher capacity. Part of GMDSS.
VSAT - K_u	Most common commercial VSAT system
VSAT – C	Larger antenna VSAT system
Iridium OpenPort	LEO System, unidirectional antenna, worldwide
AIS	Not really general purpose, included for reference
Digital VHF	System using a number of VHF channels for digital communication
WiMAX/LTE	Different systems in the 4G mobile communication group

Section 4.2 will give a more detailed description of these carriers and their general properties. Section 3.6 gives a brief overview of carriers not covered in the analysis.

3.5 Carrier properties

Each different carrier type has different capabilities. This makes it more or less suited for various applications under various conditions. The table lists the main properties considered in the analysis.

Table 6 – Overview of requirements and corresponding parameters

Reg.	Coverage	Reliability	kbps	Latency	IP
GMDSS,LRIT	See 3.5.1	See 3.5.3	kbps	See 3.3.4	Yes, No

The properties are described in more detail in the following subsections. The analysis section will contain more background on the selection of these parameters and other parameters that need to be considered for certain data traffic such as bit error rate and actual round trip delay.

3.5.1 Regulations (Reg)

This is the same codes as used in 3.3.1. The code specifies if the carrier can implement the corresponding applications.

3.5.2 Coverage

Each carrier is characterised by a coverage class. The following codes have been used:

- GEO: Geostationary satellite system that provides global beam coverage
- SGEO: geostationary system that may only provide spot beam coverage
- LEO: Low earth orbit satellite system that provide true world coverage
- SLOS: Line of sight coastal system

This classification will be converted to geographic coverage as described in section 3.7.

3.5.3 Carrier reliability

Some of the applications are critical for ship or crew safety. Thus, the use of a carrier will depend on how well this carrier can guarantee to deliver its specified service when needed. This is a very complicated area and this report will not attempt to do a full investigation of this issue. For a fairly thorough discussion of VHF, Iridium and Inmarsat in US airspace, one can, e.g., refer to [NASA06].

Carrier reliability will be divided into two components:

- *Technical reliability:* This issue will mainly cover the availability of the system used to transmit and receive data.
- *Quality of service (QoS):* This will cover the quality of the available service when the system is functioning on a technical level.

Overall service reliability will be a combination of these two factors and will be classified in three levels:

- *Very high:* This is a carrier that will be available in its specified geographic area for most of the time, except under very adverse circumstances. It will be suitable for safety critical applications, although not without some backup.
- *High:* This carrier will work as specified almost all times. It can be used for safety critical applications when combined with a backup solution of the same reliability or higher.
- *Medium:* There are several issues that may cause loss or degradation of communication. Thus, it will normally be most useful as a backup to higher reliability solutions if critical applications depend on integrity of communication.

It has not been possible to find a good qualitative measure and neither has it been possible to find accurate reliability figures for the individual carriers. Thus, this rather qualitative definition has been used. See also section 3.3.3 on application criticality for a comparison.

3.5.4 Bandwidth (kbps)

This is the nominal bandwidth of the carrier. This figure will in some cases be dependent on the actual contract entered into by the ship, but the table will list the value for the most commonly used service type.

3.5.5 Latency and IP support

The latency requirements listed for applications in section 3.3.4 did not distinguish between type of transmission (message or stream based) and latency. In most cases, it is the latency that is the critical parameter, stream or messages can be implemented on top of the carrier protocol in most cases. An example of a message based application is e-mail; and voice over Internet (VoIP) is an example of a stream based application. However, the underlying implementation is normally using packed based messaging for VoIP (UDP) and stream based communication (TCP/IP) for e-Mail transfer.

For the carrier there are additional constraints that may make a certain carrier less suitable for implementation of the TCP/IP communication protocol, which is necessary for, e.g., general purpose web browser applications. Thus, the carrier classification makes a distinction between latency and if it is easy to implement TCP/IP over the carrier or not.

Note also that the RT classification for applications implies that the application requires a direct point to point link between the ship and the entity it communicates with, e.g., another ship or shore. This constraint is also included in the carrier classification.

The carrier classification uses the same latency classification as is listed in section 3.3.4, but does also contain a flag saying if it is suitable for implementation of TCP/IP. Table 7 shows how the carrier classification parameters are related to each other and to the ability to set up a direct point to point link between a ship and another ship or shore. This capability is required for critical real-time systems such as AIS and related coordination functions.

Table 7 – Cross reference between carrier capabilities and point to point support

IP support	Latency	Point to point
Yes	RT	Yes
No	RT	Yes
Yes	IP	No
No	IP	No
No	Low	No
No	Medium	No

Note that point to point support may or may not imply that a carrier is suitable for implementation of TCP/IP. Note also that RT latency only can be supported by point to point capable carriers and that low or medium latency prohibits the use of IP over this carrier.

3.6 Carriers not covered in the analysis

There are many other communication systems that can be used by ships than those covered in this analysis. The reasons for not including them are discussed below.

3.6.1 ARGOS

This is a system of scientific telemetry transponders, on a selection of earth observation satellites that is used to transfer earth observation data to their users. The system has limited capacity and generally uses very small messages. The system is based on polar orbit satellites and will give global coverage.

3.6.2 Globalstar

This is a LEO system based on bent pipe transponders. Thus, it has limited connectivity at sea. It uses S- and L-band frequencies and offer data messaging as well as telephone services.

3.6.3 Orbcomm

This is also based on LEO satellites and has virtually global coverage, and offers a combination of bent pipe and store and forward messaging services with very limited capacity. Thus, it is not suitable for general purpose shipboard use. However, one can argue that in functionality, it is similar to Inmarsat C, although it does not offer GMDSS compliant safety functions.

3.6.4 Thuraya

This is a system with coverage over Europe and Middle East, based on a two geostationary satellites and a handheld telephone concept. It has both voice and data services, but again with limited geographical coverage, mainly over land.

3.6.5 Polar HEO systems

There are some satellite systems in highly elliptical orbits (HEO) over the poles. These satellites will appear to be stationary over the pole for about eight hours. One such orbit is called the

Molniya orbit after the Russian word for lightning. Thus, a system of three coordinated satellites will give the appearance of one stationary satellite with polar coverage. No commercial systems exist today, but this is one of the options for providing satellite coverage in Arctic regions.

In practical terms, this would be very similar to a GEO system of the VSAT type with coverage in the Arctic and sub-arctic instead of along the equator.

3.6.6 L-band satellite, digital broadcast, DVB-RCS

It is also possible to provide ship to shore communication via broadcast television satellites with return links, e.g., over Inmarsat C or other carriers. This is normally a highly asymmetric communication link with relatively large dish sizes and is not so much used in shipping. This is often called DVB-RCS (Digital Video Broadcast – Return Channel via Satellite/System).

3.6.7 Digital short and medium wave services

These systems give regional and even global coverage and they are used, but they provide very limited bandwidth and as range are very long, they do not allow more than a few subscribers to use the system at any one time. Thus, it is not relevant for commercial shipping. However, these systems may be useful as backup in arctic waters.

3.6.8 Cell phone systems

These have limited range and bandwidth in ocean regions today. They also require SIM cards and/or agreements that allow roaming and are relatively costly when used with roaming. This is a relevant communication system for ships in limited coastal traffic and will be covered under the heading “WiMAX/LTE”.

3.6.9 WiFi

Antwerp, as an example, offers WiFi connectivity in port. However, range is only a few kilometres and the system is only useful when inside the port. Thus, this system is not relevant for general communication. However, the category “WiMAX/LTE” will cover some of the issues that also apply to WiFi.

3.6.10 CDMA 450

This is a communication technology using CDMA (Carrier Detect Multiple Access) on the 450 MHz band. It is deployed in Russia, Eastern Europe and Norway and offer good bandwidth at reasonably range. In general one can see the discussion under WiMAX/LTE for the typical characteristics of this carrier.

3.6.11 Land lines

These are used by some operators when in port and offer low cost, high reliability and high capacity links, but only when moored. It is commonly used for LNG cargo operations. Land lines will be restricted to use during berthing, but can virtually provide any QoS or bandwidth desired.

3.7 Geographic coverage

The geographic sea areas defined in the below table are characterized by having different constraints as to how well various communication carriers work. These areas have specific challenges with regards to range and availability of different communication solutions. This section gives the definition of the different areas, while the analysis sections give a more detailed description of their characteristics. Some of the defined areas relate directly to the IMO defined GMDSS Sea Areas, which are described in Annex 7.2 and listed in column 2.

Table 8 – Geographic area classes

Class	Area	Description
Ship/Ship	All	Direct communication between ships or between ship and, e.g., port
In Port	A1	When ship is inside the port area with obstructions from buildings, but close to shore infrastructure.
Coastal	A1	Close to cost.
Fjord	A1	Sub-set of coast, where high mountains can obstruct communication
Selected OS	A2-A3	Selected Open Sea: Areas where one has spot beam coverage from commercial VSAT providers.
Open sea	A3 (A2)	Areas where only global beam systems can provide communication services.
Arctic	A4	Area from 75˚ North and up, where no GEO satellite coverage can be relied on.
Sub-arctic	A4	Area from about 70˚ to 75˚ North, where low inclination to GEO satellites can cause problems.

The intention is that the areas do not overlap, i.e., “Coastal” does not include the more restricted “In port” and “Fjord” areas. Likewise, “Open Sea” excludes “Selected open sea”. However, this cannot always be fully implemented. As an example, the arctic and sub-arctic areas will overlap with fjords and coastal regions. In such cases, the reader should always consider the sum of problems caused by the overlapping operational areas.

The analysis section will provide a table cross-referencing the capabilities for each carrier in each of the geographic regions. The classification will be based on the general classification system defined in section 3.1.

3.8 Overall quality of service

The carrier QoS, including regulations, reliability, bandwidth and latency will be used to classify each of the applications as suitable for implementation over a given carrier. The classification will be based on comparison of the application requirements and the carrier properties as follows:

- Regulations must be satisfied otherwise, usually not applicable.
- Criticality at “very high” must correspond to very high carrier reliability, otherwise reduced score.
- Bandwidth requirements must be satisfied, otherwise not suitable.
- Latency requirements must be satisfied, otherwise not suitable.

The quality of service for each carrier will be classified according to attributes in section 3.1 for each of the application classes listed in section 3.2, based on the above considerations.

Note that geographic coverage is not considered here. This is a separate comparison according to principles listed in 3.6.

3.9 Security requirements

As for other communication systems, there will be security requirements to ship-shore communications, both for hindering information from getting in the wrong hands and for hindering insertion of false information in the systems. The analysis will cover three types of security issues:

- *Confidentiality:* This is defined as the absence of unauthorized disclosure of information. For personal communication and business communications, confidentiality is of high importance.
- *Integrity:* This is defined as the absence of improper system alteration. For communication systems, this may be malign or accidental insertion of false data or corruption of data.
- *Denial of service (DOS):* This is defined as an attack on components of the communication system that inhibits the use of the system to exchange data.

There are different security issues with all applications defined in section 3.2. Thus, the analysis will not define security requirements for the applications, but restrict itself to an overview of the carriers' properties.

It is possible to implement good security measures in the protocols of most digital communications, if such measures are not already implemented as a standard. The main focus of this work will be on the physical systems, and not on higher-level protocols.

3.10 Cost

The cost of using a carrier can be divided into the cost of installing necessary equipment, the cost of maintaining the equipment, and the direct cost of using the carrier. In this analysis only a brief overview of typical installation and operational costs is included. The data included is only intended to give an overview.

4. Analysis

4.1 Application requirements

Table 9 summarises the requirements of the different application classes. Details about the analysis can be found below and in the following sub-sections. The last group of shaded lines list total sum bandwidth requirements for groups of applications.

Table 9 – Application requirements

Type	Component	kbps	Regulation	Criticality	Latency
Distress signalling	DSC (via MF, HF or VHF)	0.000	GMDSS	Very high	Low
	EPIRB (406 MHz COSPAS SARSAT)		GMDSS	|Very high	Low
	SSAS (Inmarsat)		SSAS	Very high	Low
Emergency operations	Communication to other ship	21.3	(GMDSS)	Very high	RT
	Communication to SAR		(GMDSS)	Very high	IP
	Communication to owner's office			High	IP
Nautical reporting	LRIT position report (Inmarsat)	0.2	LRIT	High	Medium
	AMVER (position report)			High	Medium
	NAVTEX (MSI)		GMDSS	High	Medium
	Weather fax		GMDSS	High	Medium
Nautical AIS	AIS position and AtoN reports	0.2		Very high	RT
Nautical operation	VTS coordination	1,1		Very high	Low
	MIO			High	Low
	Real time met-ocean			Medium	Low
Voyage reporting	Ship reporting	0.046	SOLAS	High	Medium
	Coast state notification		SOLAS	High	Medium
	Port arrival notification		FAL	High	Medium
	Voyage orders and reports			High	Medium
	Commercial port call services			High	Medium
	Navigational data update (ENC)		SOLAS	Very high	Medium
	Operational reports			Medium	Medium
	Operating manuals, documents			Medium	Medium
	Weather forecast			High	Medium
Cargo reporting	Cargo telemetry, online monitoring	0.022		Medium	Medium
Cargo operations	Tug/mooring coordination	0.030		Very high	RT
	Load/discharge coordination			Very high	RT
	High accuracy berthing control			Very high	RT
Technical reporting	Operating manuals, documents	0.010		Medium	Medium
	External maintenance and service			High	Medium
Technical operation	Online maintenance and diagnostics	0.2		High	IP
Crew infotainment	Crew communication to family/home	40.9		High	IP-Medium
	Crew training			Medium	IP-Medium
	Telemedicine			Very high	IP-Medium
Passenger infotainment	Passenger infotainment	813.3		Medium	IP-Medium
Billing	Payments and inventory	16.0		High	Medium
Non-RT/IP reporting type communication		**0.3**			Medium
RT/IP type ex. emergency, AIS, billing and infotainment		**1.3**			IP-RT
Emergency		**21.3**			RT
Crew infotainment		**40.9**			IP
Passenger infotainment and billing		**829.3**			IP

The first column lists the application as defined in section 3.2. Column two gives the components of this application. Abbreviations are listed at the front of the report and will not be repeated here. The next column lists the estimated accumulated bandwidth for all components of the applications. This is based on a future e-Navigation scenario with relatively high estimates on the need for bandwidth. The bandwidth estimates are means over a 24 hour period in the most demanding operational areas, typically near port, but for one ship only. The fourth column lists any applicable legislation; the following lists criticality estimates and the last latency estimates for each of the application components.

The list of applications is based on an e-Navigation scenario where application complexity and bandwidth requirements have been extrapolated to a possible future where integration between ship and shore is more advanced than today. Thus, the estimates and the components of the applications are not necessarily representative of the situation today. A previous report [Rød09] gives a more detailed description of this scenario.

However, even with this starting point, it is interesting to note that the total sum of bandwidth required when infotainment, advanced emergency and billing applications are excluded is only 1.6 kbps. Thus, a 9.6 kbps Inmarsat link should be sufficient to cover all the most common bandwidth requirements although not necessarily latency requirements.

On the other hand, some interactive services will be used for a shorter period and with higher bandwidth demands. Thus, the applications listed as IP latency will also normally require at least 64 kbps to be useful. Also, one can safely assume that any installed bandwidth will be used, both for private applications as well as for new and improved technical and operational applications.

Finally, all bandwidth figures are for *one* ship only. For the shore based infrastructure, one will have to consider the number of ships in an area and scale the bandwidth requirement to fit this number. This is issue was discussed in [Rød09] and corresponding cumulative estimates are presented there.

4.1.1 Distress signalling

This class of communications consists of highly critical messages used to alert shore and other ships that a ship is in distress. The messages are typically short, consisting of the most important information related to the distress situation, so the bandwidth requirements are very low. It is, however, very important that the carrier is available when the function is required.

Most of the distress signalling is part of the GMDSS requirements, including digital selective calling (DSC) over satellite or VHF as well as Emergency Position Indicator Radio Beacon (EPIRB) and more general communication facilities. Due to the criticality, some of the distress signalling is implemented over special carriers. The ship will also carry several such systems, each using different technology. One example of distress calling systems that can use a general purpose carrier is the ship security alert system (SSAS) and as above mentioned, the DSC calling over VHF or satellite.

4.1.2 Emergency operations

This class of communications consists of information exchanges used for emergency management and assistance during an emergency. This is a special application type that in part has been developed in Flagship and which enables digital coordination between ships and shore during emergency management. Currently, there is no legislation that applies to this type of application. As this type of application could replace some of the communication that is now sent over VHF or satellite, one could in principle say that the corresponding GMDSS requirements should apply.

Criticality has been set to high and very high, although one can argue that voice communication can be used as backup. However, if drills and general crew training were to be based on this application in an emergency one probably needs to upgrade criticality to “very high”.

The estimated bandwidth requirement of 21 kbps seems to be reasonable, based on research work done in Flagship [FC1], and similar experiments in other projects. The estimate is based on digital updates of state information between ships and between ship and shore where the actual digital display system converts the state information to a visual image. Thus, this does not include, e.g., transmission of video or graphical images.

Latency requirements are “real time” or IP (for shore side) as all parties are dependent on having the same situation parties, particularly on scene. For shore based parties, real time can be read as on the order of a few seconds for full updates, which may translate to requirements of IP category.

Note also that emergency communication is a rare occurrence and that it will pre-empt most other types of communication. Thus, it does not directly contribute to total bandwidth requirements for the ship.

4.1.3 Nautical reporting

This is a category of nautical reports that does not have very strict latency requirements. This includes LRIT and AMVER reporting as well as weather fax and NAVTEX reception. NAVTEX is on-line maritime safety information, normally sent via MF or satellite (SafetyNET). AMVER is a voluntary reporting scheme operated by the US Coast Guard.

4.1.4 Nautical AIS

This group includes the existing and possible future AIS based applications. In areas with high ship density, the capacity of the AIS system is now close to full utilization so there is not much bandwidth available for future expansion. Outgoing traffic, which is much smaller (maximum one message each two seconds) amounts to about 0.2 kbps. However, incoming traffic can be close to the available bandwidth in congested areas.

4.1.5 Nautical operations

These are services and applications directly related to safe and secure real-time operation of the ship. Thus, criticality is very high to high and latency requirements are in the RT or IP categories. Regulations applying to nautical safety are mainly GMDSS, although all services listed here are possible addition in an e-Navigation scenario that is not yet fully operational today.

Examples of such services are communication between ship and VTS and other forms of ship to port communication. In a future scenario, one can, e.g., consider the possibility of getting a sailing plan in form of waypoints directly from the VTS. One could also imagine getting a full traffic picture from the VTS, including the sailing plans for vessels in the vicinity. Other applications are transmission of maritime information objects (MIO) for inclusion in chart displays, including weather and current information.

4.1.6 Voyage reporting

Voyage reporting includes various services that are not directly safety critical, but which may be important for operational issues or by virtue of port or flag state legislation. Latency requirements are not normally very strict as messages are sent as e-mails or by similar mechanisms.

The estimates given here on bandwidth requirements are relatively speaking high as they include worst case operation requirements during port approach, combined with a relatively high estimated load from ENC updates.

4.1.7 Cargo reporting

This application covers reporting from ship to owner during the voyage. This may used for certain perishable goods, e.g., in reefer container or similar storage. It will not normally amount to much in terms of bandwidth as relatively little data is reported on each load item.

Also, latency is not normally critical as reports can go as e-mails or by similar mechanisms.

4.1.8 Cargo operations

These services are related to safer and more efficient cargo and port operations through on-line control and monitoring.

Today there are some requirements for coordination between port facilities and ship during loading and discharge. This is relatively strict for gas carriers [IGC] and will often be handled by fixed telephone lines between ship and port. Bulk ships also have requirements to communication, but this is mostly prior to loading or discharge [BLU]. These requirements are indicated with a reference to SOLAS in the table.

In the scope of e-Navigation, one can envisage various new forms of coordination, e.g., for assisted berthing or tug assistance.

Criticality and real time requirements for such services will be very high as ship and port safety will rely on them. Also, bandwidth requirements may be relatively high when the operation is in progress. However, this will only be during a relatively short period.

4.1.9 Technical reporting

These applications are related to the technical operation of the ship and covers non-interactive reporting and information exchanges. The services listed here are as examples technical reports to superintendents, the updating of manuals and other documentation and general reporting to specialists on shore on technical state of various ship systems.

The bandwidth demand is based on a relatively substantial and daily reporting from the ship. Even then, it represents limited use of bandwidth. Criticality is medium to high, mostly dependent on context.

4.1.10 Technical operations

This item has been included although it was not part of the analysis in [Rød09]. The application represents on-line and possibly interactive technical services, e.g., offered by equipment manufacturers to do diagnostics or maintenance on onboard systems. Thus, IP type latency would be needed for this. An estimate of one mega-byte per day has been used in the traffic figures.

Note that bandwidth requirements will be much higher in terms of peak demands. Interactive operations would normally require access to at least 128 kbps, although 64 kbps may work in some cases. However, mean load on the carrier is representative.

4.1.11 Crew infotainment

Crew communication, if provided for free, can be expected to fill all offered capacity. It is, also an area where money is being invested as crew welfare is an important factor in getting competent crew.

The estimates shown here are based on a daily allowance of 10 MByte per crew per day with a crew of 20 assumed. A small additional contribution from training and telemedicine is added to this.

4.1.12 Passenger infotainment

Passenger on larger ships will often request a good Internet service and this will typically translate to on the order of one megabit per second capacity with a passenger count of a few thousand (as for this estimate). This service is paid for by usage fees and it typically leaves spare capacity for operational and crew communication.

4.1.13 Billing

For passenger ships, there will also be a need for online bank transactions, e.g. for payments with bank or credit cards in the shops and restaurants on board the ship. While the transaction messages are small, they may be very frequent; the bandwidth estimate uses one transaction every second, with a message size of 1kByte (one in, one out). This may be a reasonable estimate with a few thousands of passengers onboard. Smaller ships will have substantially smaller volumes of traffic. As long waiting times will be inconvenient, the latency should be IP-class. The messages also have strict requirements to confidentiality and integrity.

4.2 Carrier properties - overview

Table 10 lists the reference carriers and their properties. This is a summary table and details are provided in the sub-sections below.

Table 10 – Carrier properties

Carrier	Regulation	Coverage	kbps	Latency	IP	Reliability
Inmarsat C	GMDSS	GEO	9.6	Low		Very high
Fleet 77	GMDSS	GEO	64	IP	Yes	High
VSAT K_u	LRIT	SGEO	128[1]	IP	Yes	High[3]
VSAT C	LRIT	GEO	128[1]	IP	Yes	High
Iridium OpenPort	LRIT	LEO	128	IP	Yes	High[3]
AIS	GMDSS	SLOS	2*6[2]	RT		Very high
Digital VHF		SLOS	4*21[2]	RT		Very high
WiMAX/LTE		SLOS	~1024	RT	Yes	Very high

NOTE 1 – VSAT can provide a number of different bandwidths, dependent on service provider contract. 128 is used here as an example.

NOTE 2 – These carriers use more than one channel, here respectively two and four.

NOTE 3 – As the analysis in section 4.2.4 shows, K_u and L band systems may have more trouble with atmospheric fading in some areas. This may be an additional issue for some applications.

The regulation column lists those carriers that currently are approved for use in GMDSS related application or, more restricted, to send LRIT (and SSAS) messages.

The next column specifies coverage class as defined in section 3.5.1. This is further elaborated in section 4.3 where carrier availability versus actual geographic areas is tabulated.

The fourth column lists the nominal bandwidth of the carrier. This figure is based on a "standard" installation, but will for many of the systems depend on the licensing agreement the user has entered into. See section 4.2.2 for details.

The fifth column specifies the expected latency. For all systems examined, this is from RT to Low. Real time latencies will only be achieved by shore based systems whereas satellites can provide close to real time Internet connectivity in the form of IP type latency. The latency as well as the expected bit error rate, as determined from manufacturer's documentation and with environmental considerations as is discussed in annex 7.7, will have an impact on how the user perceives the quality of service. Satellite links have relatively high bit error rates as well as latency and this can in some cases cause problems for certain types of data transfer.

The next to last column specifies if the system is able to provide direct Internet connectivity via TCP/IP. This requires a certain minimum QoS as discussed in annex 7.7.

The last column specifies the overall reliability classification for the carrier. This is based on the classification in 3.5.3 and is further elaborated on in annex 7.7.

4.2.1 Overview of carriers

4.2.1.1 Inmarsat C

Inmarsat C uses a unidirectional antenna on the ship. It provides two-way packet data service, approved for use under the Global Maritime Distress and Safety System (GMDSS) and it meets the requirements for Ship Security Alert Systems (SSAS) as well as for LRIT. It is a store and forward system that cannot be used for voice or direct Internet connections. It operates on L-band and gives close to global coverage with the exception of the Polar Regions.

4.2.1.2 Fleet 77

Fleet 77 is one of a number of general purpose high capacity variants of Inmarsat broadband services using stabilized antennas on the ship. Fleet 77 has been selected as case as it is the only “broadband” service currently approved for GMDSS services.

Fleet 77 operates on L-band and can provide most voice and data services, including fax, e-mails and IP connectivity. It can give world wide 64 kbps Internet connectivity with rates up to 128 kbps available in selected areas and with special terminal equipment.

4.2.1.3 VSAT – K_u

VSAT – Very Small Aperture Terminal – is a term commonly describing a satellite system operating in the C-band or K_u-band with a shipboard antenna size with a diameter of 0.6 to 2m. Systems operating in the K_a-band is also available, but currently not for bidirectional maritime traffic. Thus, VSAT is not a satellite system in it self, but a term commonly used to differentiate commercial satellite services providers from Inmarsat (which is also a VSAT system, although on L-band). This is the meaning implied in this report.

Most current VSAT systems are IP-based and applications onboard ships are mainly using Internet connections, but many VSAT systems also support voice traffic (sometimes via VoIP). The main advantages gained by installing VSAT solutions onboard are the equipment and user costs. The challenges are partly that QoS may vary with the service contract entered into and partly stronger rain fading in K_u band than Inmarsat which operates in the L-band. Also, as a complement to Inmarsat C, it requires a stabilized antenna. This is, however, the same as for Fleet 77.

Most VSAT users do not generate enough traffic to justify a dedicated transponder. Therefore, most VSAT contracts are based on shared use of transponders. This means that the full bandwidth for each subscriber cannot always be guaranteed. However, most service providers guarantee a minimum bandwidth, e.g., 16 kbps.

The VSAT K_u class of carrier covers spot beam based satellite systems where small antennas (about one meter typically) is used on the ship. This carrier class is commonly used for smaller ships or ships operating in areas with good spot beam coverage. This type of service will normally be based on a fixed equipment and service lease price, with connectivity directly over the general Internet and where bandwidth is provided on a best effort basis. See next section for the VSAT – C type carrier.

Note also that even if spot beam coverage may require the ship to change between different service providers over longer voyages, there is technology available to automatically switch between different satellites.

When considering K_u band systems one will also need to decide on an antenna size. Systems can be delivered from sub-meter up to two meter dishes. Larger antennas give better directionality and may mean reduced satellite hardware and transmission costs to provide a given service level. This may also reduce service costs for end user. Larger antennas will also provide better signal levels and may reduce any fading problems. However, there will always be a significantly higher installation costs associated with large antennas.

4.2.1.4 VSAT – C

This is also a VSAT system with much of the same properties as discussed in the previous section. However, C-band systems require significantly larger antennas on the ship, typically on the order of a two meter dish. This requires significant space on the superstructure and is normally only used by special ships or very large ships, e.g., cruise liners. C-band will often provide global beam coverage and direct connectivity between ship and owner, not going via the general Internet.

C-band VSAT systems normally has to be bought and installed on the ship by the owner or the yard and one will not normally bundle a bandwidth contract with equipment lease. Thus, different companies will provide equipment and bandwidth.

See also the previous section for discussion of the K_u band class.

4.2.1.5 Iridium OpenPort

Iridium Communications Inc. is a publicly traded company headquartered in USA. Iridium's mobile voice and data communications solutions, for a wide variety of industries, are supported by a global communications network, including also the Polar Regions.

Iridium's current satellite constellation consists of 66 low-earth orbiting (LEO) near polar satellites at an altitude of 780 km. They are placed in 6 orbital planes, with 11 satellites in each plane. The cross-linked satellites are operating as a fully meshed network and supported by multiple in-orbit spares. Voice- and data messages are transmitted from one satellite to another until the satellite covering the receiving handset or terminal is spotted.

Iridium OpenPort offers voice and digital communication services at a rate up to 128 kbps at L-band frequencies.

4.2.1.6 AIS

AIS (Automatic Identification System) was introduced by IMO for increasing safety at sea for ships and environment, and for improving traffic monitoring and ship services. It is mandatory for all ships of 300 gross tonnage and upwards.

AIS is mainly used for collision avoidance (can be looked at as an extended radar that can “see” around corners) and to gather ship information, e.g., as a support tool for VTS. AIS contains dynamic information (position, course, speed), static information (name, ship dimensions) and route information (destination, ETA, cargo), and messages containing this information is transmitted frequently from the ship, depending on speed and course. AIS is also used to transmit information about buoys, wrecks or other obstacles to safe navigation (it is used as an “Aids to Navigation” – AtoN).

AIS has limited capacity for general binary data transfer between ships and between ship and shore. Total binary bandwidth is about 6 kbps per channel, but most of this capacity is used for position reports, particularly in congested waters. AIS is included in this analysis as a reference service because it is well known in the industry.

AIS operates on VHF and has the same range as VHF radio, as much as up to 70 nm if the base station antenna is placed high enough. Typical range from ship to ship is about 25 nm. AIS currently uses two dedicated frequencies: 161.975 MHz and 162.025 MHz.

4.2.1.7 Digital VHF

In 2008, ITU adopted a new technical recommendation [ITU08] that allows the transmission of digital signals over a 25 kHz bandwidth VHF channel. This system has been deployed in Norway where it mainly serves the national transport systems, fishing fleet and various telemetry applications. In Norway it uses 9 VHF channels, each with a digital bandwidth of 21 kbps. Range is as for normal VHF, up to 70 nm when antennas are placed on mountain tops.

The concept is very interesting for digital maritime services as use of voice VHF generally declines and as the frequencies already have been assigned to the mobile maritime users. Digital VHF also gives the same range and safety levels as AIS and voice VHF. However, bandwidth is relatively limited and the service only supports store and forward messaging, unless used directly between stations within range of each other. In this case, RT latency communication can be achieved.

4.2.1.8 WiMAX/LTE

This analysis does not include general cellular telephone technology as that normally is not very useful for international shipping. The national operators and corresponding high cost of roaming makes this a relatively costly alternative if one does not have a number of different carrier agreements, i.e., one for each coast state. However, there are some developments in this segment that may offer interesting possibilities for shipping.

WiMAX (Worldwide Interoperability for Microwave Access) [IEEE09] has been deployed in Singapore port to provide visiting ships with Internet connectivity. Dependent on allowed transmitter output power, ranges of up to 30 km is possible. However, a range of 10 to 15 km is more common. This is very suitable for ports and port approaches and may be cost-effectively deployed in coastal areas, dependent on number of subscribers and subscription prices. In Singapore, subscriptions with bandwidths of 512 or 1024 kbps are offered to the ships. Higher bandwidths can be achieved when distance to the base station is relatively short. The frequency bands currently used for WiMAX depend on national regulation. Some examples of licensed frequencies are:

- Europe, Africa, Middle East, Latin America: 3.5 GHz
- India, China : 3.3 GHz
- USA, Brazil : 2.5 – 2.7 GHz
- USA, Asia & Pacific: 2.3 – 2.4 GHz

Other frequencies are also in use.

WiMAX is an example of the use of "3G" or even "4G" technology to provide relatively high capacity, wireless Internet connectivity over long distances. There are also other technologies that can be used for this. One example is CDMA 450 which operates in the 450 MHz band to provide long distance (10 – 20 km) Internet connectivity with similar bandwidths as above. CDMA has typically been used in several countries to provide wireless Internet services in the old frequency band used by the now defunct analogue mobile telephone service NMT 450.

Long Term Evolution (LTE) is a "3G" technology designed to increase the capacity and speed of mobile telephone networks. The actual standard defines a downlink max of 326 Mbps with four antennas. The uplink max is 86 Mbps to the client antennas. In each case, these values are for a channel of 20 MHz. The performances of the link depend of the distance between the transmitter and the receiver. The performance can be defined from optimal with a distance less than 5 km to acceptable for distances up to 50 km.

The carrier category WiMAX/LTE is representative of both these technologies as well as for other similar technologies such as high speed digital cell phone, CDMA 450 or even emerging 4G mobile telephone technology. However, dependent on technology and range from the base station, the available bandwidth will vary.

4.2.2 Bandwidth estimates

Nominal bandwidth for Inmarsat C is 9.6 kbps. For Fleet 77, a bandwidth of 64 kbps is provided on the global beam, but higher speeds may be available in spot beam areas and if suitable equipment is installed. The same provisions as for VSAT do also apply to Fleet: Service level will increase cost.

VSAT can provide virtually any bandwidth the user wants to pay for, up to several Mbps dedicated bandwidth. However, lower cost contracts (on K_u band) will often be entered into with a nominal bandwidth of 64 kbps or 128 kbps. Contracts may be for reserved bandwidth, various prioritization schemes or as a best effort service where actual bandwidth supplied is substantially lower in peak periods. Price will generally reflect the service level. Thus, the user needs to make a trade off between price paid and service requested.

Iridium OpenPort can provide up to 128 kbps Internet connectivity. The actual speed is configurable and will again depend on the price paid. In theory, the same speed should be available globally, but congestion may limit the number of available data channels. Little data is available on the performance and reliability of the service and some problems have been reported, although the overall impression is relatively favourable [RVTEC09].

AIS does not really have much available capacity for general purpose messaging. Nominally, each of the two channels have 6 kbps available for digital transmissions, but most of this, if not all, is used for position and AtoN messages. The carrier is included in the analysis as a reference.

Each VHF channel used by the Digital VHF system will provide about 21 kbps digital bandwidth. In this example it is assumed that four channels can be allocated to provide an overall bandwidth of about 80 kbps. This should be sufficient for most e-Navigation services in all sea and coast areas in the world [Rød09].

WiMAX can provide various bandwidths, dependent on frequency it operates on and distance to the base station. As for all other systems, the bandwidth will also have to be shared between the subscribers within the range of the base station. In this example, a bandwidth of 1024 kbps has been specified, which corresponds to the higher speed offered in Singapore in the WisePort system.

4.2.3 Latency estimates and IP support

The latency estimates and flags for IP support is based on the carriers' specified capability. Inmarsat C, AIS and Digital VHF are message based systems that cannot directly support Internet traffic. These services do, however, typically use the Internet for shore based access to their services, e.g., through standard e-mails over Internet or access portals for data.

Latency in Inmarsat C is quoted as several seconds up to a minute for "large" files. For the other satellite systems, the latency is on the order of one to two seconds, see annex in section 7.3 for some background on these figures. Iridium OpenPort latency is reported to be on the order of one second [RVTEC09].

Direct point to point systems like Digital VHF, AIS and WiMAX/LTE can provide very short latency, suitable for real time applications, when sender and receiver use the direct point to point link. However, when the link is used for general ship-shore communication, the actual latency will also depend on the back-haul from the shore base stations to the end users. This can be on the order of a few hundred ms (see section 7.3).

4.2.4 Carrier reliability

The carrier reliability classification is based on the expected environmental impact on signal transmission (discussed in 4.2.4.1) and technical reliability (discussed in 4.2.4.2) which includes sensitivity to ship movements. Table 11 summarises the reliability classifications.

Table 11 – Summary of carrier reliability

Carrier	Environmental	Technical	Overall
Inmarsat C	Very high	Very high	Very high
Fleet 77	Very high	High	High
VSAT K_u	High	High	High

VSAT C	Very high	High	High
Iridium OpenPort	High	Very high	High
AIS	Very high	Very high	Very high
Digital VHF	Very high	Very high	Very high
WiMAX/LTE	Very high	Very high	Very high

Note that reduced polar latitude margins due to rain fading are not included in the reliability analysis, as it is covered in the geographic coverage classification (see section 4.3.8).

The possible effects of reduced reliability in terms of increased bit error rate and/or loss of the communication link is discussed in Annex 7.7.

4.2.4.1 Environmental signal degradation

Reduced quality of the communication signal will result in a higher bit error rate (BER) which in severe cases may also cause loss of the communication link. In the below text, only the environmental losses in the satellite signal are considered. Technical issues are discussed in the next section. The table summarizes the carriers versus the most relevant degradation mechanisms and their overall reliability indicator.

Table 12 – Signal loss types

Carrier	Rain fade	Ionospheric scintillation	Reliability
Inmarsat C		Low	Very high
Fleet 77		Low	Very high
VSAT K_u	Yes		High
VSAT C			Very high
Iridium OpenPort		Equatorial , may be significant - L	High
AIS			Very high
Digital VHF			Very high
WiMAX/LTE			Very high

Annex 7.4 discusses some common environmental degradation factors for radio communication and satellite in particular. The dominant factors are rain fading for high frequency transmissions such as K_u and K_a band and scintillation for lower frequencies such as L-band. Rain fading will be more dominant at low elevation (longer path through atmosphere) and scintillation is mostly a problem around Equator. Although also Inmarsat is susceptible to scintillation, it is assumed that it will be less of a problem as the satellite is geostationary and the signal in general travels a shorter distance through atmosphere than Iridium.

Shore based systems should normally not be very susceptible to environmental factors. VHF has an inherently high robustness as it uses a very conservative modulation scheme and WiMAX uses various adaptive technologies to give high reliability even in adverse S/N scenarios.

4.2.4.2 Technical reliability

In this report, the technical reliability is used as a measure of the probability of absence of critical failures in the technical systems for communication. The technical systems include antennas on ship and shore, electronics for transmission and reception, satellites, and communication infrastructure on ship and shore. It does not include environmental factors such as weather and interference from other radio frequency systems that were discussed in the previous section.

Table 13 – Technical failure types

Carrier	On-ship antenna	Reliability
Inmarsat C		Very high
Fleet 77	Stabilized	High
VSAT K_u	Stabilized	High
VSAT C	Stabilized	High
Iridium OpenPort		Very high
AIS		Very high
Digital VHF		Very high
WiMAX/LTE		Very high

Annex 7.8 gives a more in detail discussion of this issue. However, for the purposes of this report, the only factor included, is the use of a stabilized antenna. It can be argued that the use of complex device like that increase susceptibility of the carrier system to ship movements and mechanical failures. Dependence of a stabilised antenna has been used to decrease the reliability to High from otherwise Very high for carriers affected.

4.3 Geographic coverage

Based on the definition of geographic areas done in section 3.6 and with the coverage classes discussed in section 4.2, the general applicability for each carrier in the various areas are indicated in Table 14 where “SO Sea” corresponds to “Selected Open Sea”.

Table 14 – Geographic coverage for different carriers

	Ship/Ship	In port	Coast	Fjord	SO Sea	Open sea	Arctic	Sub-arctic
Inmarsat C								
Inmarsat Fleet77								
VSAT K_u								
VSAT C								
Iridium								
AIS								
Digital VHF								
WiMAX/LTE								

This table is only indicative and serves mostly to highlight problems that may occur with different types of carriers in different areas. Thus, specific requirements for certain ships and regions must be compared to the arguments provided in the analysis section before a decision to use a specific carrier is made.

The following subsections give an overview of the areas and what services can be expected to be available there.

4.3.1 Ship/Ship

Ship/Ship represents the need for exchanging information directly between ships or between a ship and a costal or port installation. The distance is small (on the order of some nautical miles), but an application used in this area need to be available all over the world as these applications are related to safe navigation or emergency management.

The classification has listed satellite as not recommended for this function as it provides a less reliable platform than AIS and VHF and also a significantly longer latency in communication. Satellite may also not be available globally. However, it can be a very useful backup to LOS systems.

WiMAX and LTE have been listed as less appropriate than VHF based system. The reason for this is that the use of LTE equipment will require special base station equipment for use in ad hoc ship to ship cells. WiMAX may or may not be used to define local area networks, dependent on actual ship equipment.

4.3.2 In Port

When a ship is *In Port,* it is normally within the coverage of one or more land based short range wireless network solutions with high capacity, such as WiFi or WiMAX/LTE. A study performed in the EU project EFFORTS [EFF08] showed that even within large ports, operational communication between ship and shore to a large extent is based on telephony, fax and e-mails via VHF and mobile phones. This emphasizes the potential role of wireless communication in the port environment as it is getting more important and more widespread also for operational use. It is a relatively obvious development to also let visiting ships make use of this infrastructure. More and more ports now offers commercial services like internet connectivity to crew and passengers via wireless networks based on WiFi (e.g., Antwerp) or WiMAX (e.g. Singapore).

In the classification, the focus on the need for RT type latency in more automated port operations has led to a higher classification on SLOS type carriers than satellite. However, satellite is normally quite acceptable for less demanding applications. One should note that ports at high latitudes may have problems related to shading effects. This is discussed in the section describing the Fjord area.

One should also keep in mind that bandwidth requirements for ships normally increases near and in ports. This is due to more logistics related communication and in general a higher demand on safety and operational reporting. Access to relatively low cost and high capacity carriers, such as WiFi or WiMAX also makes it easier for crew to contact relatives. Higher quality of service for shore based services will also make it possible to use real time messaging applications such as voice over IP and video conferencing. Thus, the combination of a shore based carrier in or near port with satellite carriers at high sea would in many cases make very good sense.

4.3.3 Coastal

The coastal area is defined as the area within reach of VHF coastal radio stations, which has a maximum range of approximately 120 km when the antenna is placed on a high location (see figure below). The real range depends on weather and atmospheric conditions and antenna altitudes both on ship and on shore.

The main factor limiting the use of SLOS systems is the line of sight distance from antenna to horizon. It is plotted as a function of the antenna height in the below graph. The maximum communication range (not considering atmospheric ducting phenomena) will then be the sum of the distances for the shore and the ship antenna. Thus, a range of 120 km requires a sum of antenna and base station heights of approximately 1100m. In reality, the range may be substantially longer due to ducting and other phenomena. However, these effects depend on weather and other variable factors and cannot always be relied on.

One should also note that the distance may be shorter if signal to noise ratios are low. This can be caused by weak sender signals, environmental factors or transmission phenomena such as multi-path interference. Normally, VHF will not be very influenced by such factors. Investigations are ongoing to see the effects multi-path phenomena over sea has on WiMAX propagation. Note also that islands may create obstacles for signals, although this is also less of a problem for VHF.

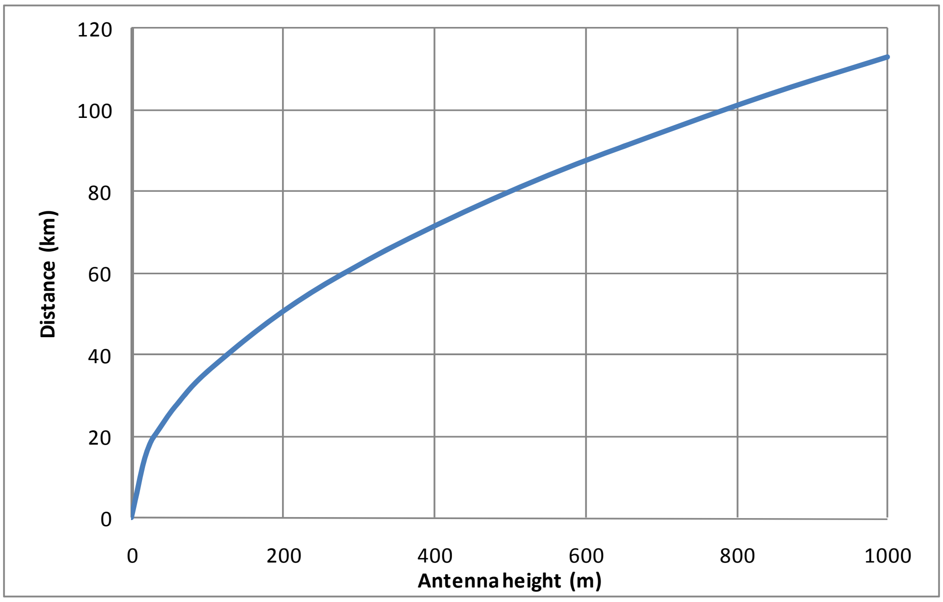

Figure 2 – LOS distance versus antenna height

Further more, the coverage of VHF and AIS in coastal areas will depend on the number of coastal base stations and the topology of the coast. Figure 3 shows an actual measured coverage map from the north of Norway where existing AIS base stations are indicated with red marks [MAS09]. Note that the measurements are based on ship observations and do not necessarily give an accurate picture of actual coverage. The two thick “lines” in the outskirts of the coverage area illustrates this as these lines shows ships in the traffic separation scheme outside the north coast of Norway.

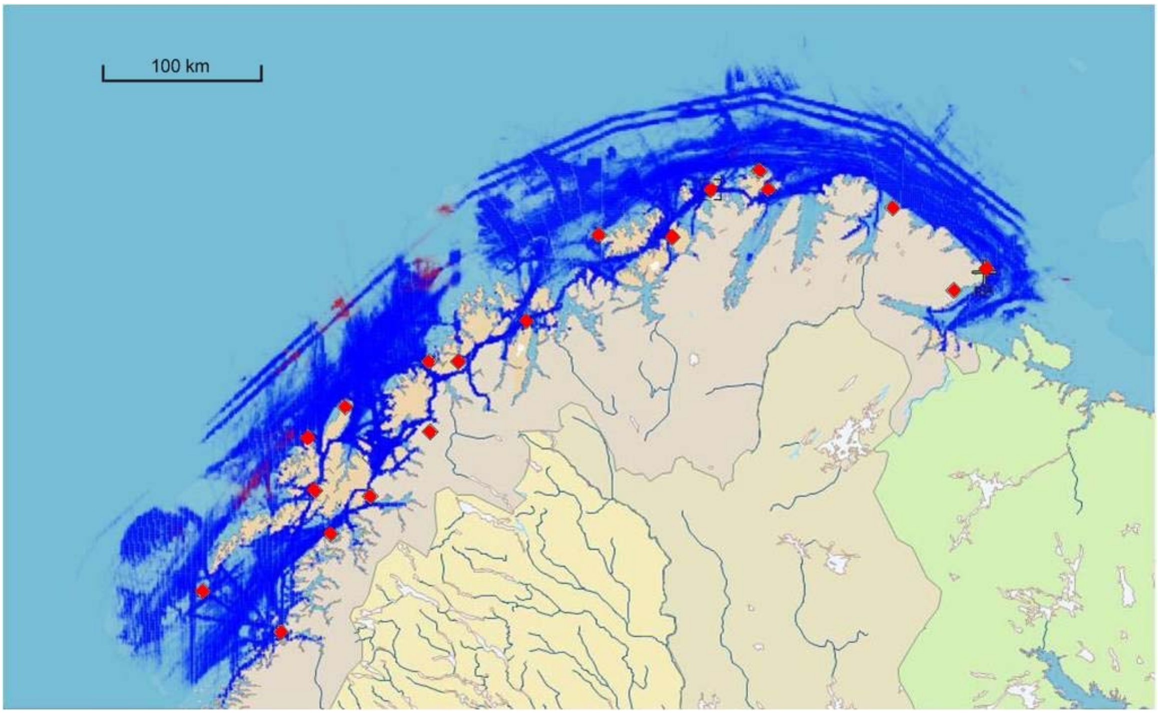

Figure 3 – Measured AIS coverage in North Norway [MAS09]

Along the Norwegian coast line, which is characterized by high mountains and deep fjords, a relatively large number of base stations are required. A study performed in the MarSafe [MAS09] project shows that even with an infrastructure consisting of 35 base stations along the Norwegian coast and at some oil platforms, there still are coverage gaps. This can also be seen in the figure where ship tracks disappear in some areas. Possible solutions to fill these gaps are 1) Move the antennas higher up or 2) Installation of additional base stations 3) Use repeaters.

Other systems than VHF based systems will also have similar coverage, although modulation techniques and signal/noise limitations will typically decrease the available bandwidth for more advanced systems such as WiMAX and LTE as distance to base station increases. However, the classification of carrier suitability in this study does not distinguish between carriers in coastal areas. All should be regularly available.

The combination of terrestrial carriers, in particular types that can carry Internet traffic, and satellites are as attractive in coastal areas as they are in ports. The same arguments regarding traffic volumes and cost profile applies also here. Digital VHF may be interesting for smaller ships and coastal traffic with regards to commercially oriented or private data traffic. However, it is a very relevant candidate for public and safety information. As has been pointed out in [Rød09], Digital VHF seems to have more than enough capacity for all ship safety and emergency traffic, even in heavily congested areas.

4.3.4 Fjords

The fjord is in practical terms a subset of the coastal area. However, fjords, particularly at high latitudes, are characterized by specific challenges for radio communication as signal shadowing and multi-path effects from surrounding mountains is a significant problem. The figures below illustrate some of the different effects.

The multi-path phenomena illustrated in Figure 5 may be both a benefit and a problem. For non-directional systems, multi-path may give coverage where shadows otherwise would inhibit signal reception by providing a signal to the antenna through an alternative route. However, multi-path reflections will also reduce signal to noise ratio and increase the error rate. The issue of increased error rate is discussed in 7.4.1.

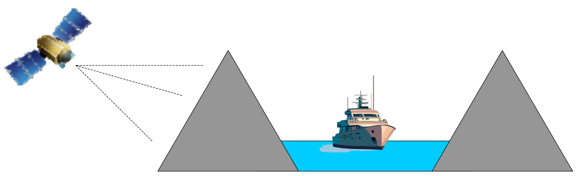

Figure 4 – Signal shadowing

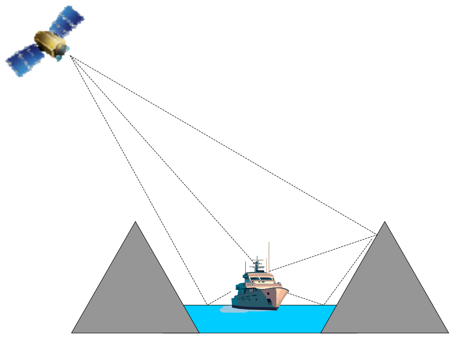

Figure 5 – Multi-path

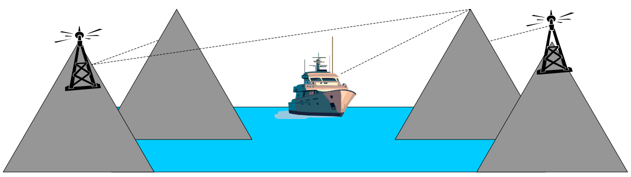

Figure 6 – Terrestrial base station signal shadowing and multi-path

For directional systems, like Fleet 77 and VSAT, multi-path signals will normally not be an issue at all as the directional antenna is insensitive to the secondary reflected signals.

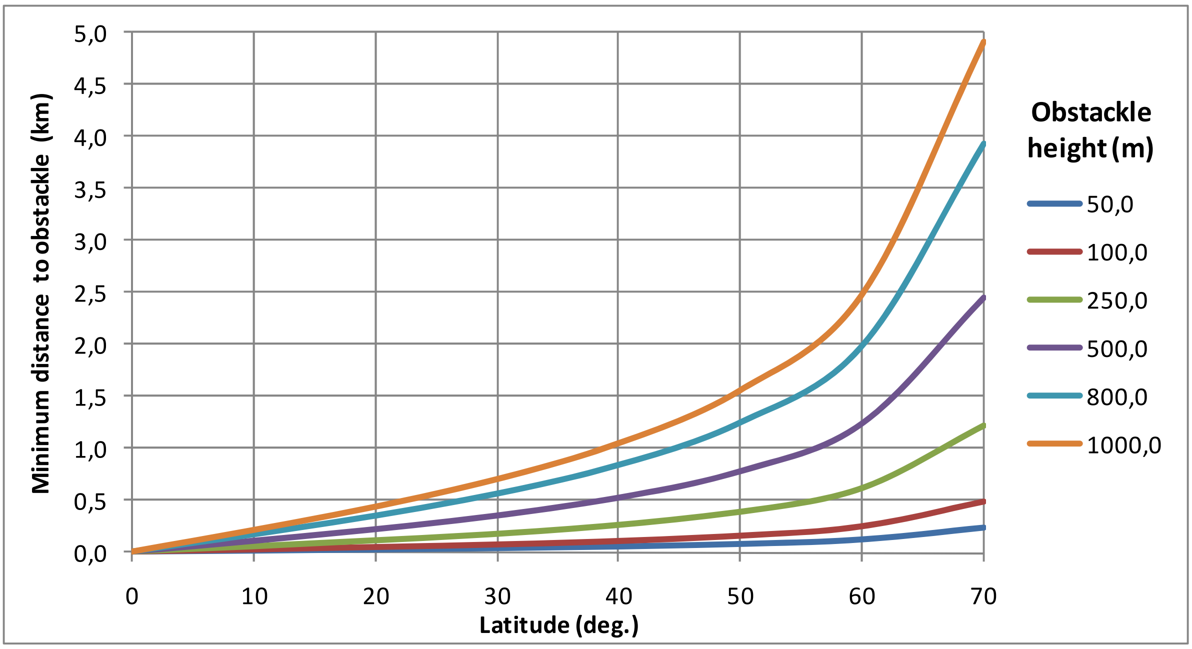

Figure 7 – Minimum distance to obstruction for GEO communication

Another issue that is a problem for directional systems is shadowing effects. Figure 4 shows how signals from satellites can be shadowed from obstructions such as high mountains. This problem is significant for systems that use geostationary satellites at high latitudes. As the latitude gets higher, the elevation angle to the satellite gets lower and even low obstructions like other ships and ice bergs can obstruct the signals. Figure 7 plots the minimum distance from the obstruction in km as a function of latitude for a number of obstruction heights for a clear sightline (at elevation 0 degrees) to the satellite. As can be seen, even at relatively low latitudes, e.g. as in the southern parts of Norway (about 60˚ N), this can be a problem in certain areas. In narrow fjords, satellite based communication links might be completely absent or highly unstable. Note also that there is an additional margin one will normally require when determining the minimum sight angle (see section 4.3.7).

Figure 6 shows an illustration of the same effects (signal shadowing and multi-path), but for a terrestrial communication system. The solutions to overcome these challenges can be to 1) User higher altitudes on antennas 2) Install new antennas that will cover the shadowed areas 3) Use more repeaters.

Finally, deep fjords at high latitudes may also be a problem for Iridium systems as each satellite becomes visible for a very short time. Thus, signal acquisition and data transmission may become a problem.

These issues are reflected in the table by listing satellite systems as not recommended in Fjords where the blocking effects is a challenge. Similarly, a lower classification of SLOS systems reflects the problem of shadowing effects for these.

4.3.5 Selected open sea

VSAT systems will normally use spot beams to cover selected areas of the earth's surface as seen from the satellite (see section 2.9). Thus, a given VSAT service provider may not be able to provide the same global service as, e.g., Inmarsat C or Fleet 77. Note also that some of the Fleet 77 services (high speed Internet) only are provided via spot beams while some VSAT providers also have global beam services.

Thus, *Selected open sea* is areas that are covered by non-global spot beams. In other ways, it has the same characteristics as Open sea: Basically, any satellite system can be used in this area while SLOS systems cannot be used (except for ship/ship direct communication).

If a spot beam solution is selected, one should keep in mind that roaming between satellite communication service providers is not always possible. Thus, although spot beam coverage is available in most areas of the northern hemisphere, different service providers may make it difficult to get full voyage coverage with one simple service contract.

4.3.6 Open Sea

The Open Sea area is the sea area outside shore reach and below about 70˚ N that is not covered by the "Selected open sea" area. In general, this is a sea area where there are few subscribers to communication services and a correspondingly lower selection of service providers. This is typically the case on the southern hemisphere, in the Pacific or Indian Ocean areas.

For communication to shore this area depends almost completely on satellite services with global coverage. The exception is again direct ship/ship communication that is discussed elsewhere. In addition, HF digital communication is often available, but with extremely limited bandwidth.

4.3.7 Arctic

Arctic is defined as a separate geographical area because of its specific challenges with regards to communication technology. The definition of the Arctic in this context is all areas above 75° N. Areas below 75° S could also be included, but this area is covered by the Antarctic continent and is not very relevant for shipping. The Arctic terrestrial radio communication systems are mainly based on HF and MF, with a few coastal stations (e.g. Vardø and Bodø in Norway) broadcasting weather updates and emergency messages to ships in the area. The mostly used satellite communication system is Iridium, which has good coverage at the poles and offers a bandwidth capacity of approximately 128 kbps. The available AIS base stations are too few in this area to be considered as a part of the available communication infrastructure. More specialized systems such as ARGOS or Orbcomm can also be used.

Communication solutions based on GEO satellites are not suitable for use in the Arctic. Several effects contribute to this, but the basis for all is a very low elevation angles between the ship antenna and the satellite at high latitudes. Some of the effects that are relevant are:

- Atmospheric disturbances due to longer travel through atmosphere. This includes absorption, rain fade, scintillation and other phenomena and is typically frequency dependent.
- Increased multi-path interference due to reflections from ground as well as fluctuations in arrival angle fluctuations.
- Shadow effects from hills, structures and in some cases vegetation will increase with lower elevation angles. This is, however, not normally applicable to ships.

The sensitivity to such effects is dependent on the link power budget for the satellite in question where also the ship's antenna plays a part. As increased power output has a high cost for the satellite, there will normally be a trade-off between the expected usage latitude, cost for the service and the power margins. Thus, for operation at high latitudes one needs to check the capabilities of the offered services. For normal "off the shelf" services, one can use Table 15 as a guidance to operating limits. See Annex 7.5.2 for more details of the calculations.

Table 15 – Nominal minimum elevation angles and corresponding latitudes

Frequency	Lowest elevation	Latitude
C-band	5°	76°
K_u-band	10°	71°
K_a-band	20°	61°

These figures are nominal and different power outputs from the satellites as well as larger ship antennas will increase these limits. However, one should also note that these limits are significantly lower when the ship is not on the same longitude as the satellite. This issue is discussed in the next section.

In September 2009, the MarSafe North project [MAS09] completed a field study on a VSAT communication solution onboard a vessel on its way from Longyearbyen (78°N 15°E) to Kirkenes (69° N 30° E). Some results from this study are presented in Annex 7.6. The results from this study show that one can get reasonable K_u performance at least up to 75°N, although one should keep in mind that this is a military ship specially equipped for operation in arctic and sub-arctic areas. Also, weather conditions were very favourable.

4.3.8 Sub Arctic

In this report, the Sub Arctic area is defined as the area between 70° and 75°N. The main communication solutions available in this area are the same as for the Arctic, except for a few more shore VHF stations and improved performance from geostationary satellites.

As mentioned in the previous section, the maximum latitude where one can get "good" satellite coverage (Table 15) will actually depend on the longitude of the ship compared to that of the satellite (or rather that of the geographic point directly under the satellite – sub satellite point). This is because the satellites will be hidden below the "horizon" both with respect to the equatorial position as well as being east or west of the ship. Figure 8 shows this as a four graphs, one for each of the margins defined in Table 15 as well as one curve for no margin. This is further discussed in annex 7.5.2.

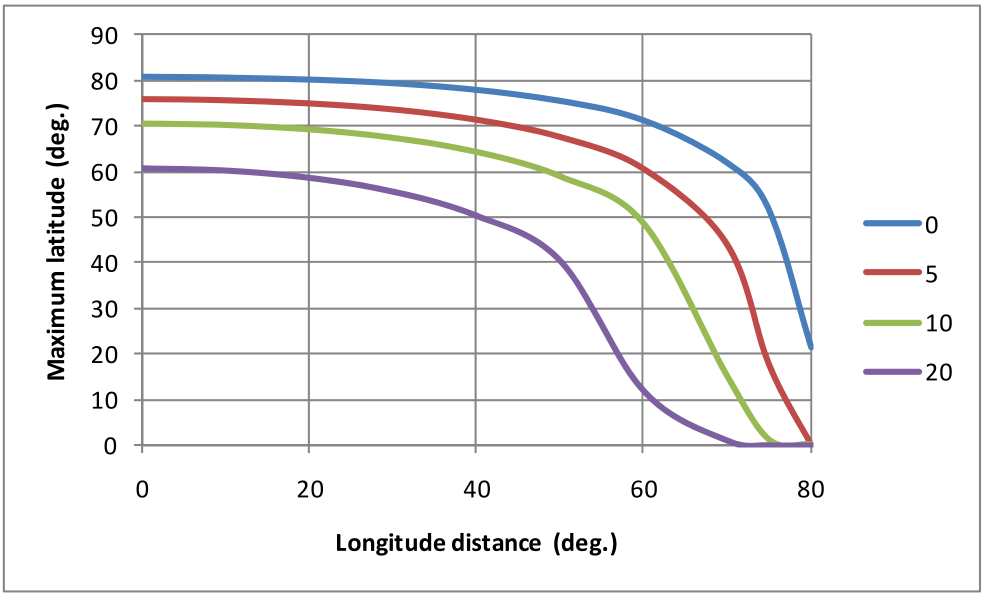

Figure 8 – Maximum latitude for GEO coverage at given longitudinal distance

Figure 9 shows the Inmarsat-3 and -4 constellations and one can see that the maximum longitudinal distance between Inmarsat-3 satellites are up to 128°.

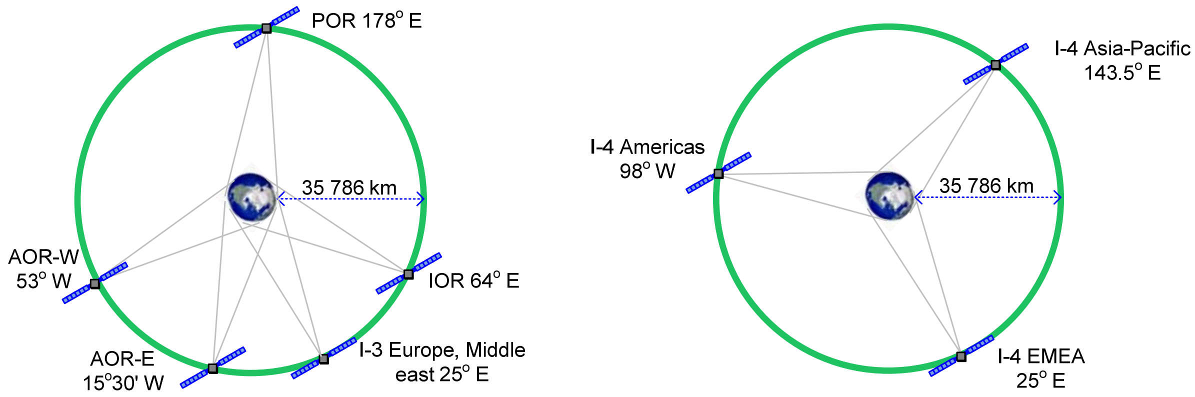

Figure 9 – Inmarsat 3 and 4 constellations

This gives a worst case longitudinal distance from sub satellite point and ship of 64°. This occurs at approximately 180°W, i.e., at the date line. At this point, one can expect problems with Inmarsat coverage down to 60°N. Similar problems occur with Inmarsat-4 that only have three satellites in the constellation, giving a worst case longitudinal distance of 60°.

4.4 Overall quality of service

For the end user, the main factors for the perceived quality of service are probably the bandwidth, the latency and the ability to support direct Internet connectivity. This is when errors in transmissions and intermittent or permanent loss of connectivity do not impair the offered service level.

Table 16 gives an overview of the comparison between application requirements and carrier properties as discussed previously. The classification is always based on the carrier operating in its "best area" as defined in Table 14. Carriers used in geographic areas with lower performance classification may need to have their quality of service classification downgraded accordingly, dependent on the actual characteristics of the service in use.

Table 16 – Offered quality of service versus application requirements

	Inmar. C	Fleet 77	VSAT-K_u	VSAT-C	Iridium	AIS	Dig. VHF	WiMAX/LTE
Distress	green	light green	red	red	red	red	pink	pink
Emergency	red	light green	light green	light green	light green	red	green	green
Nautical rep.	green	green	green	green	green	red	green	green
AIS	red	red	red	red	red	green	red	red
Nautical op.	pink	light green	light green	light green	light green	pink	green	green
Voyage rep.	green	green	green	green	green	red	green	green
Cargo rep.	green	green	green	green	green	red	green	green
Cargo op.	red	pink	pink	pink	pink	light green	green	green
Tech. rep.	green	green	green	green	green	red	green	green
Tech. op.	pink	green	green	green	green	red	green	green
Crew ift.	pink	green	green	green	green	red	pink	green
Pass. ift.	red	pink	green	green	pink	red	red	green
Billing	pink	green	green	green	green	red	light green	green

The table is only a guideline and cannot accurately represent the capabilities of an actual service offering. Dependent on the cost and quality of the service in use, better or worse performance can be expected than that indicated in the table. However, based on the assumptions in the report, the table should give an indication of what one can expect.

A brief background for classification can be found in the following paragraphs:

- *Distress signalling:* Although all carriers can carry this traffic, only GMDSS compliant systems should be used as primary carrier. Currently, that is only Inmarsat C and Fleet 77. Fleet 77 has been given a slightly lower classification as it uses a stabilized antenna that may slightly impair technical reliability. SLOS carriers have been given “Not recommended” as they are classified with very high reliability, although not being GMDSS compliant (VHF DSC is part of GMDSS though).
- *Emergency:* Inmarsat C and AIS will not have sufficient capacity and other satellite systems are less favoured due to somewhat lower reliability. Digital VHF as well as WiMAX has bandwidth and reliability.
- *Nautical reporting:* This is feasible and recommended on all carriers except AIS, due to bandwidth limitations.
- *AIS:* This is per definition only carried on the AIS system.
- *Nautical operations:* Inmarsat C does not have latency suitable for this application. AIS do not have sufficient bandwidth and is not recommended. Other carriers have been classified according to reliability (very high reliability is required).
- *Voyage reporting, cargo reporting and technical reporting:* AIS has too low capacity. All other carriers are recommended in the respective operational areas.
- *Cargo operations:* Inmarsat C does not have latency suitable for this application. General purpose satellites have lower reliability and higher latency than desired. AIS may be used, but bandwidth is probably a problem. SLOS systems are recommended.
- *Technical operations:* Inmarsat C do not have latency and probably not bandwidth suitable for this, however, it may perhaps be used. AIS does not have bandwidth and neither a suitable protocol. All other systems can be used.
- *Infotainment:* Bandwidth is main criterion, support for IP a secondary. Technically, Inmarsat can be used for crew, but cost may be an issue. Passenger infotainment requires substantially more bandwidth than crew and will normally only use VSAT systems (at bandwidths around 1 Mbps). WiMAX is a useful alternative in port.
- *Billing*: Capacity is the main criterion. Digital VHF gets a somewhat lower classification as it does not directly support IP. However, the system is actually used for billing in some areas. Inmarsat C is not generally suitable, unless its capacity fits the actual requirements.

Again, one should be careful when using these results. The summary table is mainly included to highlight potential problems, but these problems may be larger or smaller in certain circumstances. One will in any case need to compare this classification with that given on the geographic coverage.

4.5 Security issues

This section discusses security issues related to ship to shore communication. This is partly a summary classification of the carriers and partly a discussion of some remedial actions one can take. The final sub-section discusses some less obvious problems that may occur.

Security is important in all communication. Insertion of wrong data in a communication stream may cause serious accidents as well as commercial, contractual or legal problems. Denial of service can inhibit critical information from reaching its destination and breach of confidentiality can likewise be used to cause accidents or for fraud.

Wireless communication and general communication over the Internet is particularly sensitive to security problems of the types mentioned above. Thus, this analysis will briefly point to some security issues related to the examined carriers.

Table 17 – Indicative security quality classification for the carriers

Carrier	Confidentiality	Integrity	Denial of service
Inmarsat C	High	High	Medium-Low
Fleet 77	High-Low	High-Low	High-Low
VSAT K_u	High-Low	High-Low	High-Low
VSAT C	High-Low	High-Low	High-Low
Iridium OpenPort	High-Low	High-Low	Medium-Low
AIS	Low	Low	Low
Digital VHF	Low	Low	Low
WiMAX/LTE	High-Low	High-Low	Medium-Low

The security quality classification shown in Table 17 should be taken as indicative. Most of the carriers allow different protocols and access mechanisms to be used and which one is used will determine the security level. Briefly, the background for the classification is:

- *Inmarsat C:* Inmarsat C uses dedicated message delivery mechanisms which should help to ensure integrity and confidentiality. However, the use of an omni-directional antenna makes it relatively easy to, e.g., jam the ship receiver.
- *Fleet 77:* Fleet 77 allows both Internet based and dedicated communication links to be established. Use of Internet is a problem as it is relatively open for hostile attacks on the land side. This applies to confidentiality and integrity. Also denial of service attacks on the land side may be launched over the Internet, but the use of a stabilized and directionally sensitive antenna will make it more difficult to jam the signal on the ship.
- *VSAT*: The same as Fleet 77 applies. VSAT connections may be established point to point between ship and land users. In this case, high integrity levels can be ensured. However, with more common use of Internet based connections, the same vulnerabilities as Fleet 77 applies.

- *Iridium OpenPort*: As for VSAT and Fleet 77. The antenna is omni-directional and allows easier attacks by jamming the ship receiver, although Iridium may be able to pick up alternative satellites in such cases.
- *AIS*: In its current implementation, AIS is open to all types of attacks. It also uses an omni-directional antenna that is very easy to jam.
- *Digital VHF*: The transmission protocol is open and does not currently implement any security mechanisms. Thus, it is vulnerable to on the same level as AIS.
- *WiMAX/LTE*: These systems have fairly advanced protocols with high security levels. However, common use of Internet as backhaul opens connections for hostile attacks on the land side. Omni-directional antennas may also be susceptible to jamming attempts.

In general, this discussion only point to the fact that the user of such communication systems need to consider what attacks it is necessary to protect against, if any. Some mechanisms are already in place if implemented properly and others can be added on by using application layer mechanisms. The next section discusses some of the potential remedies.

4.5.1 Possible remedial actions

Once the ship is connected to the shore, whatever technology or protocol is used, the ship has to be protected from potential attacks via the communication facilities. If this is not handled by the basic communication system as discussed in the previous section, one needs to install specific security systems that provide protection. While voice calls typically are connection switched via specialised data channels and do not generally represent a problem, this is different for data streams that go via the open Internet. In such cases one will typically provide a four-tired protection system as shown in the figure.

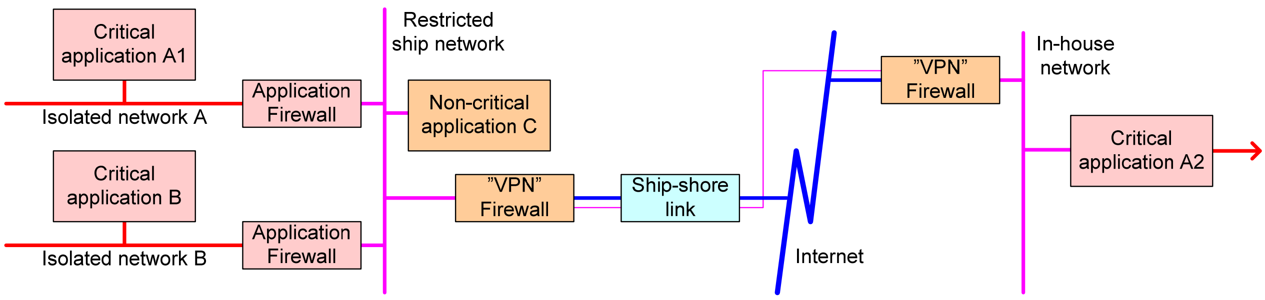

Figure 10 – Typical security implementation

Essential services (A or B) are directly connected to physically isolated networks, possibly with an application level firewall to the ship wide network. Only information that is explicitly made available by the application firewall can be reached from the restricted ship network. This is the first protection level.

Non essential services are directly connected to the restricted ship wide network (C), servers as well clients, for performance reasons.

The second protection level is between the restricted ship network and the shore. Firewalls and gateways will be used to segregate these two worlds. These systems are confidential to each ship or fleet. In some cases, e.g. for maintenance, a pipe is opened between the ship and the supplier who wants to access the system, but always for a small period and with login and password that are not reused afterwards.

The third protection level is between shore and shore. Ship owners request from their communication provider a private network (e.g., Virtual Private Network – VPN or a circuit switched line) between the ship and their shore office. It is not possible to access the ship directly through the general communication provider. Any supplier that need to access the ship shall connect first to the ship owner's shore office and only after that, the supplier can connect to the relevant application on the ship, normally through a dedicated VPN connection. The shore office has also, of course, firewall and gateways to protect them from outside intrusions.

This setup allows the owner easy access to the applications that export interfaces through the three levels of protection. However, this may reduce the available bandwidth in some cases. For third parties, e.g., equipment manufacturers, the access is significantly more cumbersome as several steps and possibly manual intervention is required. However, this depends on the level of trust between the third party and the owner. VPN access may in some cases be granted on a permanent basis.

4.5.2 Other security issues

As long as the onboard systems and networks were dedicated to specific applications and were stand alone, the only way to access them was locally onboard the ship and normally only in controlled areas of the ship. With the progress of new technologies and in particular in networking, these systems tend to be connected to or reside as part of a larger restricted network on the ship. This trend can be expected to continue with even more systems being connected to the restricted network and new links from the restricted network to shore.

Also, increasing levels of complexity and less crew onboard make more owners delegate the maintenance and management of networks and applications to third parties or to the manufacturers themselves. Consequently, systems that used to be stand alone and isolated inside the ship are now network based and are connected through the Internet to the shore. This opens up possibilities for hostile attacks, e.g., from hackers, but it also causes potential safety problems with regards to misunderstandings or bad decisions inside the owner's office or by other parties that have legal access to the systems.

Further more, ship systems and networks are normally not constructed by one party alone. On most ships, there is no IT department that manages network equipment and connections and the systems have in many cases been delivered and commissioned by different parties during the ship's building process. During the life time of the ship, systems and networks will be upgraded and exchanged several times. This adds to the problem of maintaining the complete network infrastructure. A virus or other mal-ware in the office is a great problem, on a ship it may lead to a serious accident.

On the other hand, developments on shore with respect to centralization and virtualization may also be implemented on ships. However, this causes new problems. Safety principles and also general business processes is currently based on each supplier having full responsibility for the delivery, including network, computers and software. With more distributed or integrated systems, this principle has to change and this will require updates in business practices as well as in rules and legislation. For the owner and yard it will also present new problems in terms of guarantees and maintenance.

4.6 Cost analysis

This section gives a very rough overview of the costs associated with the different systems. The prices identified in the below sub sections are based on prices found on the Internet and direct information from some suppliers. This overview is for information only and should not be used as basis for decisions. Pricing and services change continuously and prices will vary much with specific equipment and service specifications. The date of validity is October 2009 unless otherwise stated.

Costs are divided into installation costs ("fixed costs") and service costs ("variable costs"). This division is also not always applicable as many contracts mix these components into one or more packages. All prices are approximate and specified in USD ($).

4.6.1 Inmarsat C

Typical prices are listed below. The prices quoted here are for small packet transmissions. Larger messages can be assembled from a number of smaller.

	Services	Installation
Inmarsat C	Prices from 2002: o Ship-to-shore: From $0.21 to $0.33 / 256 bits o Shore-to-ship: From $0.12 to $0.60 / 256 bits o Mobile-to-mobile: $0.25 / 256 bits	$6000 Inmarsat C terminal, antenna, printer, power supply, cables, manuals

4.6.2 Inmarsat Fleet 77

Typical prices are listed below. The listed services are ISDN at 64 kbps (fixed connection between parties), shared-channel IP packet-switched data services at 64 kbps (called Mobile Packet Data Service – MPDS) and a medium speed fax/data service at 9.6 kbps.

	Services	Installation
Inmarsat Fleet 77	o $12 per MByte (ISDN) o $3.5 per MByte (MPDS) o $2.8 per minute (data)	$28000 Antenna, Terminal, handset, Power supply, Manuals and SIM card.

4.6.3 VSAT K_u

There is a wide range of K_u systems and cost models available. One factor is antenna size where larger antennas give better signal quality and may actually reduce overall service costs as this has implications for the satellite systems. On the other hand, many ships are restricted in what size antenna they have space for and larger antennas will obviously have a higher system and installation cost.

Another factor is the service model: VSAT normally offers “always online” services for a fixed monthly fee, and most of the services offer three types of price models for the end user:

1. Single user per carrier: The user is guaranteed a certain bandwidth at all times. This is the most costly model.
2. Shared bandwidth: This offers a certain bandwidth in an area with multiple users. The bandwidth is shared among the users and hence less bandwidth is guaranteed. This price model gives the lowest prices for the end user. The more common variant of this is to give the ship access to the general Internet through a link shared with a number of subscribers within the satellite’s spot beam.
3. Mix of 1 and 2: This means that a dedicated bandwidth can be shared between several ships or other installations in the end user’s company. This is a model that gives higher quality of service than for price model 2, but lower prices than for price model 1.

According to the one report [Far05], the prices of VSAT solutions in 2005 were about $2500-$3000 per month, bundling both the transponder capacity and terminal lease into a single monthly charge with very large or even unlimited usage permitted (although it is worth noting that dedicated voice channel traffic typically costs extra, except for a limited allowance of voice minutes per month).

	Services	Installation
VSAT K_u	$ 3000 (Monthly lease plus traffic)	Included in lease

In general, as the market is relatively complicated it will probably pay off to use some time or even external help to find a good overall solution.

4.6.4 VSAT C

C-band systems are usually sold as separate antenna system and bandwidth contracts. Some of the same types of service contracts as for Ku band may also be available here.

A main cost driver is the size and the weight of the stabilized antenna. With dish sizes up to 2.8m, the assemblies and the domes will be correspondingly big. Larger antennas obviously cost more than smaller antennas. Thus, a trade off is often made between signal quality (antenna size) and price.

The prices listed are only nominal. Actual price will vary with antenna size and communication services used.

	Services	Installation
VSAT C	$ 1000	$75 000

4.6.5 Iridium

Iridium services are often offered at different prices for different combinations of services. One example is given below. The pricing strategy involves a combination of speed selections, volumes, voice channels and various bundles. Some examples are shown below.

	Services	Equipment
Iridium	$800 - $1100 monthly fee (64 kbps, 0 – 300 voice minutes included, 50 or 100 Mbytes included at a speed of 32 kbps) $1000 - $1300 monthly fee (128 kbps, 0 – 300 voice minutes included, 100 or 150 Mbytes included at a speed of 32 kbps)	About $5000, including antenna, receiver, handsets and onboard Internet connection.

4.6.6 AIS

AIS is a system for automatic identification of seagoing vessels, and is not commonly used as a communication system. However, it is included here because of the AIS short message service that in principle can be used for exchange of small messages and small amounts of data. This service is free of charge, and the only investment at the end user side is the AIS terminal that needs to be installed onboard the ship.

	Services	Equipment
AIS	Free of charge	$3000 (AIS terminal with antenna)

4.6.7 Digital VHF

Digital VHF services include data exchange (e-mail and other message types, e.g., weather forecast).

	Services	Equipment
VHF data	$55 per month (e-mail) $30 - $40 per month for other services	$3000 (VHF data terminal and antenna, including installation)

4.6.8 WiMAX

Currently, the port of Singapore offers visiting ships the possibility to lease a WiMAX modem and use the wireless network for Internet connectivity. Approximate prices are listed below.

	Services	Equipment
WiMAX	$80 per month (512/ kbps), unlimited use (1024 kbps also available)	$200 one time establishment fee.

5. Conclusions

This report has discussed existing as well as possible future applications relying on digital ship to shore communication and how these applications fits onto a number of different communication carriers. This section will summarise some of the conclusions that have direct impact on ship operators, builders and in some cases authorities.

One should keep in mind that this report cannot give a detailed procedure for selecting specific carriers even for very specific requirements. Actual reliability and service quality will depend on a number of design and environmental factors that are only briefly discussed in this report. However, we have tried to point out some of the issues that one should be aware of when selecting a carrier.

The following points are some of the direct conclusions that can be drawn from the discussions. These are also mentioned in the executive summary. Note that these points apply to “normal” cargo ships in international traffic. Special ships, passenger ships and ships in special trades have different requirements that are difficult to capture in a general report. However, many of the issues discussed in the report apply, although the overall conclusions may not.

- Modern shipping will increasingly rely on digital information exchange between ship and shore. Some example applications are discussed in this report, more details can be added by looking at own operations. Thus, digital carriers will be increasingly important.
- Even with relatively advanced applications onboard, from an operational point of view one will normally only need a relatively low bandwidth carrier to satisfy communication requirements, such as, e.g., Inmarsat C.
- However, one should also consider the needs of the crew and the positive effect that frequent and easy access to relatives and family will have. This is probably the strongest driver for increased bandwidth between ship and shore.
- Before selection of a carrier system, one needs to understand the requirements in terms of operational area, types of applications and acceptable costs. This has to be compared with the actual capabilities of the carriers, with respect to geographic coverage as well as offered quality of service. No application can run on all carriers and no carrier can satisfy all applications at any location at the seas.
- Security is an increasingly important factor in communication. Both commercially and with respect to ship safety, one needs to consider security issues for carriers and communication mechanisms. Note, however, that communication security is related to end to end transfers and cannot be looked at for each system component in isolation.
- In most cases one will need more than one carrier to satisfy all requirements. This will also increase robustness if one of the carriers fails. One of these carriers will normally be used to satisfy regulatory requirements, such as GMDSS.

The following sections will discuss some additional issues that are mentioned in the report, but which may require some additional explanation.

5.1 Impact of e-Navigation and e-Maritime

As mentioned above, reliance on digital exchange of information is already significant and will increase. Today, one can in principle manage with fax and perhaps e-mails in some cases, but this is more and more being exchanged with electronic data interchange (EDI). This applies to authority reporting (port clearance), reporting into ship reporting areas (being discussed in IMO) as well as more commercially oriented reporting such as technical and voyage reports.

The IMO e-Navigation initiative will also focus on the use of EDI formats instead of voice, fax or e-mails. Likewise, regional initiatives such as e-Maritime is directly targeted at implementing EDI so that overall information management can be more automatic and information more easily accessible. In general, one must also expect that all these initiatives also will increase the amount of information exchanged. However, as this report has shown, even with a relatively high degree of information exchange, one can on the operational level manage with a bandwidth on the order of 1 kbps.

EDI will become an integral part of future shipping and it will become more and more difficult only to rely on "analogue" information exchanges through voice and fax. Thus, also the use of appropriate digital communication carriers will become important.

5.2 Need for real-time communication

Currently, only AIS can be called real-time digital exchange of information. It can provide information about other ships or aids to navigation that can be automatically incorporated in the ECDIS or ECS situation displays. In addition, the DSC functionality and NAVTEX system allows some forms of registration of incoming data electronically with associated alerts to the bridge watch keeper when new information is available. Flagship sub-project B3 (Nautical operation and bridge decision support) has also demonstrated the automatic plotting of NAVTEX messages on an ECS.

It is clear that such functions can increase safety at sea and operational efficiency. Applications for integrated support during tug operations, berthing and lock passages are available, but not commonly used. The above mentioned e-Navigation initiative can be expected to add such functions to the normal repertoire of future ships.

Future carrier systems need to consider the support for real-time applications in and near port or along coast. Real-time carriers can also have application in ship to ship communication at deep sea (emergency management, other coordination). This issue need to be addressed by port and coast state authorities.

5.3 Need for international standards

Ships move between ports, between countries and between continents. With an expected increased use of EDI, there is an acute need to look at standards both for carriers and data formats.

For commercial applications, this can probably be left to the marketplace, although parties to the processes will likely involve international standards organisations also here.

For public applications, e.g., port clearance, ship reporting etc., one should base standards on international consensus between flag and port states, through the appropriate organisations, e.g., ITU, IMO or ISO/IEC.

Future shipping information exchange requirements must be based on the use of agreed international standards, both with respect to carriers and information formats. Authorities and commercial parties must cooperate to develop these standards.

5.4 Need for a new public shore based carrier

As has been pointed out above, there is a need for both real-time and non real-time data exchanges. Non real-time includes IP enabled communication that is not suitable for ship/ship or ship/shore control. It is also obvious that while satellite is necessary at high seas, a high capacity costal LOS type communication carrier may be very useful for certain public data exchanges in conjunction with coastal passage or port approach.

A new public service should preferably be based on a costal network of line of sight communication stations, e.g., based on VHF or WiMAX/LTE. Another possibility is also to use recently freed frequencies in the 850 MHz area which has previously been used for analogue TV. This is a frequency range extremely well suited to broadband communication in relatively sparsely populated areas. Also 450 MHz is very well suited to digital ship to shore communication, although these frequencies have mostly been allocated to commercial services. This is one benefit of the VHF frequencies that have already been allocated to mobile maritime communication. See [Rød09] for a more detailed discussion on this issue.

Public authorities should consider providing and internationally standardised digital coastal radio service as a public service to shipping. The service may also offer spare capacity for commercial data exchanges.

5.5 Hybrid systems and use of least cost routers

An issue that will become more important in a future with several different carriers to choose from is automatic routing of data onto the carrier with “best” performance at a given time. Such routers may also decide to delay transmission of data if it expects to get access to better carriers within a reasonable period.

Such routers may make decisions based on a combination of least cost, optimal quality or capacity. Routers of this type do already exist today and more will most likely emerge. For ship use, the routers will typically be able to select between Inmarsat, Iridium, VSAT or even GSM or WiFi type communication when in port.

Such routers can also be combined with systems to automatically switch between different VSAT providers, possibly operating on different satellites.

An important component of the future ship communication system will be the ability to switch between carriers. This can significantly reduce cost while increasing availability and possibly also safety.

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7. Annexes

7.1 Annex A – Description of some wireless onboard radio-communication carriers

This annex gives an overview of some of the network technology used onboard ships. This is not directly applicable to the wireless ship-shore communication, but is included here to provide some background also on this area.

7.1.1 GSM and cellular phone

This is the same technology as the cell phone use on the shore. On a ship, there is different way to use it. One way is to have a GSM gateway. This gateway is in fact like a phone cell but that could be connected to the ship internal communications. In a gateway, we could have one or more SIM card for simultaneous calls. The second way is to use a GSM booster link to ship antenna network. All the calls inside the ship are caught by the internal network boosted and emitted through an external antenna. This principle is used to extend the normal coverage of the GSM. The last way is to use a GSM rack inside the ship. In this case there is again a ship antenna network that is connected to a GSM rack that manages the calls. However, the rack should also be connected to a satellite link.

7.1.2 Walkie-Talkie

UHF walkie-talkie systems are installed on all the ships. It is generally used as an internal communication system that uses an antenna network to cover the whole ship. This network includes an external antenna on the top of the ship that permits to cover the outside decks but can also cover several kilometres around the ship. These communications are free and are generally used by crew to prepare the mooring of the ship. The outside antenna is a rod. The main problem of this system is the use of free frequencies that are the same on every ship. So it could happen in ports that two different ships use the same and create interferences.

New technology based on digital UHF can solve this problem. It is called TETRA (Trans European Trunked Radio) and is a European standard. It uses TDMA (Time Division Multiple Access) protocol for transmission. The norm defines 4 time channels per frequency. In addition of standard UHF features, TETRA proposes the following new ones.

- Data transmission: Status, Short messages, packet or circuit link.
- Trunked mode: Full duplex calls, phone calls, additional services.

In addition the digital communication proposes voice and also data at a low rate.

7.1.3 DECT

Digital Enhance Cordless Telecommunications or Digital European Cordless Telephone is also an internal communication system that could be used for external communication. The range is very short, hundred of meters, but could be used between the ship and offices on the quay. It could be only used for voice or short text messages. It is a free communication that uses proprietary antennas.

DECT base stations could be of two types. Historically, they are connected to the main TDM PBX through digital lines like the digital phones sets. In this case, the architecture is a star. Because of the Ethernet/IP trend, suppliers propose now a new type of base station that could be connected on an Ethernet/IP interface. It is the same kind of base station with the same features. The only change is the interface. Few years ago, communication has been made on a third type of base station that could combine WiFi and DECT. This project was finally given up.
If the DECT is a European technology, it is also used over the world. However, the frequencies are not the same everywhere.

In particular, Europe, Australia and Asia use a different frequency band than the US for DECT telephony (1880-1900 MHz versus 1920-1930 MHz in USA). For ships, this can cause interference with other services when, e.g., a European ship visits USA. One can assume that the European frequencies are not often used in US port, but some ship owners request that their antenna network shall be compliant with both areas otherwise they have to turn off their system as they do for GSM.

7.2 Annex B – Communication coverage details

This annex gives some background to the definitions of geographic coverage for communication services [SOLAS].

7.2.1 GMDSS Sea Area A1

An area within the radiotelephone coverage of at least one VHF station in which continuous digital selective calling (ch70) alerting and radiotelephony services are available.

7.2.2 GMDSS Sea Area A2

An area, excluding Sea Area A1, within the radiotelephone coverage of at least one MF coast station in which continuous DSC (2187.5 kHz) alerting and radiotelephony services are available. GMDSS-regulated ships travelling this area must carry a DSC-equipped MF radiotelephone in addition to equipment required for Sea Area A1.

7.2.3 GMDSS Sea Area A3

An area, excluding sea areas Al and A2, within the coverage of an INMARSAT geostationary satellite in which continuous alerting is available. Ships travelling this area must carry either an Inmarsat F77, B or C ship earth station, or a DSC-equipped HF radiotelephone/telex, in addition to equipment required for an A1 and A2 Area.

7.2.4 GMDSS Sea Area A4

The area outside that covered by areas A1, A2 and A3 is called Sea Area A4. Ships travelling these polar regions must carry a DSC-equipped HF radiotelephone/telex, in addition to equipment required for areas A1 and A2.

7.3 Annex C – Latency calculations for satellite links

[Lor00] contains an analysis of expected round trip delays for terrestrial links versus links via satellite. The results are tabulated below. This is fairly representative of international Internet connectivity where a number of routers are involved. Note that the figures do not include effects of congestions or limited link capacity which is often the case for low cost satellite transmissions.

Table 18 – Estimated/reported latency for ground and satellite circuits (ms)

	Forward link router	Forward link propagation	Client/server processing	Return link propagation	Return link router	Sum
Terrestrial roundtrip	15	35	50	35	15	150
GEO Satellite roundtrip	10	260	50	260	10	590

Actual experiments documented in the same paper shows a significantly higher round trip delay of up to 2.6 seconds for the second case (satellite both ways). This was measured during a request for a 5 kByte web page. This illustrates the fact that TCP/IP throughput also is limited by other factors than the basic system latency and the bandwidth. Annex 7.7 will discuss this issue in some depth and will also look into the effect of transmission errors on the actual throughput.

7.4 Annex D – Environmental degradation factors for satellites

Degradation factors for radio transmissions can loosely be collected in three groups. The main group is loss due to distance and frequency which is independent of the medium the radio signal passes through:

- *Free space dispersion loss* is caused by the spatial propagation of the radio signal and will be proportional to the square of the distance.
- *Antenna aperture loss*, which for an isotropic (omni-directional) antenna will be proportional to the square of the frequency.
- *Antenna gain*, which for the same size directional antenna is proportional to the square of the frequency. As there is both a transmitter and receiver, the total effect is a gain increase by the fourth power of the frequency increase.
- *Transmitter electronics loss,* which can be expected to be about linear with frequency. This is mainly an issue for the satellite with a limited power budget.

Thus, for the total link budget one can roughly expect a proportionally better S/N by increasing frequencies.

The second group consists of factors that can give significant environmental signal loss either due to dispersion in atmosphere or due to effects of the electromagnetic field surrounding the earth. There are two main factors in this group:

- *Scintillation loss:* Rapid changes in amplitude and phase due to changes in atmosphere's refractive index. This is typically most noticeable on low latitudes (near equator), but it will also occur in the aurora borealis regions and at the poles. The effects will be stronger for lower frequencies, e.g., L-band transmissions.

- *Rain fade:* Rain and in particular sleet can have a substantially negative impact on signal strength. This effect is also frequency dependent and is stronger with higher frequencies. It is particularly noticeable above 11 GHz (K_u and K_a bands)

These effects can give loss at 20 dB and more, but at relatively low probability. The effects are, as stated above, dependent on position on Earth and other factors, such as time of year and solar activity. The total power link budget for satellites will take these effects into consideration and will normally provide better power margins for the most affected frequencies.

Other examples of environmental degradation factors for radio communication are listed below [Pratt02]. These factors are normally relatively small, but can have significance in some cases.

- *Ionospheric losses:* Mostly for lower frequency signals and vary considerably with time of day and sunspot activity.
- *Beam dissipation:* Loss due to the spreading of signals passing through the atmosphere.
- *Polarization loss:* Losses due to rotation of the signal passing through atmosphere.
- *Rayleigh fading:* Interference between main signals and the same signal arriving through other paths through the atmosphere.
- *Doppler effects:* If the sender is moving at high speeds relative to the receiver, Doppler effects occur that may cause losses in transmission.

Thus, for the analysis in this report, it is scintillation for L-band and rain fading for K_u-band that has been considered. This is further discussed below.

7.4.1 Rain fading

Higher frequencies are in general less robust to rain and sleet, and as a thumb of rule one can say that the attenuation increases with the square of the frequency. That is, signals in the K_a-band (30/20 GHz) are more than four times more attenuated than signals in the K_u-band (14/11 GHz).

One may compensate for such problems, e.g., by using a larger antenna to increase S/N at the receiver or directionality at the transmitter. Systems will also compensate by increasing transmission power in the satellite and the ship terminal.

The rain fading effect also goes into the geographic area consideration as discussed in section 4.3.7. However, in the context of this section we include the general loss of signal or increased error rate as one gets due to rain or snow in any area where signal reception normally would be good.

7.4.2 Ionosphere scintillation

Scintillation is rapid fluctuations of the amplitude and phase of radio waves caused by electron density irregularities in the atmosphere. The effects tend to be more severe for lower frequencies, e.g. VHF to L-band than higher frequencies. The effects also occur most strongly in special areas near the equator and to a lower degree in the aurora areas and near the poles. These effects can cause significant problems for L-band transmissions. Fluctuations of amplitude of more than 20 dB have been measured for GPS signals [Seo08] and for Inmarsat near Equator [Raya07]. This can be expected to be less problematic for higher frequencies such as K_u-band, but it may be noticeable for C-band.

Iridium has a much lower satellite density near equator as well as high transition speeds. Simulations indicate that at equator, there will be in sum about 17 seconds each 24 hours where no satellites are visible at all [Crow99]. This is not a problem during normal operation, but combined with the scintillation effects which may further decrease S/N levels; this may impair Iridium coverage for extended periods. In the arctic area, a much higher satellite density should normally help to alleviate the less intense scintillation effect. It is difficult to find actual measurements of performance in the literature. However, one paper [FS07] discusses the performance of Iridium in the USA. It quotes a percentage of not being able to connect and losing the connection before 3 minutes as 3 and 4 respectively out of 359 attempts in North California and correspondingly 4 and 15 out of 359 in Texas. Both places are at latitude above 30˚N and scintillation is probably not the main cause here. However, it illustrates that there are significant disturbances in communication even at more optimal latitudes.

Note also that L-band transmissions for Inmarsat C and Fleet 77 also will be impaired by scintillation, but the GEO orbit, shorter transit through atmosphere, no problems with Doppler shift effects as well as the possibility to use higher gain antennas may in many cases overcome the problem. However, loss of availability should be expected for these services also.

7.5 Annex E – Calculations of elevation angles and distances

7.5.1 Distance for line of sight communication

The distance over which a line of sight communication link can be used is obviously dependent on the actual line of sight. This in turn is determined by the height over the horizon as illustrated in Figure 11. However, various propagation phenomena can significantly extend the range as other atmospheric phenomena can reduce it. However, this section will briefly present the calculation of the distance.

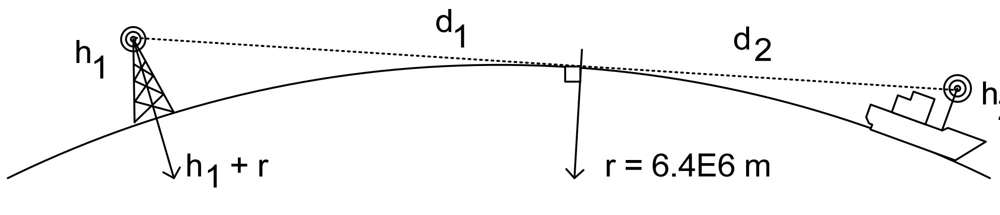

Figure 11 – Range of shore based communication

With reference to the above figure one can see that the distance *d* is one side in a triangle with the earth radius *r* and the antenna height *h* as the other sides. This gives the following simple formula for calculating *d* as function of *h* and the mean Earth radius of 6 371 km.

$$d = \sqrt{h^2 + 2rh} \qquad \text{(Eq. 1)}$$

The result of this calculation is presented in graph form in Figure 2.

7.5.2 Elevation angles for GEO satellite

The obstruction of GEO satellite signals is illustrated in Figure 12. A mountain range of height *h* will obstruct the signal for a distance *d* at latitude θ.

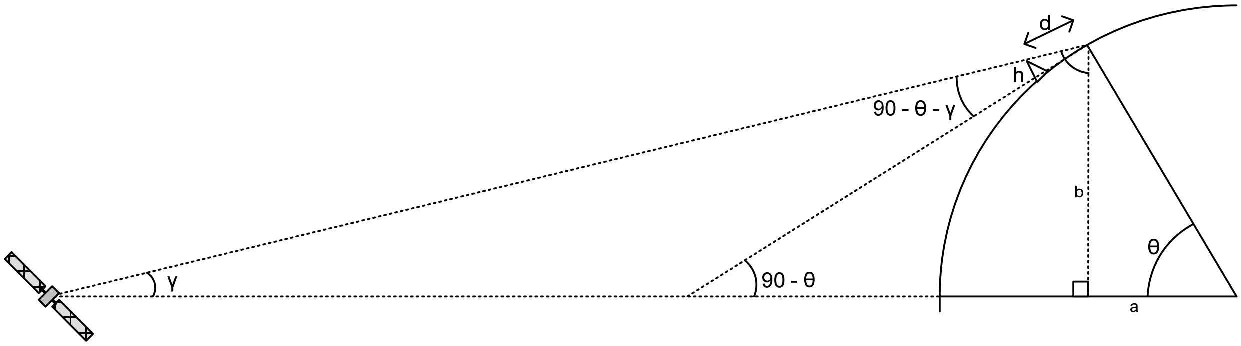

Figure 12 – Obstruction of GEO signal

By using a simplified form of triangulation, one can express *d* as a function of the Earth radius *r*, the latitude α and the distance from Earth centre to GEO orbit *R* as shown in (Eq. 2). The results of this calculation are shown as graphs in Figure 7.

One gets a multiplication factor between obstacle height and distance of 1.6 at 50˚N (Oslo, Norway), 9.0 at 75˚N (Edge of Arctic) and infinity at about 81.3˚N (End of GEO coverage).

$$b = r\sin(\Theta)$$
$$a = r\cos(\Theta)$$

$$\gamma = \arctan\left(\frac{r\sin(\Theta)}{R - r\cos(\Theta)}\right) \qquad \text{(Eq. 2)}$$

$$h = \frac{d}{\tan(90 - \Theta - \gamma)}$$

Note that the formulas do not include the effects of having the satellite at a longitude different from the ship. This will reduce the elevation angle further by increasing the effective latitude θ' as shown in (Eq. 3).

$$\cos(\dot{\Theta}) = \cos(\Theta)\cos(\Phi) \qquad \text{(Eq. 3)}$$

In this formula, the difference between the longitudes of ship and satellite is Φ [Pratt02].

7.6 Annex F – Data from tests with VSAT in sub-arctic areas

In September 2009, the MarSafe North project [MAS09] completed a field study on a VSAT communication solution onboard a vessel on its way from Longyearbyen (78°N 15°E) to Kirkenes (69° N 30° E). The main objective of this field test was to compare real measurements with the theoretical calculations on VSAT performance at high latitudes.

The test conditions were:

- VSAT K_u-band solution with two antennas, one front and one aft.

- The weather was clear (not many clouds), no wind and sea state better than 2.
- The signal-noise ration (E_b/N_0) was measured every 10th minute from Longyearbyen to Kirkenes.

The elevation angle at 75° N for the Intelsat Thor-1 satellite situated at 1° W is 5.75° (see section 4.3.7) while the elevation angle at 70° N is 10.7°. This is still a low elevation angle for VSAT which operates in the K_u-band. However, during good weather conditions and in open sea the signals will be tracked and a relatively good performance can be achieved as is evident in the measurements referred to in the previous section. The challenges occur when the weather is bad, implying large movements on the vessels, and when navigating in fjords surrounded by mountains.

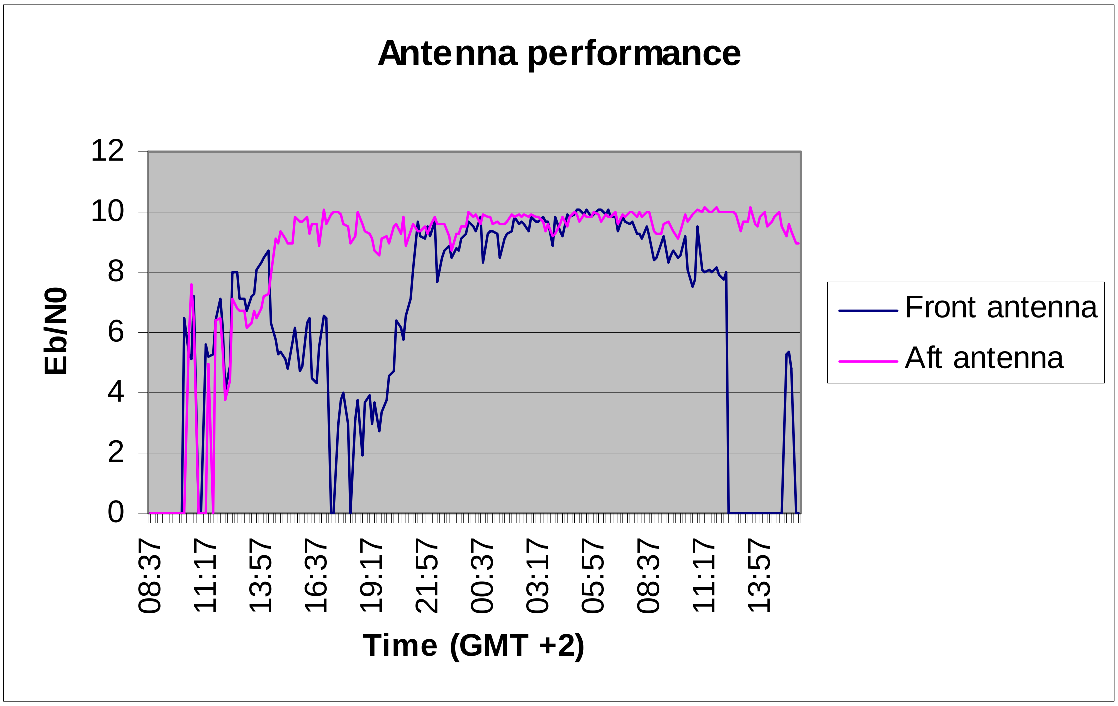

Figure 13 - E_b/N_0 for front and aft VSAT antennas

The measurements are shown in Figure 13. As can be seen, the front antenna shows significantly lower performance than the aft antenna. The exact reason for the bad performance is not known, but it was a know problem for the owners of the vessel. The main observations are:

- VSAT has no coverage in Longyearbyen (78.2° N 15.6° E).
- Satellites starts being tracked by the receivers when the vessel is in the outlet of Isfjorden (78.1° N 13.8° E), but the performance is rather unstable until the vessel reaches the southern parts of Spitsbergen (77.1° N 13.7° E).
- The performance is stable from this point on until it reaches the main land of Norway (71.9° N 27.4 E). However, a decrease in performance is observed when the vessel is passing Bjørnøya (74.9° N 20.3° E).

The reason for lack of signal in Longyearbyen is that this place has mountains in the south that reaches 1050 metres above the sea level and the elevation angle of the VSAT satellite is low

(2.5°). However, another test was run simultaneously on EGNOS, which is using Inmarsat satellites, and showed that EGNOS has indeed coverage in Longyearbyen. This is probably due to the fact that EGNOS uses L-band frequencies (the VSAT solution uses K_u-band frequencies), the antenna is omni-directional (compared to directional for VSAT) and the transmitted messages are relatively small, using a small part of the bandwidth and giving good signal-to-noise ratio. As the mountains still shadow the satellite, one can assume that it is multi-path effects that enable signal reception.

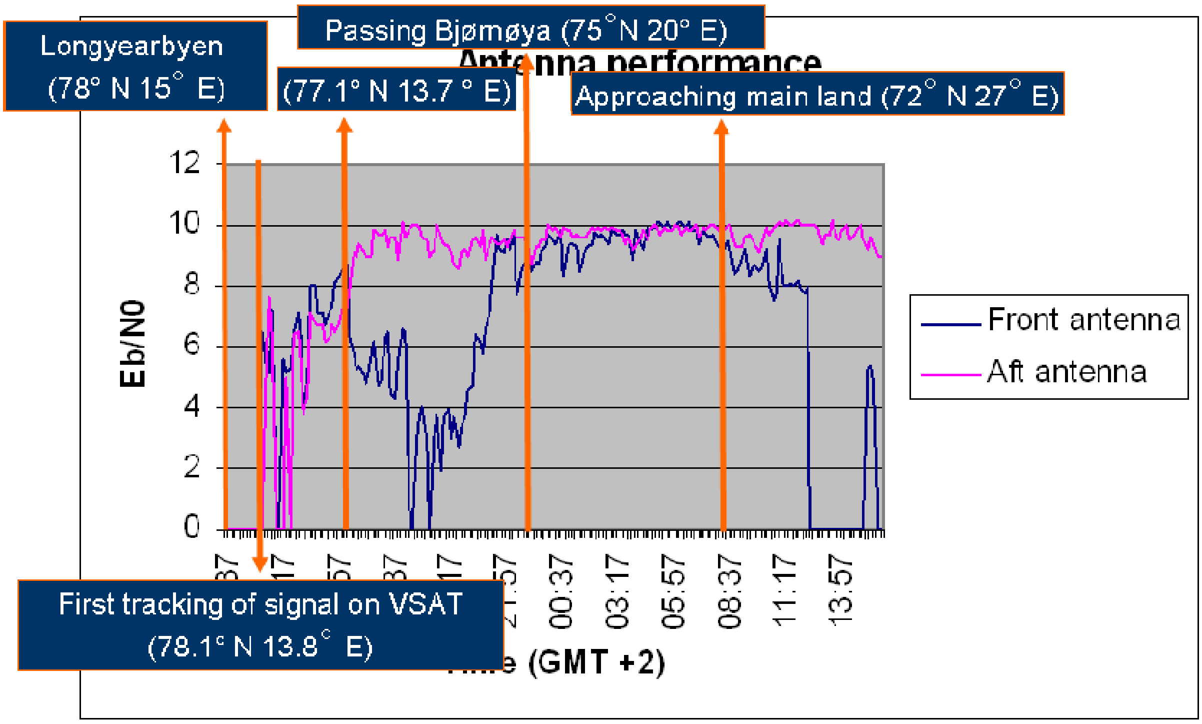

Figure 14 – Annotated measurement plot

There is definitely a potential for improvements on communication solutions in the Arctic. It is expected that climatic changes will lead to increased maritime traffic and more and new types of marine activities in the area, and new communication solutions will be necessary both for safety and operational reasons. Possible technical solutions are e.g. satellites in polar high elliptic orbits (HEO) such as Molniya. Improved infrastructure on land is also a possibility, but perhaps a bit more challenging due to the absence of e.g. power, the remoteness and the harsh environment.

7.7 Annex G – BER and latency effects on TCP/IP

The bit error rate, latency and intermittent loss of connection (in effect, high variance and high mean value on the latency) will impair the quality of transmissions of digital signals. A good overview of these issues can be found in [G.1010]. From this specification, Figure 15 shows a general model for user-centric quality of service categories based on bit error rate and latency.

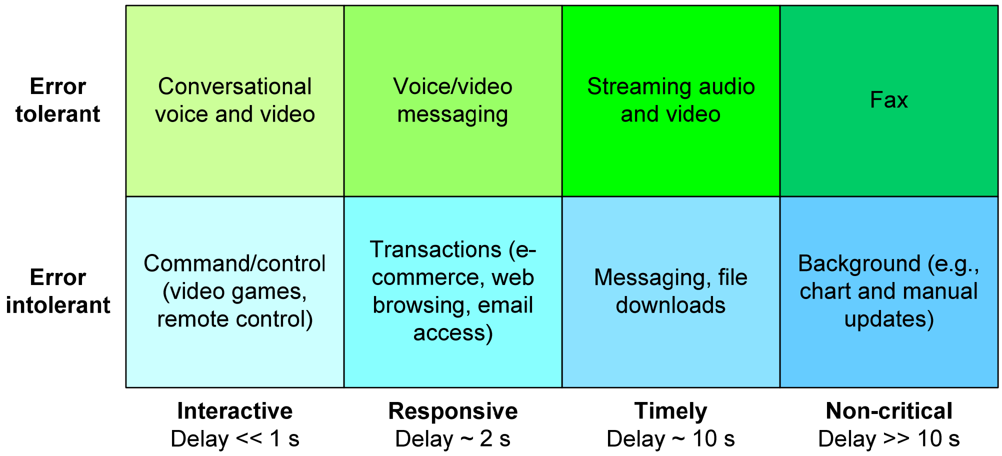

Figure 15 – Model for user-centric QoS categories [G.1010]

Of particular interest is the “error intolerant” transmission types as these require the use of various forms of error correcting protocols. This is partly implemented on low level with error checking and forward error correction schemes on the satellite links, but on higher levels, it typically implies the use of the TCP/IP protocol which is one of the main components of the Internet protocol system. This section will analyze some of the problems related to the use of TCP/IP over high error rate and high latency data links.

One should note that there are special implementations of TCP/IP that alleviates some of these problems. However, these variants require that the same protocol stack is used on both sides.

7.7.1 Bit Error Rate (BER)

BER is the probability of receiving an erroneous bit in the bit stream received. That is, the probability that a 0 is received as a 1, or opposite. The BER is a function of the energy per bit over power spectral density (Eb/N0) which is a measure of the signal to noise ratio which in turn is directly related to the environmental degradation of the signal.

The effects of the BER will vary with the applications. As an example, an uncompressed digital voice channel will normally tolerate fairly high BER levels while a TCP/IP connection, which is normally used in Internet communications, is much more sensitive to errors in the transmission. Thus, the user should consider the typical usage scenario when selecting a carrier. A carrier would normally be specified with a nominal BER which is dependent on geographic location, antenna size and frequencies used. Factors such as environmental disturbances will further increase the BER.

7.7.2 Loss of connection

A low signal to noise ratio (high level of disturbances) may also cause complete signal loss for shorter or longer periods. As an example, if the signal is sensitive to rain fading, heavy rain or snow storms in the vicinity of the ship may cause outages.

Other factors such as alignment of the sun and the satellite may cause the signal to disappear in electromagnetic noise. For locations close to the equator this may cause signal loss for about 10 minutes once a year.

Loss of connection can be modelled as a high variance and high mean value latency.

7.7.3 Effects of latency on TCP/IP throughput

TCP/IP is a reliable protocol that automatically resends segments that were lost in transmission. This requires that the receiver periodically acknowledges what data it has successfully received. To do this effectively both parties maintain an estimate of the maximum allowed number of outstanding non-acknowledged bytes. This is called the window. The sender will not send more than the window amount of data before it waits for an acknowledgment from the sender. The window size can also be configured to an overall maximum value. For a data link with limited capacity and long latency, the window size will limit actual throughput as shown in Figure 16 [Lor00].

The Y axis shows the real throughput (nominal is 256 kbps) as a function of round trip delay (seconds) for different window sizes. This shows the effect that the window has on throughput over long latency connections.

One should note that if many concurrent TCP/IP sessions are active, the capacity of the channel can still be utilized up to the maximum bit rate. The described phenomenon will apply to each TCP/IP connection and not to the satellite connection as such.

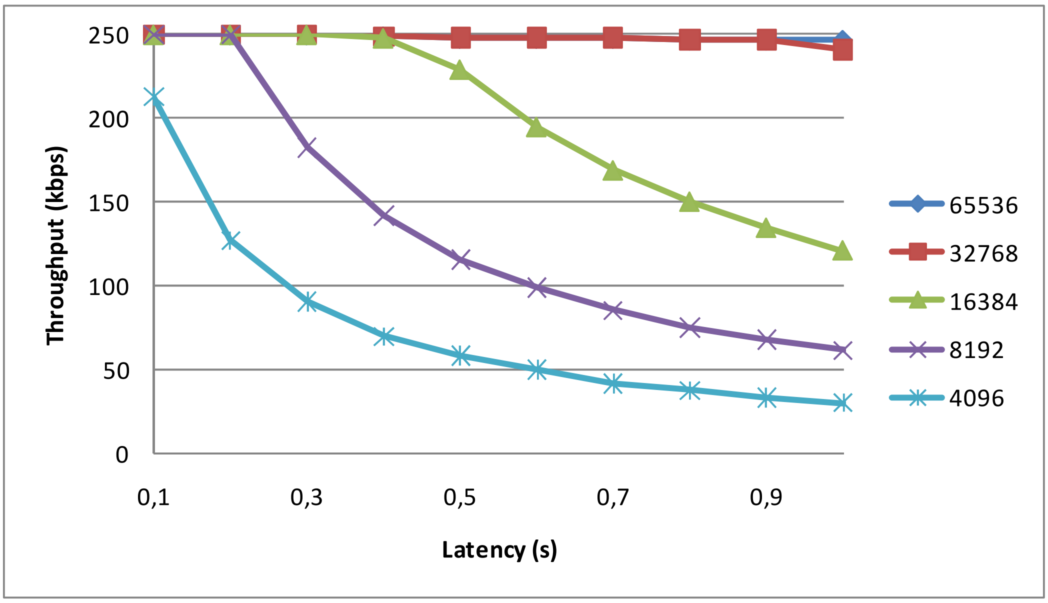

Figure 16 – TCP/IP throughput as function of delay and window size

There are also variants of TCP/IP that provides better throughput in these cases. However, these are not in common use in end user equipment. Transmissions via other protocols than TCP/IP will not see the same effects. This applies, e.g., to Voice over IP and other similar protocols.

7.7.4 Effects of BER on TCP/IP throughput

It seems obvious from the previous section that the window size should be set as high as possible. The drawback of this approach is that errors in transmissions will require retransmission of the whole outstanding window. Thus, with increasing error rates, throughput will fall.

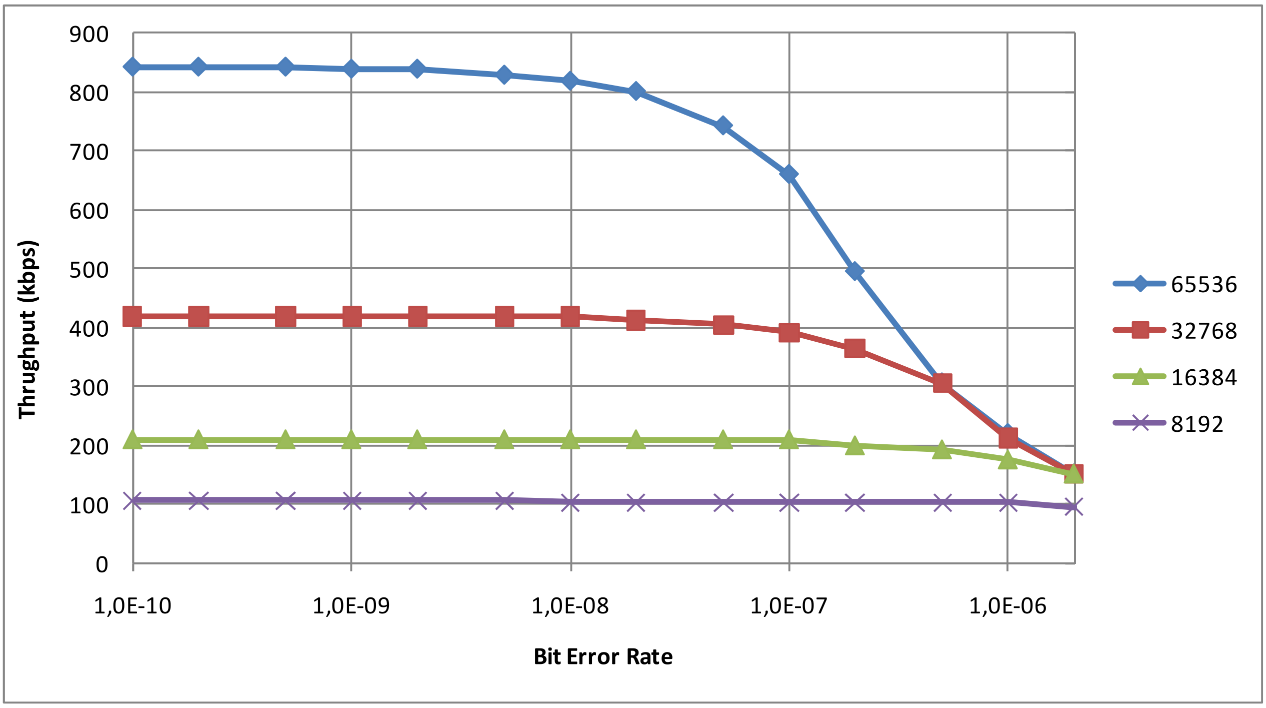

Figure 17 – Effect of error rate on TCP/IP throughput

This is illustrated in Figure 17 [Lor00]. Here the actual throughput is plotted against bit error rate (BER) and window size. The nominal speed is 2048 kbps and roundtrip delay set to 590ms. This is based on an approximate calculation with errors at drop-off points up to 30%.

As one can see, the throughput is mainly limited by the window size up to approximately a BER of 2.0E-08. After that, the curves corresponding to larger windows fall dramatically. One can see, however, that the smaller window size never outperforms the larger. This is due to the automatic resizing of the window performed internally in the TCP/IP stack. More retransmissions will automatically reduce the window size.

Note, however, that the use of Forward Error Correction (FEC) is commonly used in satellite services to reduce the BER. This will reduce available bandwidth, but the overall trade-off is normally in favour of using FEC in any case.

7.8 Annex H – Analysis of failure modes

This section gives details on how a failure mode analysis could be made for the relevant communication systems.

7.8.1 General system block diagram

The technical systems for each of the communication carriers analysed in this report fall into one of the following three classes:

- Satellite communication with omni-directional antenna on ship.
- Satellite communication with stabilized directional antenna on ship.
- Terrestrial communication system where base stations are placed on land or on offshore structures. This will normally use omni-directional antennas on the ship.

The general block diagram for the satellite systems is shown in Figure 18 and for the shore based system in Figure 19.

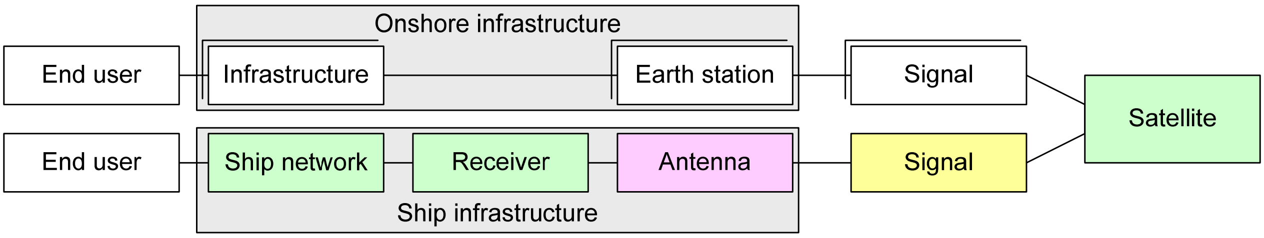

Figure 18 – Block diagram for satellite system

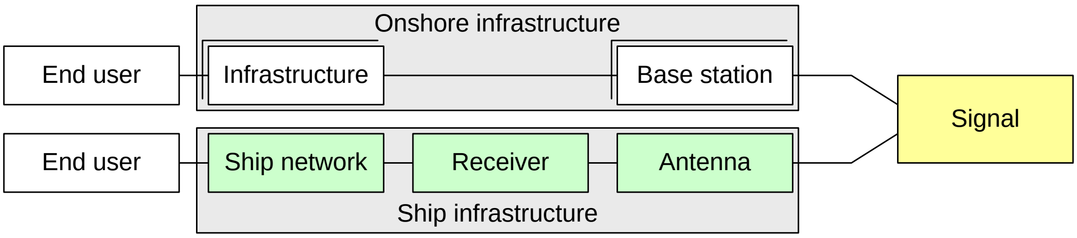

Figure 19 – Block diagram for shore based system

Details of the systems are discussed in the following sub-sections. The yellow blocks represent signal transmissions through atmosphere and were discussed in the previous section as they are not part of the technical system. The white blocks are not discussed at all as they are assumed to have enough safety mechanisms built in to ensure a specified level of availability. This includes redundancy in transmission paths and hardware. The green boxes are discussed, but are in general considered to have relatively high availability and do not warrant any special attention beyond a suitable quality on maintenance and inspections of components. The component that is assumed to potentially have the highest failure rate is the stabilized antenna for GEO satellite systems. This is indicated as a red box in the figure.

The analysis of technical reliability will mainly be qualitative. Maintenance strategies, environmental conditions (e.g. area where ship operates) and other factors affecting the probability of component failure may vary between installations.

7.8.2 On-ship antenna system failure modes – general

The physical structure of antennas, reflectors, mounts and masts are subject to most of the common failure modes for physical structures, such as failure from impact, wear and corrosion. Some of these mechanical failures develop over time, and can be prevented with inspection and maintenance of the installations.

The electronics of the communication system is subject to common failure modes for electronics, such as failures caused by aging of components, design or manufacture faults, excess heat or humidity, power loss or voltage errors, and so on.

Signal cables, power generators and power distribution networks are also subject to well known failure modes, like broken cables, noise on signals or voltage profiles etc.

7.8.3 Stabilized directional antennas

If the antenna is directional, it will need mechanisms stabilizing the antenna to compensate for ship motion, and mechanisms for tracking the satellite, so the antenna is pointed in the right direction. These mechanisms include gyroscopes, sensors, motors and control systems.

Note that such systems are available both for shore based communication and for satellite, but here the discussion will be on stabilized antennas for GEO satellite communication.

The motors and mechanics of the antenna stabilizer and tracker are subject to common failure modes for motorized moving systems, e.g. failure of motors and gears, failure of power electronics, and structural failures. Failures may cause complete lack of stabilization, or the inability to automatically track the satellite.

The control system and sensor electronics may fail as other electronic systems.

The control system software may be subject to software failures. These may be caused by faults in the design or manufacture of the software or the processing hardware, erroneous data from sensors and corruption of data during storage or transmission.

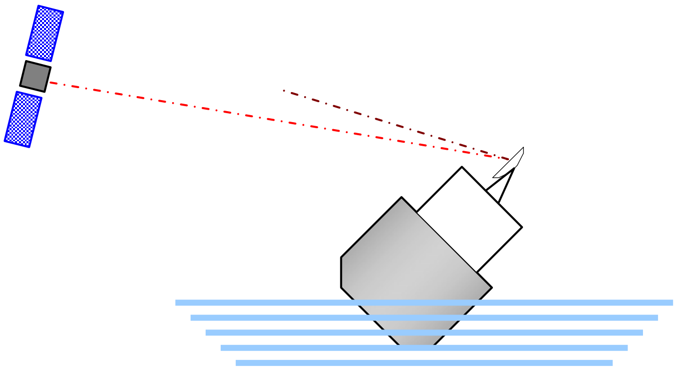

Figure 20 – Loss of satellite tracking due to list

Stabilized antennas also have failure modes related to environmental factors that omni-directional antennas usually not have: If the ship is listing heavily, the direction to the satellite may be outside the operational range of the tracker and stabilizer mechanism. The probability of these failures increase when the direction to the satellite is close to the "edge" of the operational range of the tracker, typically when the satellite is close to the horizon (i.e. when the ship is in sub-arctic waters for geostationary satellites).

Ship antennas will normally have mechanisms to compensate for some operational roll and heave. However, there will be limits to how well these mechanisms can handle situations where the ship is damaged.

There are also failure modes related to buildings, other ships or own ship superstructure that shadows for the free view to the satellite. Again, this is most likely to happen at low elevation angles such as in sub-arctic areas.

7.8.4 Satellite failure modes

The satellites used for communications may also fail, causing the failure of communication. Typically, a satellite is designed with redundant systems, as there is no way to perform normal maintenance on the satellite. The lifetime of a satellite is limited, as there is a limit to how much fuel (for orbit correction) that can be carried. Replacements are typically launched when the end of a satellite's expected lifetime draws near.

For some satellite systems, redundant satellites can be assumed, i.e. the system consists of several satellites that are visible from the same position.

An analysis of a satellite system's failure modes is outside the scope of this report. It can be assumed that the probability of unavailability due to technical failures for most satellite systems is very low.

7.8.5 On-shore communication infrastructure failure modes

On-shore antenna is subject to the same physical and electronics failure modes as on-ship antennas.

For geostationary satellite systems there is no need for tracking and stabilizing, i.e. directional antennas are fixed to point at the satellites when they are installed. This may not be the case for LEO systems where satellites move at high speed and where tracking in some cases may be required.

For satellite systems, it can be assumed that the transmitter/receiver stations and communication infrastructure on shore is highly redundant, and that most failures to the on-shore systems can be ignored in this analysis.

For terrestrial communication systems, the number of "visible" transmitter/receiver stations is limited, but the stations are usually built with some redundancy. Stations with redundant systems may still fail due to extreme situations like natural disasters.

7.8.6 Non-silent failures of communication equipment

Most of the technical failure modes described above will typically result in a "fail to silent" in the communication. These are failure modes that are reasonably easy to detect and handle. Typically, one would use redundancy to have alternative means for communication in such cases.

However, it is also possible that some equipment have non-silent failure modes, e.g. that the equipment corrupts data or generates false data. Non-silent faults may cause failure of communications even if the systems are redundant. These failures will normally be caught by checksums or other integrity checks in the data transmission format.

7.8.7 Satellite communication with omni-directional antenna

For satellite communication where the on-ship antenna is omni-directional, there will be no need for tracking and stabilizing mechanisms.

It can be assumed that the onshore subsystems for the analyzed satellite communication systems have a very high level of redundancy; while single antennas or network links may fail, the probability of complete unavailability due to silent technical failures of antennas or infrastructure is very unlikely.

As the on-ship antenna is omni-directional, there is no need for tracking and stabilizing mechanisms. This means that there are fewer subsystems that can fail when comparing to stabilized antenna systems. Also, the antenna has no moving parts, making it easier to design a robust antenna structure.

7.8.8 Satellite communication with stabilized antenna

A directional antenna on the ship must be stabilized to enable communication. Figure 21 shows a simplified reliability block diagram for the shipboard antenna component of the satellite communication systems when using a stabilized on-ship antenna.

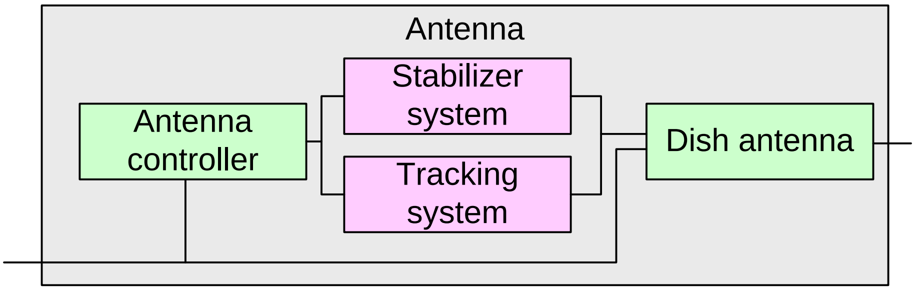

Figure 21 – Detailed stabilized antenna component

As for other satellite systems, the onshore infrastructure can be considered as highly redundant, and the probability that technical failures in the on-shore systems should cause unavailability is low.

The use of a directional antenna makes the on-ship antenna more complicated than for carriers where omni-directional antennas can be used, as the antenna needs to be pointed at the satellite when communicating. This requires both a tracking mechanism that points the antenna in the right direction, and a stabilization mechanism that keeps the antenna base stable and compensates for ship motion.

The tracker will need motors for moving the antenna, sensor systems for keeping track of the satellite position relative to the ship and control systems for controlling the motors. The base of the antenna must be stabilized to counter ship motions, which requires the use of sensors, motors and a control system or gyrostabilizers. Failure of any of the parts of these mechanisms will cause the communication to fail. Generally, since the antenna structure has moving parts, it may have a higher failure probability than a non-moving structure.

7.8.9 Terrestrial radio systems

Terrestrial radio systems will typically use omni-directional antennas on the ship, so there is no need for stabilization mechanisms.

Unlike satellite communications, the number of on-shore stations that the ship can communicate with may be few (or even only one), thus a high level of redundancy cannot be assumed. For many of the carriers, the on-shore stations will typically have redundant systems to prevent unavailability, but when redundant systems are co-located (e.g. on the same station or on the same mast), extreme situations like natural disasters may still cause failure of the station.

7.8.10 Shadowing of antenna

Shadow effects occur during certain ship operations, either as an effect of the ship's orientation in relationship to the other party (satellite or land base station) or due to excessive movements, typically roll and pitch. Directional antennas will be much more sensitive to these phenomena than omni-directional antennas.

General instructions for fitting GMDSS equipment will normally require satellite antennas to be fitted so that they have a free view of the satellite also when the ship rolls (15˚) and pitches (5˚) [MCA05]. However, stabilized antennas normally will be less able to tolerate ship movements, particularly at high latitudes. The stabilized antenna is also more directionally sensitive so it will be more likely to be shadowed by other objects.

Iridium OpenPort should in general be relatively tolerant of shadow effects as long as more than one satellite is in view. It uses a solid state antenna with a number of elements placed inside a relatively small dome. However, as it is not in general able to see below the horizon, it will be more susceptible to ship roll. Note also that Iridium has lower satellite coverage closer to equator.

It is at this stage not clear how WiMAX will perform in this setting, but it is expected that the system should be tolerant to shadow effects.

7.8.11 Electromagnetic Compatibility (EMC)

Most ship communication equipment operates with very low input signal levels and is sensitive to electromagnetic noise from other equipment. This may be other VHF or satellite transmitters, short or medium wave radio and in particular radar equipment which operates with very high output effects.

However, such problems should be discovered during commissioning and should not be a variable during operation. Thus, these effects are considered irrelevant for this analysis.