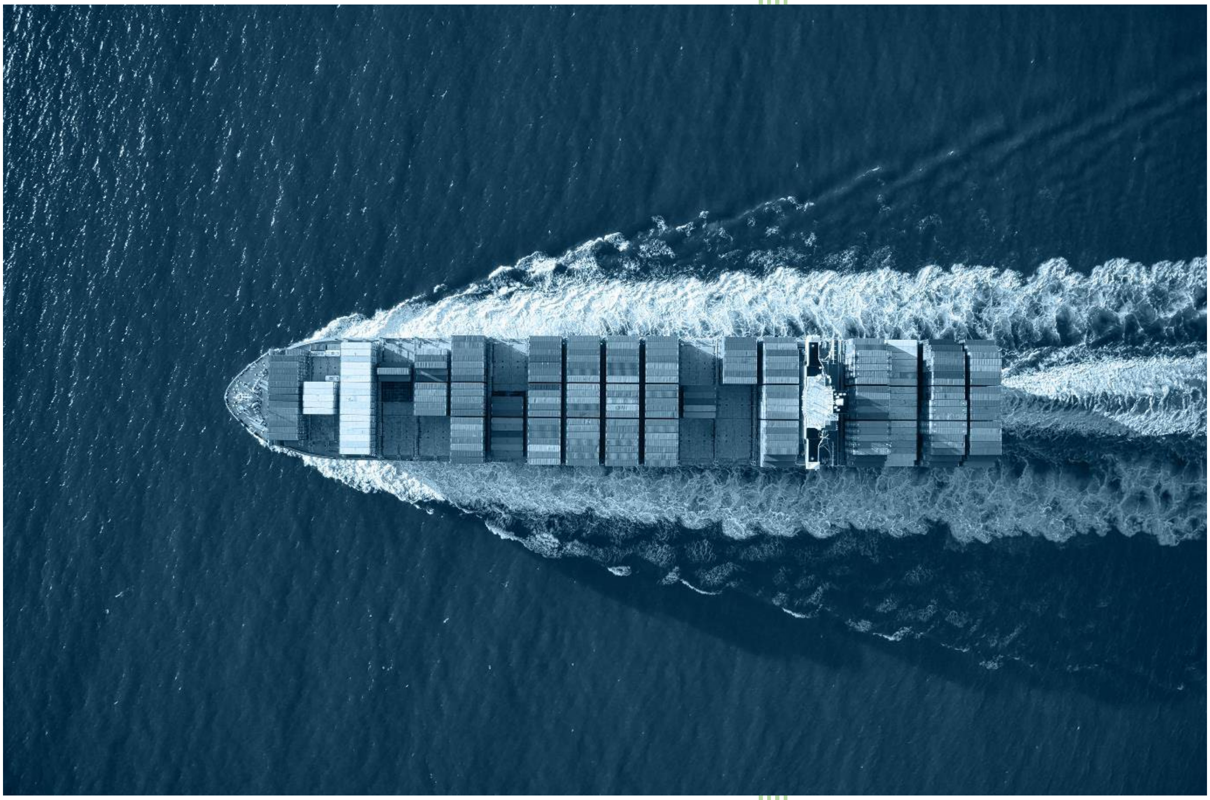
ADMO Deliverable 2.1 - Report on the state-of-the-art of the ship external connectivity



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Introduction

This deliverable discusses the current state of ship external connectivity, focusing on technologies enabling secure and seamless communication for vessels at sea.

Maritime connectivity uses various technologies, each catering to specific communication needs, safety requirements, and operational efficiency. Fundamental technologies like VHF Systems, including VHF Voice and the Automatic Identification System (AIS), are integral to maritime operations. The emerging VHF Data Exchange System (VDES), with terrestrial and satellite components, enhances data transmission and situational awareness. Medium Frequency (MF) and High Frequency (HF) communications are crucial for long-distance communication, while the integration of 4G and 5G networks into maritime connectivity shows the industry's efforts to use terrestrial infrastructure for improved communication.

Satellite communication, from Geosynchronous Satellites to Medium Earth Orbit (MEO) and Low Earth Orbit (LEO) Satellites, addresses global coverage and high mobility challenges, providing essential links for vessels in remote areas and on long voyages.

This report provides an overview of the technologies empowering maritime connectivity, their advantages, challenges, and their role in the modern maritime ecosystem. Understanding these technologies helps appreciate how ships stay connected in an interconnected world, serving as a baseline for future development of technologies like 5G-Advanced.

VHF Systems

VHF and VHF Voice

Use of VHF band 156 MHz – 162 MHz for maritime communication started in the 1940's and 1950's, the first frequency allocations were done in 1947 by ITU-R (then CCIR). In 1959 appendix 18 was added to the radio regulations (RR). This appendix (in updated versions) is still today the main regulatory document defining the frequency allocation for various applications using the maritime VHF band. Originally in 1959 the band was divided to 28 channels with 50 kHz channel spacing. The used mode was FM voice. During the 70's and 80's the channel spacing was gradually changed to 25 kHz with maximum deviation of ± 5 kHz. This change enabled addition of channels 60 to 88 by splitting the original channels resulting the slightly odd numbering of the channels still today. The frequency arrangements of the current Appendix 18 are shown in Figure 1.

Some of the channels are two frequency channels, the higher part (160 to 162 MHz band) used for coastal transmitting and the lower part (156 to 157.5 MHz band) for ship transmitting enabling duplex mode. Some of the one frequency channels (70, 75, 16 and 76) are allocated exclusive to maritime distress, safety and calling.

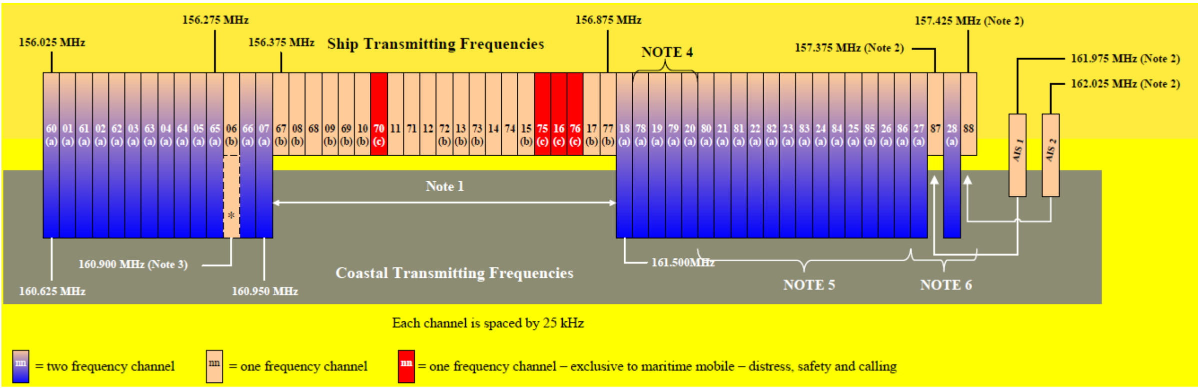

Figure 1 Frequency arrangements of maritime VHF band

The automatic identification system (AIS) channel AIS1 and AIS2 were added to the RR Appendix 18 in WRC 1997. More of the AIS below.

More recently in WRC 2012 the channels 80, 21, 81, 22, 82, 23, 83, 24, 84, 25, 85, 26, 86 were allowed to be used for new technologies and from 2017 these channels are identified for the utilization of the digital systems described in the most recent version of Recommendation ITU-R M.1842. Since that ITU has produced recommendation ITU-R M.2092-1, which describes the VHF data exchange system (VDES). Also this is explained more in detail below.

Outside the distress (GMDSS) the basic VHF voice is used for various applications:

- Use of dedicated channels for the control of, mainly local, incidents such as oil spills;
- Use of dedicated channels for on-board use;
- Use of channels for port control and ship movement;
- Use of channels for communication between ships;
- Use of channels for public correspondence (“link calls” via the PSTN);

The last was originally the service that enabled shipping to make telephone calls via local coastal radio stations to public telephone network (PSTN), but this service has been largely replaced by mobile cellular and mobile satellite systems and is not anymore supported by many coastal stations.

AIS

The automatic identification system (AIS) is an automatic tracking system that uses VHF transceivers on ships. The purpose of the AIS is to enable ships to see other ships on their area and to be seen by other ships and thus avoiding collisions. However, AIS is not an automatic collision avoidance system, but provides information to the ship personnel. Using shore-based receivers authorities like Vessel Traffic Services (VTS) and other instances can also see local traffic within the coverage range of the receivers.

AIS was originally using terrestrial marine VHF radio with channels 87 and 88 (AIS1 161.975 MHz and AIS2 162.025 MHz), but has since been extended so that the same frequencies can be received by satellites (AIS-S) when the ships are outside the range of coastal AIS (AIS-T) receivers.

Ships will have a VHF transceiver that automatically broadcasts at regular intervals information of the vessel’s position, speed, navigational status, name, call sign etc. Navigation information is obtained typically from GNSS receiver and other ships sensors like gyrocompass. AIS signals are received by AIS transceivers fitted on other ships or on shore-based transceivers. Received information can be displayed on a screen or chart plotter, showing the other vessels' positions. AIS range is limited to the VHF range nominally 10–20 nautical miles (19-37 km) but can be extended by repeaters. AIS is required on international voyaging ships with 300 or more tons, and all passenger ships. Nowadays also many smaller leisure vessels have AIS transceivers.

The radio resource allocation in AIS is based on self-organized time division multiple access (SOTDMA) in Class A transceivers and carrier sensing TDMA (CSTDMA) in the simpler Class B transceivers. SOTDMA transceivers are required to maintain in the device memory updated slot map of the other devices in the radio range while Class B CSTDMA transceivers listen slot map just before transmitting and select a free slot. There are also more capable Class B receivers which use SOTDMA.

Each station determines its own transmission schedule (slot), based upon data link traffic history and knowledge of future actions by other stations. A position report from one AIS station fits into one of 2250 time slots established every 60 seconds. AIS stations continuously synchronize themselves to each other, to avoid overlap of slot transmissions. When a station changes its slot assignment, it pre-announces both the new location and the timeout for that location. In this way new stations, including those stations which suddenly come within radio range close to other vessels, will always be received by those vessels, see Figure 2.

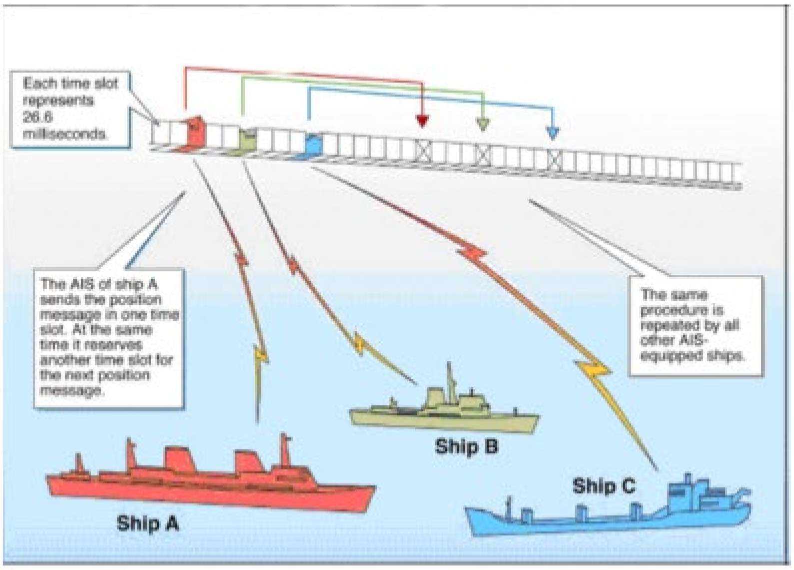

Figure 2 AIS time slot reservation.

The non-return-to-zero inverted (NRZI) encoded data is coded with Gaussian Minimum Shift Keying (GMSK) before being frequency modulated in the 25 kHz/12.5 kHz VHF channel (GMSK/FM modulation). Bit-rate is 9600 bit/s. Each AIS slot is 26.66 ms long having 256 bits of which 168 carry data. AIS transceiver has two receivers and one transmitter.

Class A AIS must have an integrated display, transmit at 12.5 W, interface capability with multiple ship systems, and offer a sophisticated selection of features and functions. Default transmit rate is every few seconds.

Class B "CS" AIS transmits at 2 W and is not required to have an integrated display. Default transmit rate is normally every thirty seconds, but this can be varied according to vessel speed or instructions from base stations. The more advanced Class B "SO" AIS transmits at 5W and has a wider range of transmit intervals. In general Class B is intended to be a simpler and cheaper system enabling it to be installed also on smaller vessels.

Receiving AIS signals by satellites will augment the terrestrial coverage. Satellite reception is challenging as the footprint of the satellite is large and would receive signals from a large number of vessels simultaneously. The SOTDMA system is normally taking care that the vessels within the VHF radio range are avoiding slot collisions, but as the satellite sees a much wider area, there will be vessels using the same slots simultaneously causing interference. However, improved technology and high number of satellites in relatively low orbits has improved the performance of satellite AIS.

AIS has been amended by Application Specific Message (ASM) system adding two VHF channels 27 and 28 and using higher modulation (π/4QPSK) and achieving 19200 bit/s.

Publicly available ship monitoring websites rely on largely unauthenticated data feeds from volunteer-operated AIS receiver networks.

VDES

VHF Data Exchange System (VDES) is the most recent technology to be using the maritime VHF band. AIS system is capable of transmitting data to vessels but having only two channels (4 with ASM1 and ASM2) could lead to overloading of the system. To prevent this, a new digital system -VDES- with higher capacity has been developed. VDES is building over the AIS and ASM systems and these can be now considered to be part of the VDES. The development phases are shown in Figure 3.

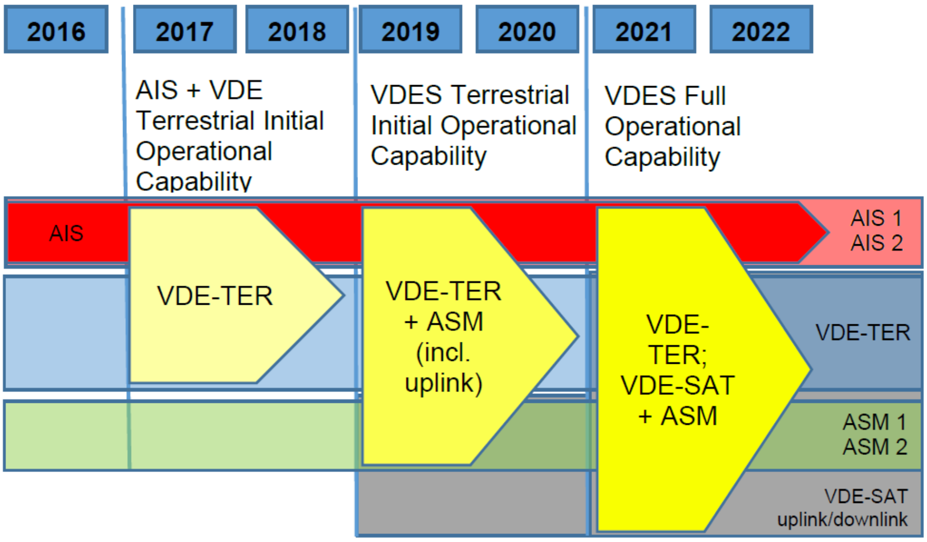

Figure 3 VDES development phases

VDES can be used to communicate:

- a specific vessel (addressed)
- all units in the vicinity (broadcast)
- a group of vessels (addressed)
- a fleet of vessels (addressed).

Terrestrial VDES (VDE-TER) has four two-way 25 kHz channels 24, 84, 25 and 85 available. These can also be grouped to 50 kHz or 100 kHz bandwidths. In addition, for satellite VDES (VDE-SAT) two two-way channels 26 and 86 are available. Detailed list of the frequencies used is given in Table 1.
VDES uses π/4QPSK or 16 Quadrature Amplitude Modulation (16QAM) and forward error correction (FEC) and can provide bit rates up to 307 kbit/s, 32 times more than was possible with AIS. VDE has been designed to co-exist with AIS as not to interfere with AIS. VDE-ASM is intended to move ASM traffic away from the existing AIS channels to improve safety at sea.

The slot structure of the VDES is the same as in AIS and ASM comprising of 2250 slots per RF-channel. AIS and ASM are now considers to be part of the VDES as shown in Figure 4.

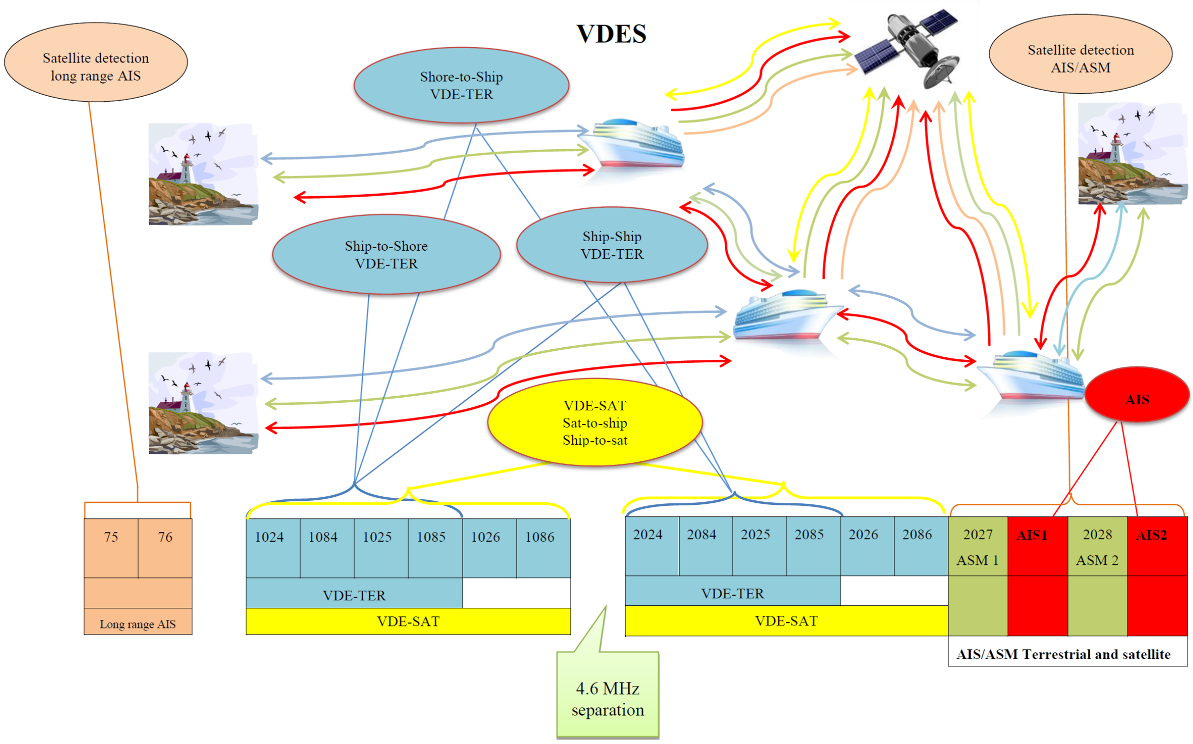

Figure 4 VDES System and frequency arrangements

Table 1 Frequencies allocated to VDES

Technology	Radio Frequencies used	Radio Regulations channel number
AIS 1	161.975 (25kHz)	2087
AIS 2	162.025 (25kHz)	2088
AIS Long Range 1	156.775 (25kHz) (ships are TX only)	75
AIS Long range 2	156.825 (25kHz) (ships are TX only)	76
ASM 1	161.950 (25kHz)	2027
ASM 2	162.000 (25kHz)	2028
VDE-TER (lower leg)	157.200 to 157.275 (100kHz)	1024, 1084, 1025 and 1085 combined
VDE-TER (upper leg)	161.800 to 161.875 (100kHz)	2024, 2084, 2025 and 2085 combined
VDE-SAT (lower leg)	157.200 to 157.325 (150kHz)	1024, 1084, 1025, 1085, 1026 and 1086 combined
VDE-SAT (upper leg)	161.800 to 161.925 (150kHz)	2024, 2084, 2025, 2085, 2026 and 2086 combined

VDE-TER

Terrestrial VDE Channel resources are managed as logical channels. One of 5 logical channels are dynamically allocated to carry the data in the User Data Channel (UDCH). The Terrestrial Bulletin Board (TBB), Assignment Channel (ASC) and Random Access Channel (RACH) are defined too ensure that the VDE channel is optimally used to carry user data.
A ship station requests access to a logical channel from the Control Station when it needs to transfer data over VDE. The logical channels have been designed in such a way that a VDES terminal can provide both VDE and AIS functionality without affecting AIS. Multiple terminals can simultaneously transmit using a TDMA access scheme that makes optimum use of the available resources.

The Random Access Channel is used to request resources and can also be used for small data messages allowing the User Data Channels to be available for larger messages.

The User Data Channel is allocated to the ship station for a fixed period. The user can continue to request the resource for as long as it has data to transmit. This is done in an optimal way on the Data Channel without having to use the Random Access Channel again. The Control Station determines if the request is granted or not.

The VDE control station transmits the TBB at the start of a frame. VDE-TER frame is one minute in duration and comprises 2250 slots.

When a ship station is outside the service area of a control station, the ship can transmit data directly to another ship using ship to ship mode.

VDE-SAT

Satellite VDE Channel resources are managed as logical channels to carry link layer and user data between the Control Station on the Satellite and the Ship Stations.

Logical channels are the Satellite Bulletin Board (SBB), Assignment Channel (ASC), Data Channels for broadcast and addressed data in up- and downlink direction, and Random Access Channel (RACH) are defined to ensure that the VDE channel is optimally used to carry user data.

A ship station requests access to a logical channel from the satellite Control Station when it needs to transfer data over VDE-SAT.

The Random Access Channel is used to request resources and can also be used for small data messages allowing the User Data Channels to be available for larger messages.

A User Data Channel is allocated to a ship station for a fixed period. The user can continue to request the resource for as long as it has data to transmit. This is done in an optimal way on the Data Channel without having to use the Random Access Channel again. The Control Station determines if the request is granted or not.

The VDE-SAT control station transmits the SBB at the start of a frame. VDE-SAT frame is one minute in duration and comprises 2250 slots.

An orthogonalization technique is used to distinguish transmissions from different VDE satellites, should these happen simultaneously. Transmissions from ships are always directed to a specific VDE satellite

VDES R-Mode

VDES R-Mode is developed to be integrated to VDE-TER to be used as backup system for satellite positioning systems (GNSS).

The VDES R-Mode System will send accurately timed VHF transmissions from a network of land-based and, possibly, offshore Base Stations (BSs). A shipborne VDES R-Mode Sensor (VRMS) will measure the timing parameters of the received signals and output the signal observables to an external PNT-processor (Positioning, Navigation and Timing), which will then use the information to determine the user's position, speed over ground and other navigation parameters.

R-Mode should, as far as possible, use pre-existing shore side infrastructure and will be synchronized to an external Time Source traceable to a common time scale in order to facilitate interoperability with other PNT systems.

The R-Mode system consists in general of the following components:

- R-Mode transmitter station: A station that provides R-Mode service. It is intended to use existing VDES base stations.
- R-Mode monitor: Station that monitors broadcasted signals of R-Mode transmitter.
- R-Mode system time (RMST: Time distribution infrastructure that provides in a region the RMST which is used for R-Mode service provision.
- Command and control, Security center is a central infrastructure of a region that is used to control and command the complete network. It provides a security service for the R-Mode system and service.
- R-Mode user: User of R-Mode service.

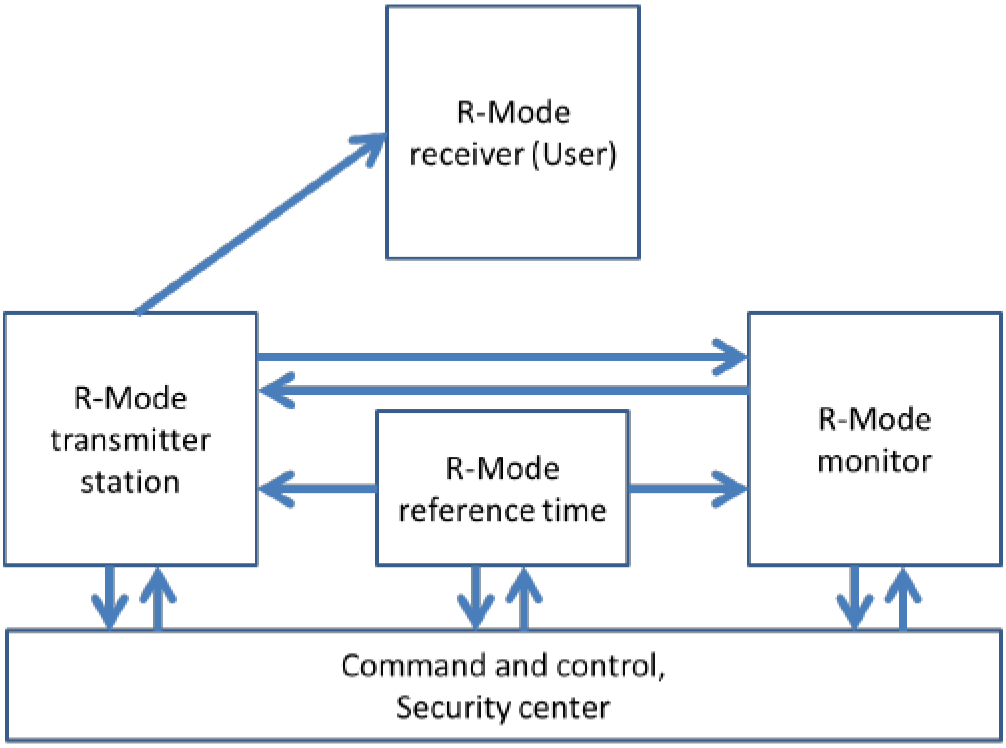

Figure 5 R-Mode logical architecture

The physical layer of the R-Mode application requires a ranging sequence and additional navigation data to determine the distance between VDES R-Mode base stations, transmitters, and receiver. The ranging sequence is predefined and adapted by the network depending on the expected coverage areas. VDE-TER schedules the resources based on a TDMA scheme between VDES base stations that are coordinated by the network provider. The VDES R-Mode base stations shall transmit their ranging sequence every second and additional navigation data every minute.

MF and HF communications

Medium Frequency (MF) (300 kHz- 3MHz) and High Frequency (HF) (3-30 MHz) have traditionally been used in ship communications over very long distances due to the propagation properties. At these frequencies the radio waves are reflected from the ionosphere making communication around the world possible. However, the reflections depend on the time of day giving different propagation at different frequencies during day and night. Therefore, a suitable frequency should be selected for depending on the location of the stations and time of day. Lower frequencies will also propagate with ground wave.

The frequencies used for marine communications at bands 2, 4, 6, 8, 12, 16, 18, 22 and 25 MHz are regulated by ITU. Channel raster is 3 KHz and voice communication is with USB (upper sideband). Some channels are for simplex and some for duplex (channel pairs) communication. Uses are ship to ship, ship to shore and distress messaging.

Duplex for ship to shore were used for making telephone calls via shore stations, but today there are very few if any shore stations providing such a service as satellite has replaced this.

Digital software defined radios (SDR) and cognitive radio technology have brought new life to MF/HF marine communication. The Finnish KNL (former Kyynel) has developed Cognitive Networked HF Radio (CNHF), which can intelligently detect whether any portion of the spectrum is in use and can temporarily use it without interfering with the transmissions of other users. CNHF solution receives the whole HF spectrum at once with thousands of simultaneously listened calling channels. Several KNL radios can form a mesh network. KNL was acquired by Telenor, which markets the KNL CNHF radio for maritime use as WaveAccess HF Radio. Some features:

- Bandwidth: up to 48 kHz
- Modulations: BPSK - 256QAM
- FEC
- Data rates: up to 300 kbit/s
- ALE: GNSS independent cognitive ALE with more than 2500 calling channels listened simultaneously
- ARQ & Non-ARQ modes
- Unicast, multicast, broadcast
- Multihop
- Analog SSB (J3E), CW.

4G and 5G Mobile networks

4G (LTE) and more recently 5G have revolutionized mobile (and even fixed) data communication on land based terrestrial use providing in best case hundreds of Mbit/s bit rates and almost universal coverage. This has increased interest in using mobile networks also for maritime, especially due to increased requirements for high-speed data in many new applications like remote operations.

LTE is using OFDM for downlink and SC-FDMA for uplink with maximum bandwidth of 20 MHz giving theoretical bit rates of 300 Mbit/s for DL and 75 Mbit/s uplink. However, in practice the maximum bitrates are lower, in many cases in the order of 100 Mbit/s and 20 Mbit/s for a 20 MHz bandwidth. In addition, these are maximum bitrates of a cell and are shared with all the users in the cell area and in a congested cell the bit rates may drop to a few Mbit/s or even lower. LTE can use FDMA or TDMA depending on the used frequency band. LTE has been deployed on many different bands from 700/800 MHz (B20/B28), 1800 MHz (B3), 2100 (B1), 2300 (B40) to 2600 MHz (B7). For maritime use (as for any rural area) probably the most important are the low frequencies (700/800 MHz) as the propagation is much better than at higher frequencies, which are mainly used to cover densely populated areas with smaller cell sizes. For large rural and archipelago areas the lower frequencies provide possibilities for much larger cell sizes thus resulting in more economical network deployment. The downside of this is that in a large cell the number of users can also be high and the bitrate per user drops. Especially if a large passenger ship, with thousands of users comes to a coverage area of a single cell, the drop of bitrates can be dramatic.

5G is in many ways very similar to 4G/LTE, but has more flexibility, many improvements and new features. Bandwidths up to 100 MHz and higher are used increasing the theoretical bitrates up to 1 Gbit/s (3.5 GHz band), although in practice the maximum bitrates are lower in the order of few hundred Mbit/s. 5G was deployed first in the 3.5 GHz band (n77, n78), now going also to 26 GHz band and more importantly from the maritime use point to 700 MHz band (n28). However, the larger bandwidths in the order of 100 MHz are not available at the 700 MHz band, and 5G is using the same 10 MHz bandwidth as the low frequency LTE. Therefore, the advertised high bitrates are not available on the 700 MHz rural deployments. Still 5G will give an improvement over the LTE.

Although radio propagation over the water is typically better than over the land and in many cases line of sight (LOS) conditions apply, the available range from the base station is limited to a few tens of kilometers even using the 700/800 MHz bands. The consequence of this is that mobile network service is limited to coastal waters, giving less range than for example VHF communication. The situation is somewhat different if there is an archipelago, where the mobile networks can be built using the islands. In this case the backhaul network may be more critical than finding places for the base stations. Population in the islands also forms a basic customer base, so building the network is economically more viable. A good example of this is the archipelago between Turku and Åland, which makes it possible to have an almost full coverage for the sea route between Turku and Stockholm, having only a short gap between Åland and Stockholm archipelago. In general Finnish coastal waters are fairly well covered due to large number of islands. Table 2 gives some properties of the different mobile bands. For the range of the lower 700/800 MHz frequencies a higher upper limit has been added to reflect the better propagation over water.

Table 2: 4G/5G properties at different bands (Source: Traficom-Viestintäverkkojen kustannusselvitys)

Band [MHz]	Technology [4G/5G]	Range [km]	Bandwidth [MHz]	Mode [FDD/TDD]	DL bitrate [Mbit/s]	UL bitrate [Mbit/s]
700	5G	10-30	10	TDD	110	55
800	4G	10-20	10	FDD	75	25
900	4G	10	10	FDD	75	25
1800	4G	5	20	FDD	150	50
2100	4G	4	20	FDD	150	50
2600	4G	2	20	TDD	150	50
3500	5G	2	130	TDD	1200	400
26000	5G	0.5	800	TDD	8800	3000

For critical communication it is possible to use multi-channel routers, which use several operators simultaneously (multiple SIMs), always selecting the best for data. However, in rural areas operators are often using the same infra (masts), so the benefit could be somewhat reduced.

LTE maritime communication system has been studied in Korea as a research project with the aim to provide high speed data in coastal waters. Having a base station at 350m high mountain a range of 75 km has been achieved[1].

5G has been specified also for satellite use. It would provide coverage also in areas where the land-based network can't, i.e. open seas. However, satellite access has very different latency and bandwidth characteristics compared to terrestrial 5G and could be compared in this respect more with the other satellite systems. It remains to be seen what effect this could have on maritime use and how it compares with other existing and emerging satellite systems.

5G also has a possibility for Side link, where ships could communicate directly with each other using 5G technology.

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[1] A Validation of Field Test Results for LTE-Maritime - https://www.sciencedirect.com/science/article/pii/S2405896318321748

Satellite communications

Satellite communications can provide almost seamless coverage all over the world, somewhat depending on the satellite system used. Satellites can be divided by the used orbit to Low Earth Orbit (LEO), Medium Earth Orbit (MEO), High Earth Orbit (HEO) and Geosynchronous Equatorial Orbit (GEO). For maritime use the most relevant probably are Geosynchronous and new LEO systems which will have a huge number of orbiting satellites to enable continuous coverage in large areas. Figure 6 gives an overview of the various satellite systems.

	GEO (~36,000 km)	MEO (~8,000 km)	LEO (~1,000 km)
Latency	Medium (~700 m/s)	Low (~150 m/s)	Very low (~50 m/s)
Network size for global services	3 satellites (99% coverage)	6 satellites (96% coverage)	Thousands of satellites (100% coverage)
Data gateways required	Few, fixed	Several, flexible	Numerous, local
Technology readiness level	Proven, deployable technology	Proven, deployable technology	Technology still in development for satellite internet
Cost to deploy network	$1 - 1½bn	Approx. $1½bn	$5 - 15bn
Satellite design life (replacement cycle)	15 years	12 years	5 - 7 years

Figure 6 GEO, MEO and LEO Satellite, source:dgtlinfra.com

Geosynchronous satellites

Geosynchronous satellites orbit earth at 35 786 km height with an orbital period that matches Earth's rotation. Therefore, the satellites seem to be in a fixed position in the sky. Theoretically just 3 satellites would provide full coverage, but in practice the operators like Inmarsat have more satellites (4 series-4 satellites and 5 series-5 satellites, with series-6 starting and some series-3 still in backup use). Although one satellite can cover 1/3 of the globe with just a single beam, in practice there are several beams targeting for smaller areas and thus easing up the link budget (higher received power=> smaller antenna). Partly due to the height of the satellite the latency for any GEO system is rather high, claimed to be in the order of 700 ms (one signal roundtrip is 2x36e6m/3e8m/s = 240 ms). Whether this is a problem or not depends on the application, but for general ship data communication latency is not a big issue. Even if the satellites seem to be at fixed position a moving (and rolling etc.) ship needs a tracking system on the satellite antenna. For larger antennas tracking accuracy must be better as the antenna beamwidth is smaller.

Satellites communicate with ground stations (gateways), which controls the satellites and connects the satellite network to other communication networks. GEO satellite constellations only need a few gateways on earth.

GEO satellites have a long lifetime mainly limited by the amount of fuel for thrusters that are used for station-keeping (maintaining orbit). Non-operational GEO satellites must have enough fuel to raise the orbit by several hundred km to a graveyard orbit.

For marine use probably the best-known GEO satellite operator is Inmarsat, originally an intergovernmental organization intended to provide maritime satellite services. It was privatized in 1999. Other GEO satellite operators providing maritime satellite services are Intelsat, Eutelsat, SES and Telenor (Thor 7 satellite). There are also operators, which don't own the satellites, but buy capacity from the satellite operating companies. An example of this is Vizada, an EADS owned operator, which provides both mobile and fixed satellite telecommunications to markets including merchant shipping.

As an example, the Inmarsat satellites provide the following coverages:

- Global beam coverage
  Each satellite is equipped with a single global beam that covers up to one-third of the Earth's surface, apart from the poles.
- Regional spot beam coverage
  Each regional beam covers a fraction of the area covered by a global beam, but collectively all of the regional beams offer virtually the same coverage as the global beams. Use of regional beams allow user terminals to operate with significantly smaller antennas. Regional beams were introduced with the I-3 satellites. Each I-3 satellite provides four to six spot beams; each I-4 satellite provides 19 regional beams.
- Narrow spot beam coverage
  Narrow beams are offered by the three Inmarsat-4 satellites. Narrow beams vary in size, tend to be several hundred kilometers across. The narrow beams, while much smaller than the global or regional beams, are far more numerous and hence offer the same global coverage. Narrow spot beams allow yet smaller antennas and much higher data rates. They form the backbone of Inmarsat's handheld (GSPS) and broadband services (BGAN).

This coverage was introduced with the I-4 satellites. Each I-4 satellite provides around 200 narrow spot beams.

- Global Xpress (I-5)
  The Inmarsat I-5 satellites provide global coverage using four geostationary satellites. Each satellite supports 89 beams, giving a total coverage of approximately one-third of the Earth's surface per satellite. In addition, 6 steerable beams are available per satellite, which may be moved to provide higher capacity to selected locations.

With these beams using L- (1-2 GHz), S- (2-4 GHz) and Ka-Bands (27-40 GHz), the satellites can provide a multitude of services ranging from global voice services (4.8 kbit/s) to Broadband Global Area Network (BGAN), a shared-channel IP packet-switched service of up to 800 kbit/s. FleetBroadband (FB) is similar to BGAN but intended for maritime use. Global Xpress network service with I-5 satellites at Ka-band provides an IP based global service of up to 50 Mbit/s downlink and 5 Mbit/s uplink at a latency of 700 ms.

Medium Earth Orbit Satellites

A medium Earth orbit (MEO) is an Earth-centered orbit with an altitude above a low Earth orbit (LEO) and below a high Earth orbit (HEO) – between 2000 and 35786 km. Well known MEO satellites are the navigation satellites of different systems. Communications satellites in MEO include the O3b with an altitude of 8063 km.

One benefit of MEO satellites is that the latency is significantly better, claimed to be in the order of 150 milliseconds. MEO providers can cover the entire globe with 6 satellites in orbit and have 96% coverage.

An example of MEO satellite service is the SES Networks O3b and forthcoming O3b mPOWER for telecommunications and data backhaul to maritime, aero and remote locations As SES is also GEO operator, they can combine GEO and MEO service combining wide coverage and reliability with MEO satellite constellation's low latency (less than 150 ms) and higher data throughput.

Low Earth Orbit Satellites

LEO satellites orbit around Earth with a period of 128 minutes or less, being in heights of less than 2000 km. Most of the artificial satellites are actually in LEO orbit. The satellite systems intended to provide global communication are typically at heights less than 1000 km. Due to the low orbit the LEO satellites can provide lower latency than GEO or even MEO satellites in the order of 50 ms. As the satellites are moving fast the serving satellite is visible only a short time and connection has to be handed over to the next visible satellite. Therefore, LEO satellite systems has to have a satellite to satellite communication capability. This is either radio or optical in some new Starlink satellites. A large number of satellites are required to have global coverage. This may range from a few tens to thousands and even tens of thousands. Having this kind of number of satellites is claimed to be harmful for astronomy and is also increasing the number of space debris.

The first commercial LEO satellite system intended to provide global coverage initially for voice use with mobile phones was Iridium, originally started as Motorola venture in early 1990's. It was intended to have 77 satellites (thus the name Iridium), but eventually the constellation of 66 active satellites at 781 km height at six orbital planes spaced 30° apart, with 11 satellites in each plane and some spares. The satellites orbit from pole to same pole with an orbital period of roughly 100 minutes, giving good service coverage especially at the North and South poles. The system was operational in 1998 with global coverage in 2002 but failed commercially leading to bankruptcy. No new satellites were launched between 2002 and 2017. A company continued to operate the satellites and developed a different strategy, offering communication services to a niche market of customers who required reliable services in areas not covered by other services. Since 2017 Iridium has launched 75 new satellites, with more to come. Currently Iridium provides L-band voice and data to satellite phones and data terminals globally.

As a satellite can only be in view of a terminal for about 7 minutes, the handover to another satellite has to be done automatically. Satellites communicate with neighboring satellites via Ka-band inter-satellite links. Each satellite can have four inter-satellite links: one each to neighbors fore and aft in the same orbital plane, and one each to satellites in neighboring planes to either side.

Originally Iridium data rates were low, just 2.4 kbit/s as the system was intended for voice use. Since 2019 Iridium has offered Certus service, which has three classes. Certus 100 has 22 kbit/s uplink and 88 kbit/s downlink, Certus 200 176 kbit/s up- and downlink and Certus 700 352 kbit/s uplink and 704 kbit/s downlink.

The more recent LEO satellite system intended to provide wideband data services is the Starlink developed by SpaceX, which started launching Starlink satellites in 2019. As of August 2023, it consists of over 5,000 mass-produced small satellites in low Earth orbit (LEO). FCC has granted licenses for 12000 satellites and there are plans for up to 42000 satellites. SpaceX estimated the cost of designing, building, and deploying the constellation to be at least US$10 billion. At least originally the Starlink targeted to carry up to 50% of all backhaul communications traffic, and up to 10% of local Internet traffic, in high-density cities.

The Starlink satellites use Ka-, Ku and V-bands and orbit at 550 km or slightly lower at 500 km - 530 km. The satellites employ optical inter-satellite links and phased array beam-forming and digital processing technologies in microwave bands. The satellites will be mass-produced, at a much lower cost per unit of capability than previously existing satellites and launched with SpaceX Falcon 9 (60 satellites), Falcon heavy (250 satellites) and Starship (400 satellites). Starlink satellites have a mass between 227 kg up to 1250 kg and use Hall-effect thrusters with krypton or argon gas as the reaction mass for orbit raising and station keeping. Orbit inclinations are 53, 70 and 98 degrees.

The system includes flat user terminals, which have phased array antennas and track the satellites. Terminals also have motors to self-adjust optimal angle to view sky and can be mounted anywhere, as long as they can see the sky. This includes fast-moving objects. A larger, high-performance version of the antenna is available for use with the Starlink Business service.

At the beta test phase Starlink's broadband service had download speeds of 11 Mbps to 60 Mbps and upload speeds of 5 Mbps to 18 Mbps, claimed to improve in the future with more satellites. The system will use a peer-to-peer protocol claimed to be "simpler than IPv6" and it will also incorporate end-to-end encryption natively. After the first service year 2021 Starlink had 150000 subscribers and by the end of 2023 2 million subscribers.

Starlink or Iridium are not the only LEO broadband operators although the best known. Amazon, Boeing, OneWeb, and Telesat are five other companies proving or planning to provide broadband services, see Figure 7.

Satellite Operators – Broadband Services

Dgtl Infra REAL ESTATE 2.0

Provider	Satellites *(Potential)*	Frequency Band	Altitude *(Above the Earth)*	Purpose
STARLINK	11,943 (**Long-Term:** 42,000)	Ka, Ku and V	550km	Broadband Connectivity Globally
amazon | project kuiper	3,236	Ka and Ku	590km to 630km	Broadband Connectivity Globally
BOEING	3,016	Ka and V	1,200km 27,355km to 44,221km	Advanced Internet-based Services
OneWeb	648	Ku	1,200km	Broadband Connectivity Globally
TELESAT	292	Ka	1,000km 1,248km	Wide Band and Narrow Band Communication Services

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Figure 7. 5 LEO satellite broadband operators. Source: Dgtl Infra.

The planned large number of satellites (not only Starlink but also others) has been met with criticism from the astronomical community because of concerns over light pollution. Astronomers claim that the number of visible satellites will outnumber visible stars and that their brightness in both optical and radio wavelengths will severely impact scientific observations. While astronomers can schedule observations to avoid pointing where satellites currently orbit, it is "getting more difficult" as more satellites come online.

Conclusions

Maritime connectivity, a necessity in the 21st century, will continue to evolve with innovations like advanced satellite constellations and enhanced data exchange systems. Staying updated with these developments is crucial for the maritime industry to remain competitive, secure, and eco-friendly.

This report provides a detailed overview of current maritime connectivity, aiming to assist maritime professionals, regulators, and stakeholders in making informed decisions to advance the industry while maintaining its tradition of reliability, safety, and global interconnectedness.