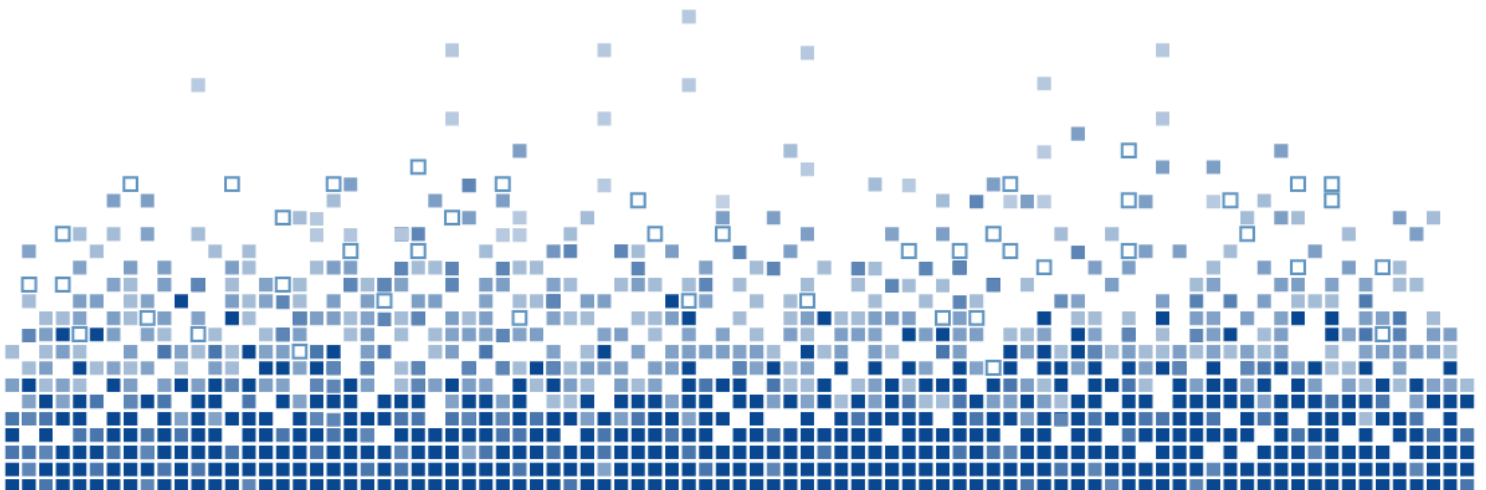

VDES Waveform Scoping Study Report

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Executive Summary

The VHF Data Exchange System (VDES) is one of the key elements of the International Maritime Organisation (IMO) concept of e-navigation. Work is currently being undertaken within IALA and the International Telecommunication Union (ITU) to develop an international standard for VDES and secure access to radio spectrum.

This report presents the results of a scoping study conducted by the General Lighthouse Authorities of the United Kingdom and Ireland (GLA), contracting the Institute for Telecommunications Research (ITR) at the University of South Australia (UniSA). The scoping study represents Phase 1 of a VDES Waveform Design study, as follows:

Phase 1 – Scoping

Phase 2 – Initial Candidate Shortlisting

Phase 3 – Reference Model Implementation and Simulation Study

Phase 4 – Testbed Implementation and Laboratory Performance Evaluation

Phase 5 – Field Trials

This report provides a comprehensive review of literature relating to VDES development, and captures the current state of design considerations for VDES waveform and access scheme development.

The proposed VDES waveform study will derive technical requirements from the existing base of user requirements for e-navigation. It will also draw upon recent maritime channel sounding studies to produce an appropriate terrestrial maritime channel model for simulation and laboratory channel emulation.

A work plan is presented for the remaining phases of the VDES waveform study, which will focus on waveform and link layer design and testing for the terrestrial functions of VDES.

The VDES waveform study will develop and compare Application-Specific Message (ASM) and terrestrial VHF Data Exchange (VDE-TER) waveform and access scheme candidates via simulation and testing, in the laboratory and in the field. Each phase of the study will narrow the field of consideration for waveform design in order to deliver a system that exploits and customises modern communication techniques for VDES application. In each case the channel used for testing will be consistent with real world maritime conditions.

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1 Introduction

The VHF Data Exchange System (VDES) is seen as one of the key elements of the International Maritime Organisation (IMO) concept of e-navigation. Work is currently being undertaken within the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) and the International Telecommunication Union (ITU) to develop an international standard for VDES and secure access to radio spectrum.

A plan for a VDES Waveform Study has been presented at IALA e-Navigation Committee Communications Working Group (IALA ENAV Communications WG) meetings [1], [2]. The overall program of work follows a staged approach, allowing for external review of results and input from the sponsor at each stage.

The five phases proposed for the VDES Waveform Study program are:

Phase 1 – Scoping

Phase 2 – Initial Candidate Shortlisting

Phase 3 – Reference Model Implementation and Simulation Study

Phase 4 – Testbed Implementation and Laboratory Performance Evaluation

Phase 5 – Field Trials

This report presents the results of the VDES Waveform Scoping Study (Phase 1) conducted by the General Lighthouse Authorities of the United Kingdom and Ireland (GLA), contracting the Institute for Telecommunications Research (ITR) at the University of South Australia (UniSA).

Phase 1 work largely consists of literature review and planning. The purpose of this phase is to set the scope of the remaining phases of work, and ensure alignment of the proposed work with end user requirements.

2 Key Concepts and Input Document Sources

This document reviews the concepts relevant to VDES waveform design shown in Figure 1. The remaining chapters of the document summarise the current literature related to each concept. Sources of literature include IALA, ITU and IMO, along with academic journals, related industry standards and reports. Key documents include:

- *User Requirement Document* [3]:
This IALA ENAV Communications WG meeting working document provides the user requirements for the development of VDES. It is a primary input to the technical development of the primary specification of the VDES and provides criteria against which the system will be evaluated.
- *Working Document Towards Draft CPM Text, WRC-15 Agenda Item 1.16* [4]:
This ITU-R WP5B meeting output document summarises the regulatory measures needed to implement VDES. It will be used to introduce VDES at the World Radio Conference (WRC) 2015. Section 3/1.16/3.5 contains references to other relevant ITU-R documents.
- *Liaison Note to ITU-R WP 5B Regarding a Working Document toward a Preliminary Draft New Recommendation ITU-R M.[VDES]* [5]:
This IALA ENAV meeting working document contains the latest revisions proposed by IALA for the Preliminary Draft New Recommendation (PDNR) ITU-R M.[VDES]. It includes background information on VDES and the proposed channel plan, and some considerations on access schemes and waveforms for VDES.
- *Working towards IALA Guideline No. ##### On VHF Data Exchange System (VDES)* [6]:
This IALA working document contains background information and technical considerations for the implementation of VDES. It presents a VDES development roadmap that targets the completion of waveform selection by 2018. It provides information on typical VHF voice radio transmitter power spectral density and estimated power levels delivered to the VDES from the voice radio. Annex B assesses candidate channel plans against a set of use cases, presenting a basis for the selection of the proposed channel plan. Annex D proposes a transition period during which ASM 1, 2 channels will be used with the current AIS modulation and describes plans for the transition to VDES full operational capability (FOC). A list of completed and on-going testbeds is provided in Annex E. Mesh networking concepts are introduced in Annex G.
- *Selection of the Channel Plan for a VHF Data Exchange System, ITU-R M.[VDES-SELECT]* [7]:
This ITU-R WP5B preliminary draft new report describes the rationale for selecting IALA Channel plan A. The latest revisions proposed by IALA for this document are available as reference [8]. This version of the document also evaluates the recently proposed Channel plan D.
- *Report of 2nd Workshop on International Standardization of VDES* [9]:
This report provides details of meetings and presentations given at the VDES workshop co-hosted in Tokyo by JCG and the Ocean Policy Research Foundation. The workshop covered various technical and operational fields of VDES.
- *Technical Characteristics for an Automatic Identification System Using Time Division Multiple Access in the VHF Maritime Mobile Frequency Band, ITU-R M.1371-5* [10]:
This ITU recommendation provides the latest version of the AIS specification.
- *Characteristics of VHF Radio Systems and Equipment for the Exchange of Data and Electronic Mail in the Maritime Mobile Service RR Appendix 18 channels, ITU-R M.1842-*

1 [11]:

This ITU recommendation describes candidate waveforms for VDES based on the ETSI TETRA standard.

- *Use of Appendix 18 to the Radio Regulations for the Maritime Mobile Service* [12]: This ITU-R WP5B meeting output document provides an overview of the use of the VHF band in the maritime mobile service, including a brief history of its evolution.
- *IALA Recommendation [X-###] On Introduction of VDES and Protection of the AIS* [13]: This IALA working document contains rationale for recommending the transition period for the ASM channels.
- *VHF Data Exchange System Channel Sounding Campaign* [14]: This ITU-R WP5B draft new report presents the results of a VDES channel sounding campaign, supported by the administrations of the United Kingdom and Australia.
- *Investigation of the Radio Propagation for the Maritime VHF Band* [83]: This IALA input document presents the results of a channel sounding study conducted by JRC.

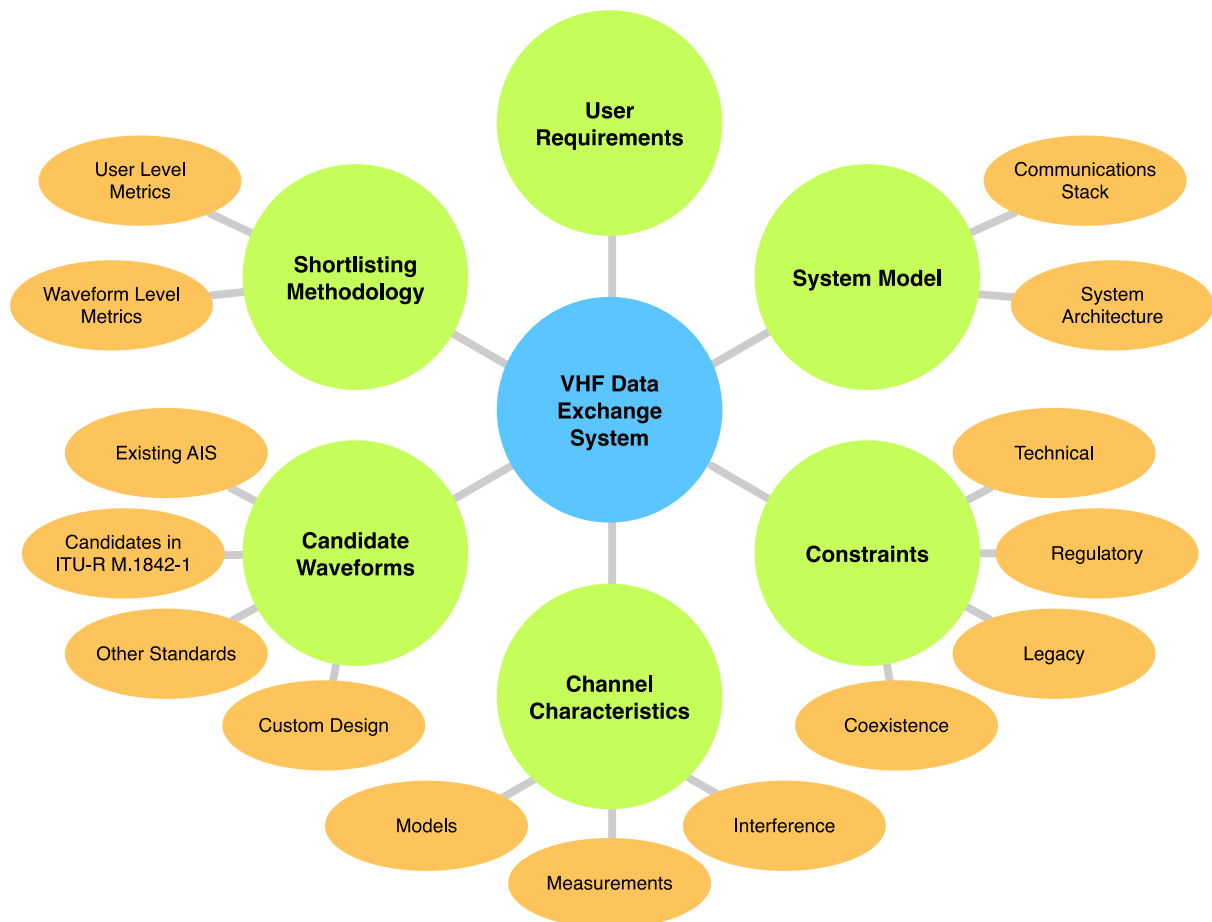


Figure 1: Key concepts for VDES waveform design

3 User Requirements

This section considers the current maritime VHF band and the use made of it and explains the key drivers for the introduction of the VDES. It also introduces the concept of the Maritime Cloud and explores the potential role of VDES within this concept. An overview of user requirements identified in previous e-navigation and VDES studies is provided in Annex A. This information will be used in Phase 2 of this project as a basis for compiling a consolidated set of requirements, against which the system will be designed and evaluated.

3.1 Current Use of the Maritime VHF Band

The maritime VHF band refers to the radio frequency range between approximately 156 MHz and 162 MHz. Various uses are made of the VHF radio spectrum by the maritime community for communication of voice and data, in ship-to-ship, shore-to-ship and ship-to-shore modes of operation [15]:

- Voice communication using the maritime VHF band is prevalent and the primary means of radio communication in the domain. It is used for distress, safety information and general communications.
- Digital Selective Calling (DSC) as an element of the Global Maritime Distress and Safety System (GMDSS) is available as standard on maritime VHF radios and on Automatic Identification System (AIS) transponders.
- The VHF frequency 121.5 MHz has historically been used as a distress channel for the maritime, aviation and land communities. Its use is in decline especially since recent developments in the COSPAS/SARSAT system; however, it remains a tool for short range localisation of those in distress and is likely to be in place for a number of years to come.
- The AIS uses VHF communications links to allow the transmission of vessel information. The primary purpose of AIS is to enable the identification and tracking of ships. However, since the system was introduced numerous additional applications have emerged, such as AIS aid-to-navigation (AIS AtoN), AIS search and rescue transmitter (AIS SART), AIS man overboard (AIS MOB) units and AIS emergency position-indicating radio beacon (AIS EPIRB) units. AIS is also being used on search and rescue (SAR) aircraft [16], [17]. New AIS messages were added in recent editions of Recommendation ITU-R M.1371 and new AIS applications can also be created through the use of Application-Specific Messages (ASM) [10], [18].
- Satellite detection of AIS allows the monitoring of ship traffic on a global scale, although the detectability of ships is limited where traffic density is high [19], [20]. It is expected that the performance of satellite AIS will be improved in the near future with the allocation of two new frequencies for the reception of long-range AIS broadcasts (see Message 27 in ITU-R M.1371).

The use of VHF for digital data transfer has yet to be broadly implemented by the maritime community. A shore based network of digital transceivers has been installed in Norway [21], but has not seen wider adoption. The system claims to offer the capacity for hundreds of ships serving applications ranging from providing e-mail through point of sale services to limited browsing of web pages.

Investigations are on-going into other techniques to be applied more widely, as will be described below.

Further detail about the definition and current use of the maritime VHF band can be found in Section 5.1 and references [12], [22].

3.2 Key Drivers for VDES

The VHF Data Exchange System (VDES) is a technological concept being developed by IALA and ITU in order to enhance digital data communication in the maritime VHF band. The key drivers for introducing VDES are to:

- Protect the integrity of AIS;
- Facilitate the implementation of e-navigation;
- Contribute to the modernisation of GMDSS.

These are discussed in turn in the sections below.

3.2.1 AIS Protection

Monitoring by three national administrations has shown that the AIS VHF data link (AIS VDL) loading is increasing and in some parts of the world reaches values as high as 64% [23]. The introduction of new AIS applications is expected to lead to a further increase in the AIS channel loading, as discussed in reference [16]. To protect the integrity of the AIS VDL, AIS subject matter experts in IALA are considering an approach in which non-safety-critical AIS applications and ASM would be moved to two additional simplex (single-frequency) VHF channels [13]. The World Radio Conference (WRC) 2012 acknowledged this concept in its revision of Radio Regulations Appendix 18 [24] and provided candidate channels on an experimental basis for evaluation.

The need for new AIS channels has also been acknowledged by IMO, who states that [25]:

‘The continued introduction of new [AIS] applications will require new channels.’

and further that:

‘Modifications should not be required to existing AIS equipment on board existing vessels, but rather allow for new applications using AIS technology to evolve, supported by communication primarily on the new frequencies identified by WRC-12, while protecting the integrity of the original operational purpose of AIS as the primary function on the existing AIS frequencies.’

It is expected that IALA will coordinate and provide guidance for the transition of applications to the new ASM channels in the form of a Recommendation [6], [13].

3.2.2 e-Navigation Implementation

e-Navigation is an IMO led concept based on the harmonisation of marine navigation systems and supporting shore services.

The definition of e-navigation, as adopted by IMO is:

‘e-Navigation is the harmonized collection, integration, exchange, presentation and analysis of maritime information onboard and ashore by electronic means to enhance berth to berth navigation and related services, for safety and security at sea and protection of the marine environment.’

The focus of the e-navigation concept would appear to be oriented entirely at the end user and stakeholder benefits but in practice the task of making it work rests largely on the ability of the maritime community to develop a comprehensive, future proof communications architecture [15].

The choice of communications technologies for e-navigation has not yet been determined; however, it is expected that most of the spectrum to be used will lie within existing maritime mobile or shared bands and prominent among these will be the VHF band [26].

It has long been recognised that the efficiency with which the VHF band is currently used is far from optimal – mostly analogue voice channels, with 25 kHz spacing and only low-data rate digital technologies such as DSC and AIS, which cannot satisfy the communications requirements of e-navigation¹.

The VDES concept enables robust, high-speed, data exchange between ships and shore through the use of six duplex (dual-frequency) VHF channels and novel communication techniques. These six channels are referred to as the VHF Data Exchange (VDE) channels. Applications with low data rate requirements will be implemented on the ASM and AIS channels (see above). Together, the AIS, ASM and VDE form the VDES.

Example e-navigation services that could be realised using the VDES include [28]:

- Maritime Safety Information² (MSI) Service (status of aids-to-navigation, restrictions on safe navigation, weather warnings and forecasts, chart correction data, etc.);
- Vessel Shore Reporting (single-entry of reportable information in a single-window solution using standardized digital reporting formats based on the IMO FAL forms [29], [30]);
- Real-time Hydrographic and Environmental Information Service (current speed and direction, wave height, tide surge prediction tables, etc.);
- Ice Navigation Service; etc.

Other applications could include:

- Virtual AtoN deployment beyond the range of coastal VHF radios;
- GNSS augmentation outside the coverage of geo-stationary satellites [31];
- Route exchange [32]

3.2.3 GMDSS Modernisation

The Global Maritime Distress and Safety System is an internationally agreed-upon set of safety procedures, types of equipment, and communication protocols used to increase safety at sea and make it easier to rescue distressed ships. Under the GMDSS, all passenger ships and all cargo ships over 300 gross tonnes on international voyages have to carry specified terrestrial and satellite radiocommunication equipment for sending and receiving distress alerts and MSI, as well as for general communications.

The GMDSS functions are classified into distress/urgency/safety alerting, distress/urgency/safety communications, locating, homing, on scene communications, MSI promulgation and general communications. To achieve these functions, a variety of communications equipment is used such as: VHF/MF/HF DSC, EPIRB, VHF/MF/HF radiotelephone, Radar SART and AIS SART, NAVTEX, SafetyNET, and Inmarsat.

The current GMDSS system was designed over 25 years ago and is currently undergoing a review process. As part of the process, inclusion of AIS and VDES functions in the GMDSS is being considered. New distress devices, using AIS or AIS like technology, are evolving and may be appropriate for inclusion in the modernized GMDSS. The VDES may be a candidate for promulgation of MSI and emerging ship-ship / ship-shore applications. The VDES and MF/HF data communications [33], [34] may also be candidates for general communications in addition to the existing radiotelephone and satellite communications.

¹ The IMO/ITU Joint Experts Group has recognized that data rates higher than 200 kbps will be required for e-navigation [27].

² Maritime Safety Information means navigational and meteorological warnings, meteorological forecasts, other urgent safety-related messages, (IHO definition).

3.3 VDES as a Partner to the Maritime Cloud

The Maritime Cloud is a concept being developed to connect all maritime actors in a communication framework with the aim of providing a single platform for all information exchange between all actors in maritime traffic [35], [36]. Its key components are:

- Maritime Messaging Service / Geo-messaging: how to exchange data;
- Maritime Identity Register: how to identify actors and solve security concerns;
- Maritime Service Portfolio Register: how to locate providers of services.

In development of the Maritime Cloud it is anticipated that Internet will become an important communication channel in e-navigation. For realising the targets set for the Maritime Cloud, a new geo-aware messaging protocol is proposed, a private overlay network to the Internet. Geo-awareness makes it possible to send and receive messages that are relevant to the exact location of the vessel.

The Maritime Identity Register gives each actor a unique identity. This should enable the use of public key cryptography to ensure authenticity and integrity of communications.

The Maritime Service Portfolio Register in essence is an electronic meeting place where providers and users of services meet. Service providers maintain updated information of services and areas where the services are provided. Service users then make queries of services that they see relevant and valuable for them³.

One of the key aims of the Maritime Cloud is to enable seamless roaming between different available data links, such as Inmarsat, Iridium, VSAT solutions, cellular mobile data connections, AIS – or new technologies like MF/HF NAVDAT and the VDES [37].

It is envisaged that VTS stations, ports, coastal states etc. will establish terrestrial VDES infrastructure and provide connectivity to the Maritime Cloud. The utilisation of the VDES infrastructure will be free of charge to the mobile user. Costs for the infrastructure will be carried by those who utilise the infrastructures for provision of public service obligations, or have other incentives for its establishment.

Satellite VDES infrastructure could be implemented using a scheme similar to that used by the COSPAS SARSAT system where each participant fund their contribution to the system.

This would enable participation in a global system where maritime information could be shared free of charge through the VDES, or commercially available data links acting as a supplement and backup.

The concepts of the Maritime Cloud and VDES were endorsed by the IMO in its e-Navigation Strategy Implementation Plan (Annex 7 to report [28]), which states:

‘Future [e-navigation] communication systems could include VHF data (VDES) and NAVDAT, and be developed for internet based solutions, such as a maritime cloud, facilitating system wide information management solutions.

Existing and future communication links could be integrated via a maritime intranet, although each technical service will be limited by the capabilities of the available communication links. This infrastructure will primarily be based on IP communications links but will enable the utilization of free communication links for safety and mandatory reporting where appropriate, enabling a seamless integration and transition between available communications technologies. ...

³ A demonstration of the Maritime Service Portfolio Registry is provided by the Danish Maritime Authority (DMA) and may be found at the URL <http://demo.maritimecloud.net/>

The concept of the "Maritime Cloud" should be further investigated.'

3.4 User Requirements Identified in Previous Studies

Many studies have been carried out in recent years to investigate user needs and develop user requirements for e-navigation and the VDES. Annex A of this document contains a summary of the available studies which could serve as a basis for determining a consolidated set of requirements to be used in system design and testing.

4 System Model

4.1 VDES System

The VDES system consists of the following communication functions [5], [9, pp. 45–52]. It includes terrestrial and satellite components for global coverage [38], [39].

- Automatic Identification System (AIS)
 - Functions: identification of ships; position reporting and tracking; navigational ship data; support of search and rescue.
 - Has highest priority and all other functions should be organised such that AIS is not adversely affected [4].
 - Original purpose of existing system unchanged [10].
 - Bidirectional communications between ships and shore
 - Unidirectional (ship transmitter, satellite receiver) global coverage
- Application-Specific Messages (ASM)
 - Existing application specific messages [18], [40] and new messages
 - IMO and regionally defined messages
 - High reliability of message delivery and message acknowledgement support
 - Bidirectional communications between ships and shore
 - Unidirectional (ship transmitter, satellite receiver) global coverage
- VHF Data Exchange (VDE)
 - Data exchange requiring higher capacity than ASM
 - High reliability of message delivery and message acknowledgement support
 - Terrestrial (VDE-TER) and satellite (VDE-SAT) components
 - Bidirectional global coverage

The VDES system architecture is shown in Figure 2 and consists of the following entities:

- Ship-borne Stations⁴
- Shore Stations
- Satellites

The figure also shows VDES functions supported by each link between entity types.

Satellites (or hosted payloads) will support one or more VDES functions. It is likely that these satellites will be in low-earth orbit (LEO) or medium-earth orbit (MEO) and provisions will need to be taken for the discontinuous contact that ships will have with individual satellites [5]. LEO satellites could offer fast deployment [41]. It is assumed that the satellite also communicates with the operator via a suitable ground segment (outside of VDES scope) either directly [41], or through a relay via an inter-satellite link [42].

Stations could integrate VDE equipment along with ASM and AIS functionalities [5], [43, pp. 11–13 Annex B]. VDE-SAT receive-only terminals may also be considered for disseminating maritime information to smaller ships outside terrestrial VHF coverage [5]. It has also been suggested that integration of AIS and VDE functions may compromise VDE data throughput and further research and development should be considered [44].

⁴ This category may also include equipment for use in SAR aircraft, AtoNs and other applications of VDES for mobile users. The term ‘ship-borne station’ is used here for consistency with existing literature.

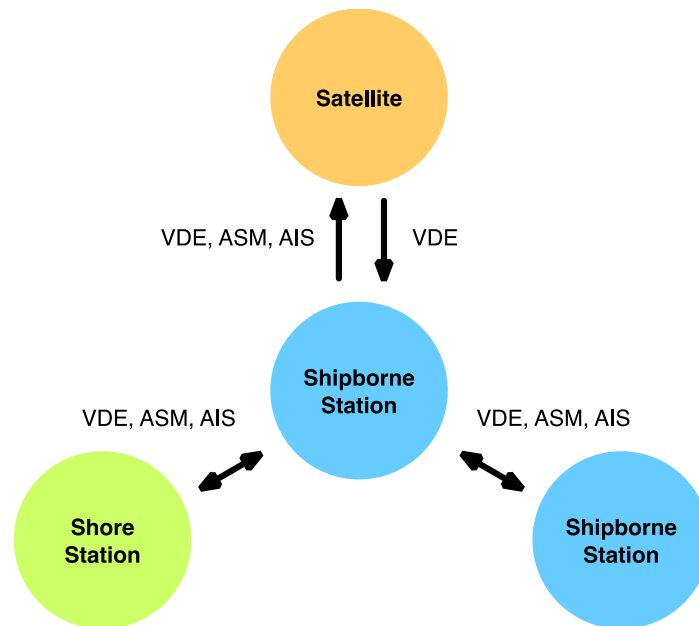


Figure 2: VDES System Architecture

Figure 3 provides a detailed view of VDES functions and frequency usage according to the proposed channel plan described in [5]. Separate 25 kHz VHF channels can be merged as 50 kHz channel(s) or a 100 kHz channel, allowing higher data throughput than a single 25 kHz channel [4]. The satellite downlink frequency spectrum consists of six 25 kHz channels. These may be combined into one 150 kHz channel to reduce the Doppler guard band requirements. Allowing a single carrier downlink on the combined channel also improves satellite power amplifier efficiency when compared to a multicarrier downlink [5].

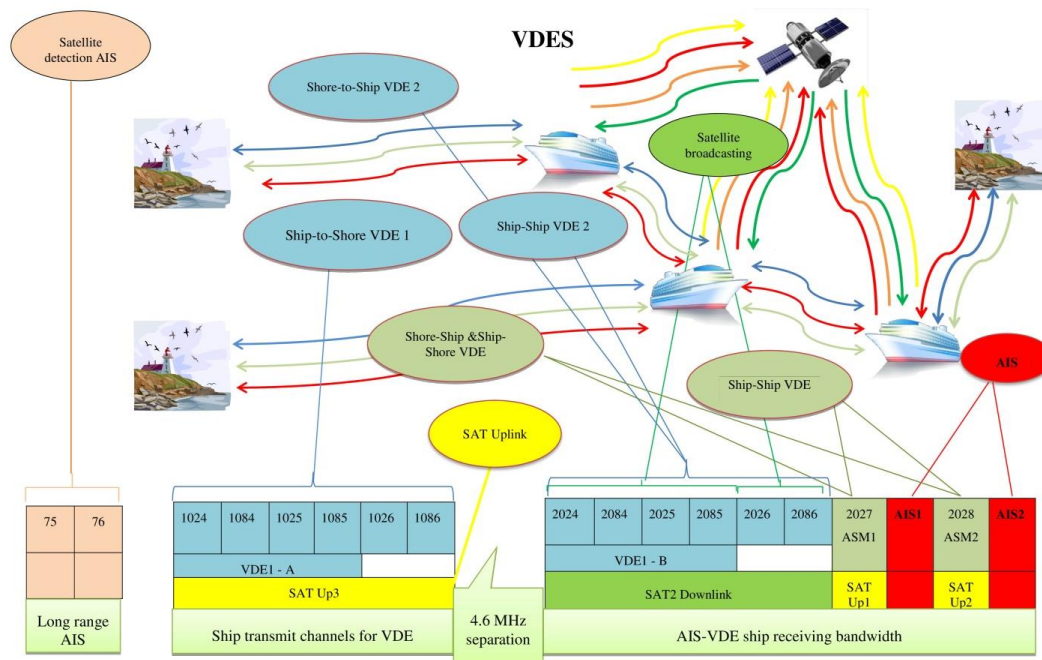


Figure 3: VDES functions and frequency usage [5]

4.2 Communications Stack

Figure 4 shows how the protocols of a communications system can be divided into a stack of layers, such as the seven layer OSI model, or a five layer model [45]. The five layer model is based on the TCP/IP protocol model and collapses the functionality of the top three OSI layers into a single application layer. The layers provide an abstraction mechanism for system designers. However, advances in wireless communication for ad hoc networks have identified advantages in relaxing layer boundary constraints to permit cross-layer designs [45].

The VDES architecture addresses OSI layers 1 to 4 (physical layer, data link layer, network layer, transport layer) [5], as highlighted in Figure 4. The figure also shows the scope of the AIS specification, which again spans layers 1 to 4. AIS divides layer 2 into three sub-layers, i.e. medium access control, data link service, and a link management entity [10].

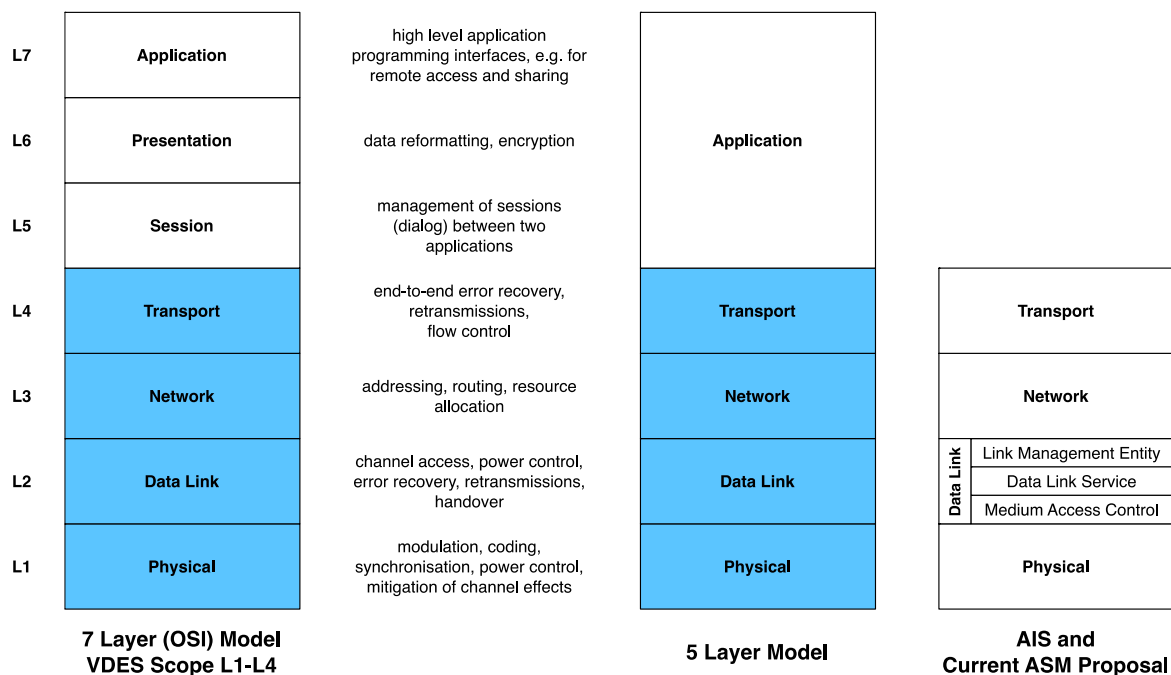


Figure 4: Protocol Stack Models

VDE and ASM subsystems are not necessarily constrained to use the same waveform and access techniques specified for AIS, and the designer may exploit recent advances in communications technology. However, all VDES functions must coexist, and must not adversely affect the existing AIS system. Furthermore, common design elements may allow system components to be shared between VDES subsystems and reduce overall system complexity. Coexistence and complexity constraints are discussed further in Section 5.

VDE and ASM protocol stack details are currently under development. The roadmap suggested in [6] is shown in Figure 5. The target for completion of waveform candidate selection based on studies and field trials is 2018.

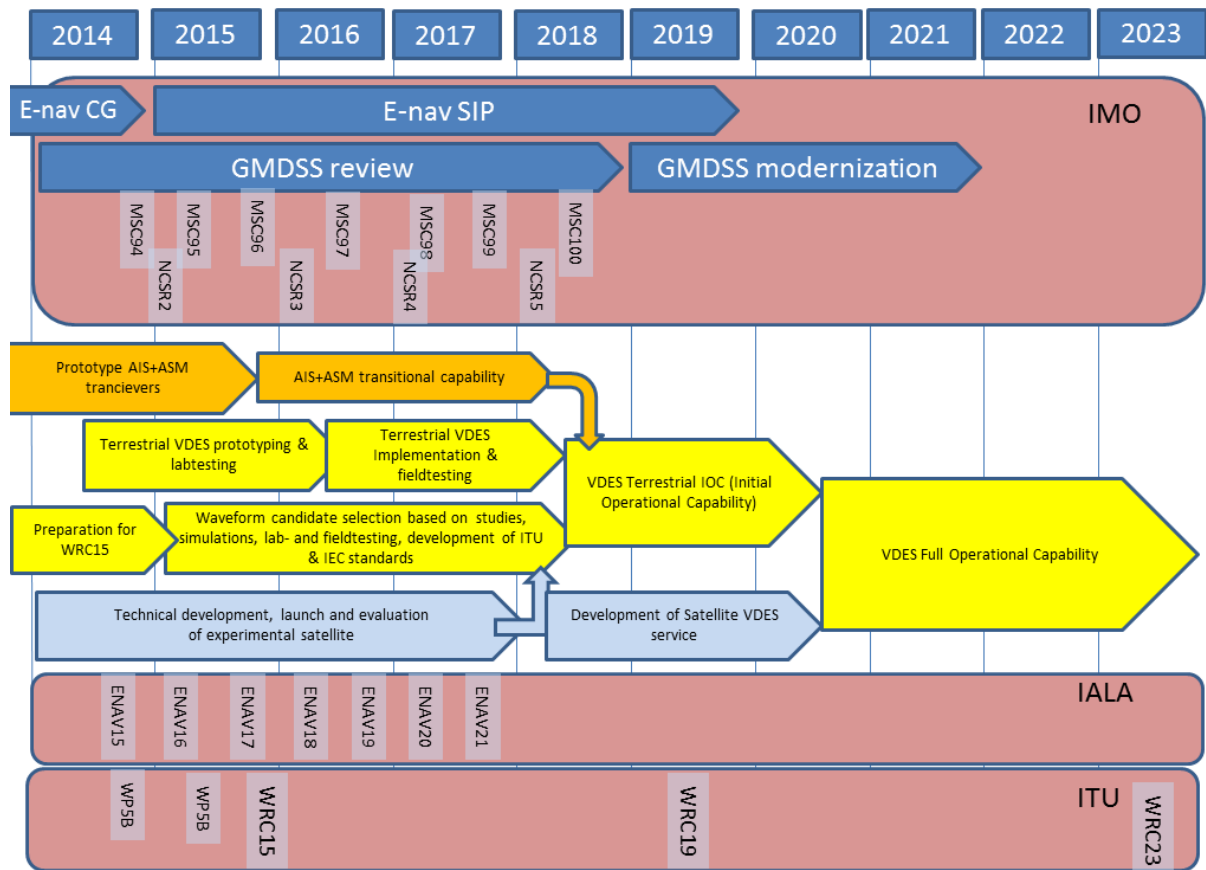


Figure 5: Possible roadmap for the development of VDES [6]

4.2.1 Physical Layer

At the physical layer, VDE throughput requirements motivate modulation schemes that can support higher data rates than the Gaussian Minimum-Shift Keying (GMSK) scheme specified for AIS, such as variants of Phase Shift Keying (PSK) and Quadrature Amplitude Modulation (QAM) [11].

The current ASM physical layer proposal specifies a $\pi/4$ Differential Quadrature PSK (DQPSK) modulation scheme. The use of 32 carrier 16-QAM modulation for the 100 kHz terrestrial VDE channels has been proposed [5], [11].

Modulation schemes are yet to be finalised. Other physical layer components are yet to be determined, e.g. for synchronisation, equalisation and channel coding.

4.2.2 Data Link Layer

A data link layer proposal for ASM can be found in [5]. It divides the layer into the same sub-layers as AIS, and specifies medium access control via time division multiple access (TDMA) using a common time reference. Communications is divided into frames, with one frame equal to one minute. Each frame contains 2250 slots (or some integer portion of a slot) providing a relationship to AIS slot timing.

ASM and VDE access schemes that employ Carrier-Sense TDMA (CSTDMA) and Incremental TDMA (ITDMA) are discussed in [5]. It is also noted that the VDE-SAT downlink should support broadcast, multicast or unicast communication, along with priority, pre-emption and precedence for different services.

The current channel plan shares spectrum between VDE-TER and VDE-SAT, as shown in Figure 3. VDE-SAT downlink spectrum is also used for ship-to-ship and shore-to-ship VDE-TER communications. VDE-SAT uplink spectrum is also used for ship-to-shore VDE-TER communications. The VDE access scheme must therefore efficiently share the spectrum between these functions. Sharing schemes are considered in [5] based upon TDMA, frequency division multiple access (FDMA), and the potential to use a modulation and coding scheme for VDE-TER that adapts to the presence of a satellite.

Access schemes for sharing between terrestrial and satellite services are proposed in [46, pp. 165–177 Annex 9], based on frequency sharing for the 25 kHz channels and time sharing for wider bandwidth channels. An AIS compatible TDMA frame structure is also described. The need to simulate the maritime mobile propagation environment in order to inform modulation scheme and communication protocol development is also noted.

Options for the sharing between terrestrial and satellite services are also discussed in [47]. A Fixed Access TDMA (FA-TDMA) approach could be applied, using pre-selected slots for the satellite with the possibility to extend the allocation. It is noted that the a-priori need to assign allocation may limit effectiveness. Alternatively, an approach is described to allocate separate channels for terrestrial VDE and the VDE-SAT downlink.

The access method suggested in [48] is based on the ETSI S-band Mobile Interactive Multimedia (S-MIM) standard and supports uncoordinated multiple access by performing interference cancellation at the receiver. Further detail on S-MIM and the Enhanced Spread Spectrum Aloha Random Access (E-SSA RA) scheme is provided in [49].

4.2.3 Network Layer

The current network layer proposal for ASM can be found in [5]. The ASM network layer is responsible for the management of priority assignments of messages, distribution of transmission packets between channels, and data link congestion resolution. Four levels of message priority are specified.

The use of mesh networking is considered in [6, pp. 32–33 Annex G]. A mesh network could support multi-hop relaying and ad-hoc networking, peer group data sharing and safety monitoring, and automated mayday message relay. The document proposes that the functionality could reside at a higher logical level, not necessarily within the VDES system. Maritime mesh networks are also explored in [50] with a focus on broadband communications in the 5.8 GHz and 2.3 GHz bands rather than VHF.

4.2.4 Transport Layer

The current transport layer proposals for ASM can be found in [5]. The ASM transport layer is responsible for converting data into transmission packets of the correct size, sequencing of data packets, and interfacing to upper layers.

The VDE and ASM interface between the transport layer and higher layers is performed by the presentation interface [5]. The formats and protocol used for data streams should be in accordance with IEC 61162.

It has been noted that VDES data transfer rates will require the use of IEC 61662-450 or similar, as the default serial port data rate for IEC 61662-2 interfaces is not sufficient [51].

4.3 Comparison to Cooperative Intelligent Transportation Systems

Road transport and maritime use cases share similar challenges in the areas of safety, efficiency and environmental sustainability. In the case of road transport cooperative intelligent transport systems (C-ITS) have been developed to address these challenges by equipping vehicles and traffic management systems with the capacity to:

- Cooperate, via vehicle-to-vehicle and vehicle-to-infrastructure communications,
- Operate intelligently, using on board sensors, processors and control mechanisms,
- Perform system optimisation and control, using real-time information from vehicles.

An overview of C-ITS is provided in Appendix A. In this section we compare some of the features of the C-ITS effort in relation to VDES development.

The evolution of C-ITS has required unprecedented cooperation between vehicle manufacturers, equipment suppliers, road authorities and regulatory bodies. The successful deployment and adoption of cooperative intelligent transport systems relies on a number of key inter-related factors: technology standards and interoperability, radio spectrum, system architecture, policy and regulation. Development of VDES is progressing via similar global scale cooperation between industry and governments, through bodies such as IALA, ITU and IMO. Deployment and adoption of VDES will also rely upon the interrelated factors identified for C-ITS, spanning technical, policy and regulatory domains, and both systems require industry standards that can encourage adoption by manufacturers and suppliers.

C-ITS systems combine reliable, low-latency wireless connectivity, accurate positioning and an on-board applications processor to allow vehicles to communicate directly to each other (vehicle-to-vehicle, or V2V links), and to road-side units (vehicle-to-infrastructure or V2I). At a top level the C-ITS system architecture is therefore similar to the terrestrial VDES architecture, having ship-borne stations that can communicate directly with each other and that can also communicate with shore stations. Moreover, for both C-ITS and VDES, ownership of the mobile segment is distributed across private, commercial and government users, whereas infrastructure is typically operated by a government authority.

Standards based C-ITS systems are in the final stages of pre-deployment trials worldwide. These trials are intended to prove the concept of operations, validate the technology and standards, demonstrate the applications and evaluate the benefits provided. VDES development will proceed via field demonstration in real world deployments along a similar path [6].

C-ITS spectrum is allocated at 5.9 GHz and the band plan specifies seven 10 MHz wide channels (see Figure 12 in Section A). Comparing the features of C-ITS to the current state of VDES development we observe some similarities:

- C-ITS recognises the critical nature of safety messages by providing a dedicated channel for this purpose. Similarly, the introduction of VDES aims to reduce VDL load in order to ensure reliable transfer of AIS position report messages [4].
- C-ITS services are offered on service channels. This is analogous to the provision of applications on VDE and ASM channels.
- 10 MHz C-ITS service channels can be combined to form 20 MHz channels. Optional channel combining is also being considered for VDES [4].
- C-ITS devices advertise services on a special control channel. Devices regularly check the control channel, and then switch to the relevant service channel to receive those services. This scheme is similar to the approach considered for VDES in [5], whereby the TDMA access scheme for the VDE1-A ship-shore link could be by reservation from an ASM on either one of the ASM channels.

- The Society of Automotive Engineers SAE J2735 standard provides a message set dictionary in order to provide a consistent interface to applications [52]. The IMO provides a similar recommendation for ASM construction [18].
- By default vehicles operate independently, but can also organise themselves into small networks called WAVE basic service sets [53]. Similar applications for local maritime networks are discussed in [6, pp. 32–33 Annex G].
- Given the similarities between C-ITS and VDES network topologies noted above, the techniques for network security for C-ITS may also be worth consideration for VDES [54].
- C-ITS enabled infrastructure can broadcast environmental notification messages alerting drivers to hazards such as icy conditions or roadwork. This application is similar to the aids to navigation provided by VDES.
- If the proposed use of 802.11ac proceeds in the 5.9 GHz band, coexistence mechanisms will be required. This should be possible, due to the fact that 802.11ac and 802.11p come from the same family of standards and use similar access methods [55]. In the case of VDES, coexistence and sharing through compatibility of access methods across the different VDES functions is also being considered [46].

We also observe some key differences between VDES and CITS:

- C-ITS is allocated at a much higher frequency than VDES, with much wider channels, and hence high data rates (from 3 Mbps to 27 Mbps).
- C-ITS is a land based system and has been designed to operate in the presence of strong multipath fades, e.g. as induced in urban environments, that can be much narrower than the transmission bandwidth. In contrast, multipath induced fading for VDES deployments is expected to span a significant portion of the operating bandwidth [14].

Due to the differences in operating frequency, bandwidth and propagation characteristics, the C-ITS physical layer design is not considered to be a candidate for VDES. However, above the physical layer there are similarities between the two systems, development and test methodologies, and deployment strategies that are worth exploring further.

5 Technical and Regulatory Constraints

5.1 Regulatory, Coexistence and Legacy Requirements

5.1.1 Spectrum Definition

Appendix 18 of The Radio Regulations [24] defines the channelization of the maritime VHF band, along with the permitted usage and the mode of operation for each channel (simplex or duplex).

Key features of the maritime VHF band are [24], [26]:

- 25 kHz channel spacing; 12.5 kHz channel interleaving is permitted where there is an urgent need to reduce local congestion;
- Channels are designated as single (simplex) or two (duplex) frequency working, or a choice of one or the other;
- Ship stations transmit on frequencies in the lower leg from 156.025 MHz to 157.425 MHz, and on AIS 1 and AIS 2 channels (see below);
- Coast stations transmit on frequencies in the upper leg from 160.625 MHz to 162.025 MHz;
- Duplex spacing of 4.6 MHz (the “duplex guard-band”).

Designated applications for the maritime VHF channels break down as follows:

- Distress, safety and calling - 2 simplex channels (Ch 16, 70 – DSC);
- Inter ship only – 4 Simplex channels (Ch 6, 8, 72, 77);
- Inter ship or port operations and ship movement – 8 simplex channels (Ch 67, 9, 69, 10, 13, 73, 15, 17);
- Port operations and ship movement – 6 simplex channels (Ch 68, 11, 71, 12, 14, 74) plus 2 ship station only channels (Ch 75, 76) plus Ch 87, 88 (the lower legs of the two channels used by AIS);
- Port operations or public correspondence – 2 duplex-only channels (Ch 27, 28);
- The remaining 31 channels are available for simplex or duplex working in port operations or public correspondence;
- The frequencies 161.975 MHz and 162.025 MHz (AIS 1 and AIS 2, resp.) are used for the AIS (unless other frequencies are designated on a regional basis for this purpose); AIS 1 and AIS 2 may be used by the mobile-satellite service for the reception of AIS transmissions from ships.
- Channels 75 and 76 are also allocated to the mobile-satellite service for the reception of long-range AIS messages from ships.

Only Channels 16, 75, 76 and 70 are reserved exclusively for maritime use on an international basis.

Of particular relevance to this study, the notes accompanying the Table of Transmitting Frequencies identify:

- A contiguous block of 6 channels (Ch 24, 84, 25, 85, 26, 86) that will be globally available from 1st January 2017 for the utilisation of digital systems described in the most recent version of Recommendation ITU-R M.1842 (notes ‘w’ and ‘ww’); these channels may be operated as single or duplex frequency channels (note ‘y’); in ITU Regions 1 and 3, until 1st January 2017, these channels may be used for testing of

new technologies (note 'w').

- Two simplex channels (Ch 87, 88) and two duplex channels (Ch 27, 28) which may be used for testing of future AIS applications.
- Additional channels that may be available for digital data transmission in some parts of the world.

Other notes place certain restrictions on the use of some channels. For example, simplex Channels 75 and 76 are restricted to 1 W transmit power (with the exception of AIS), to limit interference to Ch 16.

5.1.2 Regional Variations on Use of the Maritime VHF Band

Significant regional variations exist in the way the maritime VHF band is used. Most notably, in the USA and Canada, some frequencies in the band are used for land mobile services, meaning that a number of the duplex channels are only available for single frequency working, or not at all. This obviously restricts the number of channels available to marine users, and has a bearing on any plans to re-organise the band.

Decline in the use of public correspondence has meant that such services have been withdrawn in many countries, effectively freeing numerous duplex channels. This is recognised by note 'm' in RR18, although the affected duplex channels are typically still operated as such, albeit for applications other than public correspondence.

It was reported at the April 2014 meeting of IALA ENAV Communications WG that the Republic of Korea was working to clear the channels intended for global VDES use of voice communications by Q2 of 2014 [56].

Proposals have been made for using additional VHF channels potentially available for VDE in some parts of the world. Japan proposed a channel plan which uses up to 7 additional duplex VDE channels [57]. The latest version of ITU-R PDNR M.[VDES-SELECT] [7] introduces a proposal (Channel plan D) that makes use of two additional regional channels.

5.1.3 Coexistence Requirements

As described earlier, the maritime community uses the VHF spectrum for a variety of purposes and coexistence with incumbent maritime and non-maritime VHF systems, as well as mutual compatibility between the components of VDES, will therefore be an important consideration in the system design.

An overview of existing maritime VHF systems was given in Section 3.1 and further information can be found in references [12], [22]. In particular, the following systems may need to be considered in the compatibility assessment: VHF radiotelephone [58], VHF DSC⁵ [59], AIS [10], and possibly also VHF EPIRB [60], [61]. For satellite sharing studies it will also be necessary to consider land mobile radio systems.

Various studies have been conducted over the past years analysing potential coexistence issues relating to VHF data communication as summarised below.

⁵ Comments were received at a meeting of the UK Radio Navigation Equipment and Standards Committee regarding adjacent channel interference concerns with VDES, especially for Ch 70.

- *Options and Impacts for VDE and AIS Systems [44]*

Study [44], commissioned by the Canadian Coast Guard, examined the implications of the proposed VDES Channel Plans A, B and C⁶, and the key RF risks associated with the introduction of the VDES. The study also included risks to other VHF maritime systems and voice frequencies, both on shore and on ship. It was concluded that the three proposed plans may not allow for optimal wireless communications:

- 'With Plans A and B, the VDE 1 upper legs frequencies are too close to those of AIS to give uncompromising options for mitigating receiver desensitization issues to a level comparable to an AIS system alone. This would result in reduced radio coverage unless AIS and VDE systems are coordinated or not co-sited;
- Unless the AIS and VDE systems are coordinated, the three frequency plans would imply significant challenges with the design of satellite radio subsystems as there are risks of adjacent channel interference and receiver desensitization;
- Plan C implementation would yield a limited net data throughput compared to one of Plan A or B;
- A self-interference cancellation subsystem would address, to a certain extent, issues related to co-sited transmitters. This would however involve a trade-off on AIS receiver sensitivity and increased system complexity.'

The results of this study are further discussed in reference [62]. Amongst other points, the document emphasises that it is essential for Canada to be able to co-locate VDES equipment with existing AIS facilities without impacting AIS coverage or service level.

This report has been submitted to ITU-R WP 5B.

- *Design Considerations for VDES [63]*

This document summarises functional requirements for VDES identified by the IALA ENAV Communications WG as of October 2014 (see Section 3.4). The requirements relating to coexistence are as follows:

- 'VDES shall protect AIS integrity for collision avoidance and identification purposes;
 - Consider scheduled AIS transmissions;
 - Consider slot selection rules of AIS to avoid the loss of near targets on AIS.
- The duty cycle of any given transmission shall respect AIS and voice communications;
 - Limit length of ASM and VDE transmissions;
 - Limit amount of ASM and VDE transmissions per minute (mobile, base station), may be adapted dynamically depending on channel load.
- The ASM component shall protect AIS integrity for collision avoidance and identification purposes;

⁶ Note that the latest version of ITU-R M.[VDES-SELECT] [7] also describes Channel Plan D. IALA e-Navigation Committee Communications WG evaluated this channel plan during its February meeting and concluded that: 'Channel Plan D is inferior to Channel Plan A with regards to the shore infrastructure, with regards to potential conflicts between regional channel use and the Satellite link and with regards to the added complexity of channel management (switching between global and regional channels)'.

- The ASM shall protect AIS integrity for shore side monitoring and control purposes (cargo type, etc.);
- The duty cycle of any given ASM transmission must respect AIS and voice communications, and if practical VDE;
- The ASM should maximize, to the extent that is practical, satellite reception; (e.g. FEC);
- The VDE shall support a satellite sharing scheme (freq. and/or time);
- The duty cycle of any given VDE transmission shall respect AIS, ASM, and voice communications.'

The following studies examined coexistence issues relating to the terrestrial segment:

- *Study of the Isolation between VHF Land Mobile Radio Antennas in Close Proximity, ITU-R Report M.2141 [64]*

This ITU-R report investigates coupling effects between collocated VHF antennas. Analytical, simulation and experimental results are presented for frequencies between 30 MHz and 108 MHz.

In general the isolation was found to be higher than would be predicted from the free space loss equation; however, it is a complex function of a number of parameters such as operating frequency, separation between the antennas and antenna length.

- *Preliminary Draft New Report ITU-R M.[AIS.PROTECTION] [65]*

This ITU document quantifies the impact of voice transmissions in the upper legs of the maritime VHF band on the performance of AIS. Experiments were conducted in which considerable reduction in the number of observed AIS targets and the maximum detection range was observed as a result of the voice transmissions.

- *Utilization of the Marine VHF Band in e-Navigation [66]*

This IALA ENAV Communications WG meeting input document presents concerns regarding potential interference to VDES reception caused by co-located VHF radiotelephone and DSC transceivers.

The document also contains estimates of the maximum communication range based on ETSI spurious emission specifications for VHF radiotelephone equipment, although it should be noted that analyses based purely on emission masks may be overly pessimistic.

- *EMC Assessment of Shore-based Electronic Navigation (eNAV)* Infrastructure and New Draft Standards for Data Exchange in the VHF Maritime Mobile Band (156-174 MHz), ITU-R Report M.2122 [67]*

This ITU-R report was published in 2007 and therefore is not entirely consistent with the current VDES concept.

The document evaluates the suitability of two possible channel arrangements and several modulation methods for VHF data exchange.

1. A '225 kHz wideband system based on ETSI ETS 300 113-1 v.1.5.1'.

2. Separate 25 kHz channels with ETSI TETRA-TEDS modulations ($\pi/4$ DQPSK, $\pi/8$ D8-PSK at various bit rates)

Option 2. was considered preferable, mainly because:

- Some administrations did not have all of the proposed 9 channels required for implementing Option 1. available.
- The modulation used in Option 1. did not meet the adjacent channel power limit of $-70 \text{ dBc}/\pm 25 \text{ kHz}$ specified by IEC.

The report also includes some considerations regarding potential interference issues between AIS, VHF public correspondence (VPC) and future VHF data exchange. Estimates of the minimum separation distance between AIS and VPC stations operating on channels 27 and 28 (now ASM 1, 2) are also included.

- *Report from the 2nd JCG Workshop on International Standardization of VDES [9, pp. 127–163]*

A presentation was given at the Workshop by FURUNO which raises concerns about interference between AIS 1, 2 and VDES ASM. **This may affect the maximum range of virtual AtoNs**, as pointed out in another presentation by FURUNO [68, pp. 69–92].

The following studies investigated options for spectrum sharing between terrestrial services and the satellite component of VDES. Note that the different spectrum sharing options were also discussed in Section 4.2.2 of this document, which contains additional references on the subject.

- *Investigation of VHF Data Exchange System (VDES) by JRC [46]*

According to Radio Regulations Annex 1 of Appendix 5, a coordination threshold is proposed for terrestrial non-aeronautical mobile systems protection of -125 dBW/m^2 per 4 kHz for some systems using the 137 MHz – 138 MHz and 400.15 MHz – 401 MHz bands. It had been proposed that this criterion could be extended to the 156 MHz – 162 MHz band. This document provided by JRC suggests that the -125 dBW/m^2 per 4 kHz coordination threshold is not sufficient to provide adequate communication range for terrestrial VDE.

An FDMA scheme allocating 4 VHF channels to VDE-TER and 2 channels to VDE-SAT and a TDMA scheme with carrier sensing were proposed in the document.

- *ESA Contribution to WRC-15 Agenda Item 1.16 [69]*

This document defines a Power Spectral and Flux Density (PSFD) mask to ensure that there is no harmful interference caused by the VDE-SAT downlink on non-maritime terrestrial services sharing the same frequency band. The mask proposed in this document appears to be slightly different from that in PDNR ITU-R M.[VDES] [5].

- *Co-frequency Sharing between Stations in the Mobile Service below 1 GHz and Mobile Earth Stations of Non-geostationary Mobile-Satellite Systems (Earth-space) using Frequency Division Multiple Access (FDMA), ITU-R Recommendation M.1039-3 [70]*

This ITU-R report does not specifically relate to VDES, however, it describes methodologies for evaluating interference between non-GEO satellites and stations in the mobile service that may prove useful in VDES sharing studies.

Several studies have been published regarding the impact of incumbent terrestrial VHF systems on the satellite detection of AIS/ASM transmissions:

- *Satellite Detection of Automatic Identification System Messages, ITU-R Report M.2084 [19]*

This ITU-R report introduces the concept of satellite detection of AIS, evaluates the capacity of the detection system and investigates techniques to enhance detection probability. Section 9 assesses compatibility with other incumbent fixed and mobile systems (VPC, land mobile radio).

- *Improved satellite detection of AIS, ITU-R Report M.2169 [20]*

This report addresses some of the technical limitations identified in ITU-R Report M.2084 and introduces the concept of long range AIS broadcasts (Message 27).

- *Global AIS VDE Noise Floor Characteristics [71]*

This IALA ENAV Communications WG meeting input document provided by exactEarth contains results of noise floor measurements on AIS 1, 2 and ASM 1, 2 channels made from a LEO satellite.

The results show that, as expected, the ASM channel noise floor over the poles has a noise floor approaching kT (absolute thermal noise floor), however many other regions have elevated noise floors (20 dB or greater, above kT), especially North America and Europe, severely impairing weak signal detection.

5.1.4 Legacy Requirements

As described earlier in this document, a key requirement in the design of VDES is to protect the integrity of AIS. This may place constraints, for example, on the ASM and VDE time slot structure, allowable transmission duty cycle, etc.

IALA ENAV Communications WG meeting input document [72] provided by USCG proposes to allow the use of GMSK AIS type modulation on the ASM 1, 2 channels during a transition period (expected to last until January 2019). The proposal was also incorporated into the draft IALA Recommendation on the Introduction of VDES [13]. Therefore there may be a requirement for VDES ASM to coexist with AIS-like transmissions on the same channels.

There is also a requirement that the ASM channels shall, to the extent that is practical, support all currently existing ASM formats [63].

5.2 Implementation Complexity

Another key requirement for VDES is to minimize the complexity of the ship-borne equipment [73]. The data rates being targeted for VDES are considered low enough to permit software (and firmware) implementation of waveform processing using modern software-defined radio (SDR) systems. SDR implementation offers to reduce development and test effort as it allows the re-use of existing platforms and components, and enables rapid prototyping. It is therefore advantageous to design VDES waveform processing algorithms for ship-borne and shore stations that can meet the implementation constraints of SDR platforms being developed by existing maritime equipment manufacturers. Candidate ASM modulation schemes from [11] have been bench tested using SDR based maritime equipment [51].

A study on modulation methods for VDES is presented in [74], based on the schemes described in [10] and [11]. Computational requirements for channel equalisation (excluding

channel estimation) were compared between a single carrier scheme and a multicarrier orthogonal frequency division multiplexing (OFDM) scheme. In the case of the data rates being considered for VDES, the study concluded that there is not a significant difference in equaliser computational complexity between the two schemes.

The study presented in [74] noted that the use of multicarrier modulation requires a power amplifier (PA) capable of significantly higher output power than single carrier modulation, due to the higher peak to average power ratio (PAPR) of multicarrier modulation. The study did not consider the use of PAPR reduction techniques.

Tight constraints on satellite mass, volume and power consumption also imply a requirement for low complexity in the VDES space segment. A use case study for the VDES satellite component notes that the transmit modulation schemes considered will require a PA with a certain degree of linearity, in order to cope with non-unity PAPR of the downlink signal [38]. However, it is anticipated that at least a 60% DC to RF efficiency number is feasible via the use of linearization techniques.

Following on from [51], experimentation with candidate VDES waveforms using a new SDR research platform [75] has recently commenced. Initial work has provided practical insight into the PAPR issue and the use of linearization techniques. Results are provided from some initial tests using a method based on the cancellation of inter-modulation products. It is noted that the method may be suitable for simple multicarrier systems but becomes too complex for a system with 32 subcarriers (as proposed in [11]).

A study on options and impacts for VDE and AIS systems has suggested that unnecessary complexity may arise from introducing dependencies between AIS and VDE functions, e.g. where one would be dependent on the transmission of the other and vice versa [44]. The same study also presents a conceptual radio architecture aimed at integrating VDE and AIS into one radio, to be considered as a topic for research and development.

6 Channel Models and Characteristics

An understanding of the channel propagation characteristics for VDES is fundamental to the waveform design, test and selection process. Considering the system architecture presented in Figure 2, there are three channels (propagation paths) to be considered:

- Ship-borne station to/from ship-borne station
- Ship-borne station to/from shore station
- Ship-borne station to/from satellite

6.1 Channel Characteristics

A general overview of the wireless propagation environment and associated modelling techniques is provided in [45], and for land mobile use cases in [76]. Specific features relevant to maritime use cases are described in [14] and [77].

Development of VDES channel models should consider the following effects:

- **Changes to Complex Gain:** Changes to the amplitude and phase of the signal. Causes include free space propagation, shadowing from objects between the transmitter and receiver, reflection, diffraction and ionospheric scintillation.
- **Time Offset:** The delay between transmit and receive time due to propagation across the channel.
- **Frequency Offset:** Movement of received signal (in frequency) with respect to the transmit carrier frequency. Causes include Doppler shift induced by relative mobility, and local oscillator drift.
- **Change of Frequency Offset:** In a highly dynamic channel, such as a LEO satellite channel, the frequency offset can change at a rate that is significant.
- **Multipath:** The presence of multiple propagation paths, in addition to the line-of-sight (LOS) path (if present) resulting from signal reflection and diffraction.
- **Noise:** Thermal noise introduced by electronic components.
- **Interference:** Undesired signals that are in the receiver band. These may come from non-VDES systems, or from other VDES transmissions. Existing maritime interference studies are discussed in Section 5.1.

6.1.1 Antenna Characteristics and Placement

The antenna provides the interface between the radio equipment and its environment, thus antenna gain, pattern, polarisation, orientation and height affect radio propagation. In the case of AIS, ship-borne and shore side deployments are typically fitted with omni-directional, vertically polarised, vertically oriented antennas. Shore side deployments may increase antenna gain via the use of high-gain collinear, stacked dipole, or Yagi antennas. It is advantageous to mount the antenna as high as possible in order to avoid obstructions. Ship-borne antennas are typically mounted at heights ranging from a few metres (e.g. for a boat) to 45 m above sea level [77][7, Annex 11]. Shore side antennas are typically mounted tens of metres above sea level [14][47]. VDES ship-borne and shore side antenna deployments are expected to be similar to those used for AIS, however this is not currently considered to be a design constraint.

6.1.2 Path between Transmitter and Receiver

Separation between the transmitter and receiver introduces attenuation due to path loss that increases by 20 dB per distance decade in free space. Time offset also increases with distance, by D/c seconds per metre in free space, where D is the separation distance and c is the speed of light.

Propagation range predictions for VDES terrestrial links are provided in [5, Annexe 2] using the methods described in [78]. A maximum range of 85 km (46 NM) is predicted between ship and shore, assuming a 75 m antenna height at the shore. Example link budgets for shore-to-ship and satellite-to-ship communications are provided in [47].

LEO and MEO satellite orbits are being considered for VDES. LEO orbits have an altitude of several hundreds of kilometres, and MEO altitude is approximately 10,000 km to 17,000 km. Investigations to date have focused on LEO deployments, e.g. at orbital heights of approximately 600 km and 850 km [47][79][36, Annex 11]. Propagation distance and time offset are significantly larger than orbital height when the satellite is on the edge of coverage at the horizon. For long range AIS, Message 27 allows 9.1 ms of buffer for increased propagation delay (equivalent to 2717 km) in order to support satellite orbits up to 1000 km.

Obstructions between the transmitter and receiver further attenuate (shadow) the signal. The signal may also be diffracted around such objects in the path. Reflections from objects in the environment produce multipath [45][77][80]. Terrain conditions are considered in several of the modelling approaches discussed in Section 6.2. Clutter close to the antennas can also lead to significant shadowing loss [14].

6.1.3 Environmental Factors and Dynamic Conditions

Attenuation from rain, fog and cloud is expected to be negligible at VDES frequencies [81][82]. Extremely low temperatures in the polar regions can cause icing on antennas and snow build-up and adversely affect system performance [35]. Rough sea state can induce significant time varying loss due to polarisation mismatch between transmit and receive antennas [14].

In the case of the satellite channel, variation in signal amplitude and phase can result from scintillation, i.e. variations in the refractive index of the ionosphere and troposphere [83][46]. This effect is greatest for low frequencies, when the earth station is closer to the equator [83] and during summer [82]. The ionosphere also introduces Faraday rotation [83][84]. This is a rotation of the plane of polarisation of a linearly polarised wave, and can introduce a loss due to polarisation mismatch. Scintillation and Faraday rotation both vary with time.

Relative motion between transmitter and receiver can induce time variant behaviour such as frequency offset (Doppler offset) and variation to channel gain. At VDES frequencies, the maximum Doppler offset induced by vessel motion is expected to be approximately ± 20 Hz, e.g. for two high speed craft heading directly toward or away from each other [9, Annex 11]. The maximum Doppler offset for VDES satellite channels is expected to be approximately ± 4 kHz for LEO and ± 2 kHz for MEO [57][85]. Maximum Doppler shift will occur as the satellite enters/exits coverage at the horizon. Doppler shift will be close to zero when the satellite is directly above the ship. At this point the change in Doppler (from positive to negative) will be greatest, as the satellite passes from approach to departure. The corresponding rate of change in frequency offset should be considered during waveform design, e.g. when selecting an appropriate maximum packet duration.

6.2 Channel Models and Measurements

The ITU provides the following documents relating to channel models.

- *ITU-R P.680-3, Propagation Data Required for the Design of Earth-Space Maritime Mobile Telecommunication Systems* [82]

This recommendation covers tropospheric and ionospheric effects, fading due to sea reflections and interference from adjacent satellite systems.

- *ITU-R P.1406-1, Propagation Effects Relating to Terrestrial Land Mobile and Broadcasting Services in the VHF and UHF Bands* [76]

This recommendation provides information on aspects of propagation which are likely to affect the terrestrial land mobile services, including some information on multipath fading.

- *ITU-R P.1407-4, Multipath Propagation and Parameterization of its Characteristics* [77]

This recommendation provides general background on multipath propagation and recommends ways to describe it statistically.

- *Recommendation ITU-R P.1546-4, Method for Point-to-Area Predictions for Terrestrial Services in the Frequency Range 30 MHz to 3 000 MHz* [78]

This recommendation provides an empirical signal field strength prediction method that is often used in AIS/VDES studies. The technique is based on propagation curves for a 1 kW ERP transmission over land, sea or mixed paths between 1 km and 1000 km. The method also includes corrections for terrain clearance and terminal clutter obstructions.

- *ITU-R P.1812-2, A Path-specific Propagation Prediction Method for Point-to-Area Terrestrial Services in the VHF and UHF Bands* [81]

This recommendation describes a terrestrial propagation prediction method suitable for transmissions in the range 30 MHz to 3 GHz, for path lengths from 0.25 km up to approximately 3000 km. The method predicts signal levels at the median of the multipath distribution exceeded for a given percentage of time, $p\%$, in the range $1\% \leq p \leq 50\%$ and a given percentage of locations, p_L , in the range $1\% \leq p_L \leq 99\%$. Diffraction theory may be used to model propagation over irregular terrain (requiring a terrain height profile). The method also allows for the effects of tropospheric scatter, ducting and layer refraction, and height-gain variation in clutter.

- *ITU-R P.2001, A General Purpose Wide-range Terrestrial Propagation Model in the Frequency Range 30 MHz to 50 GHz* [82]

This recommendation describes a terrestrial propagation prediction method suitable for path lengths up to at least 1000 km. It predicts the basic transmission loss not exceeded for a given percentage of an average year (as input into the model). The technique combines four propagation mechanisms: diffraction, ducting, troposcatter, and sporadic E. Terrain height profile data is required.

Techniques for the prediction of transmission loss in terrestrial conditions can also be found in [86][87]. The approach was developed for frequency planning of television broadcasting in the United States in the 1960s and was used extensively for preparing the tables of VHF/UHF broadcast channel allocations. Several implementations are available online⁷.

⁷ SPLAT! <http://www.gsl.net/kd2bd/splat.html>
Radio Mobile: <http://www.cplus.org/rmw/english1.html>

Terrestrial UHF propagation models developed for the Terrestrial Trunked Radio (TETRA) standard are described in [88].

Interactions between antenna orientations, propagation link geometry and Faraday rotation are investigated for the VHF satellite channel in [84]. The paper presents a three dimensional (3D) equivalent baseband model that incorporates link geometry, antenna radiation patterns and the rotation of the polarization of the radio wave as it passes through the electron plasma of the ionosphere in the presence of Earth's magnetic field. A recent consideration for VDE satellite downlink design [89] assumes a Rician channel model based upon [90] and provides some statistics on expected ionospheric effects.

Recent studies have been conducted to characterise proposed VDES frequencies in a maritime operating environment [14][77]. Results from a VDES channel sounding campaign conducted at sea near Harwich in the United Kingdom are provided in [14]. Five operational scenarios were examined for the channel between ship and shore, using 12.5 W transmit power. Line-of-sight and non line-of-sight environments were examined, spanning four of the six IMO Maritime Service Portfolio area categories. Several channel characteristics were identified that are specific to maritime use. During periods of vessel movement in moderate to rough sea state large fluctuations in received power (at rate 5 dB per second) were observed due to polarisation mismatch between transmit and receive antennas. These fluctuations were accompanied by Doppler induced changes to frequency offset (at rate 1 Hz per second). Rooftop clutter also caused vessel orientation dependent shadowing, with variation of up to 20 dB. Across all trials the communications range varied between 1.1 km (0.57 NM) and 30.8 km (16.6 NM). Received power varied between -43 dBm and -98 dBm. Figure 6 compares receive power measured during the channel sounding to predictions from the model provided in [78]. At short ranges (less than two miles or so), the model compares perfectly with measurements. Received power measured at longer ranges was up to 8 dB lower than predicted by the model, potentially due to the maritime specific channel characteristics noted above and destructive signal interference arising from multipath.

Results from a VDES channel sounding campaign conducted at sea in Tokyo are provided in [77]. The study used a similar approach to that presented in [14] but employed a significantly wider bandwidth waveform and higher transmit power (25 W). Two multipath components are resolvable if their delay difference significantly exceeds the inverse signal bandwidth, otherwise the components combine to form a single component representing their sum [45]. The wide signal bandwidth used in this study therefore provides fine resolution of multipath. Example power-delay profiles were generated for urban, cove, and coastal areas, for ranges up to 10 km. Significant multipath effects were observed, gradually emerging from more than 2 km (relative distance) between transmitter and receiver.

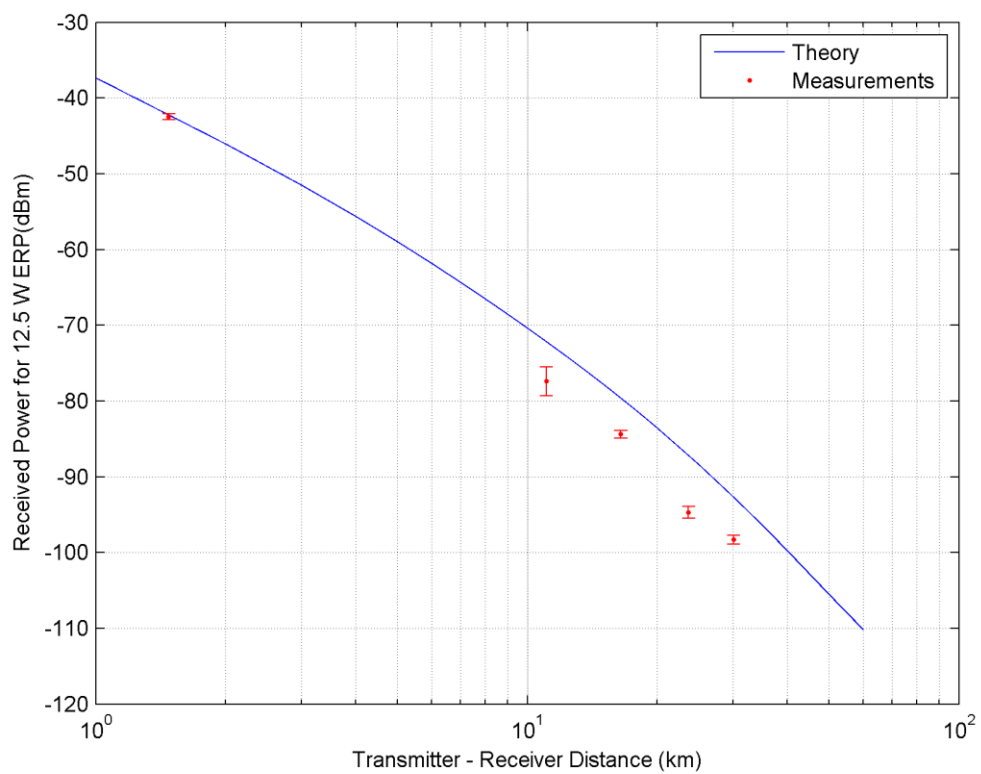


Figure 6: Received power for a 12.5 W transmission as a function of distance – theory (ITU-R M.1546 [78]) vs. measurements (VDES Channel Sounding Campaign [14]).

7 Candidate Waveforms and Access Protocols

The existing AIS waveform and access protocols are to remain unchanged [10]. A summary of waveform components and access schemes that have been considered for ASM are provided in Table 1 and Table 2 respectively. Differential PSK modulation schemes are typical. Some recent proposals suggest multiple modulation and coding schemes, specified via a MODCOD field in the packet header, allowing adaptive modulation and coding. A requirement for channel coding is acknowledged although the coding scheme is yet to be determined. Modern coding schemes being considered for VDE waveforms, such as Low Density Parity Check (LDPC) or Turbo codes may also be suitable for ASM. There have been few studies to date focusing on synchronisation techniques. Access via CSTDMA, or combined CSTDMA/ITDMA is considered.

A summary of waveform components and access schemes that have been considered for terrestrial VDE are provided in Table 3 and Table 4 respectively. The majority of these studies focus upon TETRA based multicarrier waveforms. Differential PSK and QAM modulation schemes are typical, with consideration for adaptive modulation and coding schemes. There have been few studies to date focusing on synchronisation techniques. Access schemes considered include CSTDMA, combined CSTDMA/ITDMA and ALOHA initiated TDMA.

A summary of waveform components and access schemes that have been considered for satellite VDE are provided in Table 5 and Table 6 respectively. Several studies focus upon DVB based waveforms. Differential PSK and QAM modulation schemes are typical, with consideration for adaptive modulation and coding schemes. Suggested channel coding schemes include LDPC (concatenated with BCH) and Turbo. Some recent work has been done to customise the DVB waveform for maritime needs. Access schemes considered include TDMA, FDMA, and VDE-TER/SAT resource sharing mechanisms.

A common suggestion across the proposed waveforms is the exclusion of the bit-stuffing mechanism used in AIS, e.g. replacing it with a conventional scrambler. The scrambler performs an XOR of the data with a pseudo random binary sequence, and therefore does not introduce data dependent changes to packet length.

Several studies consider techniques for sharing channel resources between satellite and terrestrial VDE, via FDMA, TDMA, partial or full frequency reuse. Hence the design of access schemes for VDE-TER and VDE-SAT cannot be performed in isolation, and strong coordination between the two activities will be required. Moreover, if the channel resource is shared without orthogonality between VDE-TER and VDE-SAT (e.g. in the case of partial or full frequency reuse) then strong coordination between the waveform design activities will also be required.

Document	Modulation Scheme(s)	Channel Coding Scheme(s)	Synchronisation, Channel Estimation & Equalisation	Comments
ITU-R M.1842-1 [11], Annex 1	$\pi/4$ DQPSK, $\pi/8$ D8-PSK	Not specified	Not specified	Based on TETRA
ENAV15-14.2.42 [5]	$\pi/4$ DQPSK	Requirement noted. Technique not specified.	Not specified	ITU-R M.1842-1 Annex 1 Similar consideration in [57]
VDES Research Status in Korea [56]	$\pi/8$ D8-PSK	Not specified	Not specified	ITU-R M.1842-1 Annex 1 based prototype and field results
Options and impacts for VDE and AIS systems [44]	Multicarrier GMSK	Not specified	Not specified	Intended to be backward compatible with existing AIS
ASM protocol proposal for PDNR ITU-R M.[VDES] [85]	$\pi/4$ DQPSK	Not specified	24 bit training sequence	Reduced data rate (compared to ITU-R M.1842-1 [11], Annex 1) to guard against Doppler induced interference with existing satellite AIS reception.
e-Navigation Synchronization Design Considerations for VDES and ASM [91]	Low bit rate, highly robust for synchronisation component, e.g. BPSK Reference to [85] for message modulation	Specified by Encoded Type field Type 0, for uncoded messages, type 1-15 (TBC) encoded Message coding scheme not specified	Predefined unique sync word/start flag Low temporal circular auto-correlation properties (e.g. Barker, Zadoff-Chu) Low temporal cross-correlation properties if multiple codes to be used in the future	Also notes that bit stuffing is not required.

Table 1: Summary of PHY components considered for ASM

Document	Access Scheme(s)
ITU-R M.1842-1 [11], Annex 1	CSTDMA
ENAV15-14.2.42 [5]	CSTDMA, ITDMA CSTDMA for the first transmission in a frame, followed by ITDMA for subsequent transmissions in that frame.

Table 2: Summary of access schemes considered for ASM

Document	Modulation Scheme(s)	Channel Coding Scheme(s)	Synchronisation, Channel Estimation & Equalisation	Comments
ITU-R M.1842-1 [11], Annex 4	16-QAM, 32 multi-carriers, 2.7 kHz spacing	Not specified	Not specified	Based on TETRA
ENAV15-14.2.42 [5]	16-QAM, 32 multi-carriers, 2.7 kHz spacing	Not specified	Not specified	ITU-R M.1842-1 Annex 4 Adapt to ITU-R M.1842-1 Annex 1 if higher robustness is required Similar consideration in [57]
VDES Research Status in Korea [56]	16 multi-carrier 16-QAM 32 multi-carrier 16-QAM	Not specified	Not specified	ITU-R M.1842-1 Annex 3, 4 prototype and field results Potential intellectual property issues with the use of TETRA were noted during presentation at IALA
Options and impacts for VDE and AIS systems [44]	Multicarrier $\pi/4$ DQPSK, $\pi/8$ D8-PSK, QAM (4 to 16)	Not specified	Not specified	TETRA based
ITU-R M.2127 [21]	2-level GMSK	Not specified	Not specified	Wideband VHF data system operated in Norway
DLR position on VDES [48]	Adaptive Coding and Modulation	Turbo, LDPC, Upper Layer FEC	Not specified	Suggests using techniques from 3G/4G terrestrial and 2/2.5 satellite standards
VDES considerations [92]	Adaptive Coding and Modulation	Turbo	Not specified	
Considerations on Terrestrial and Satellite Links Coexistence [93]	QPSK, 16-QAM	Turbo	Not specified	Based on TETRA2, also described in [79] Experiments using results from maritime channel sounding campaigns Interleaving performance improvements Investigation of frequency and delay diversity techniques

Table 3: Summary of PHY components considered for VDE-TER

Document	Access Scheme(s)	Comments
ENAV15-14.2.42 [5]	CSTDMA, ITDMA Ship-shore and shore-ship links could be by reservation through ITDMA from an ASM on either one of the ASM channels. Ship-ship link could be done initially by CSTDMA for the first transmission in a frame, followed by ITDMA for subsequent transmissions in that frame.	
Options and impacts for VDE and AIS systems [44]	TDMA with slotted ALOHA for initiating transfer to base station.	TETRA based
ITU-R M.2127 [21]	TDMA	Wideband VHF data system operated in Norway
Development of VHF Data Exchange System (VDES) [9, Annex 9]	CSTDMA with frame structure with high AIS compatibility. Terrestrial / satellite sharing scheme. Six slot frame used by VDE-TER; Satellite downlink uses four slots (inc. guard). VDE-TER switches to using the two slots that are orthogonal to the VDE-SAT downlink slots when the downlink becomes available.	Also discussed in [77] Sharing – also relevant to VDE-SAT
Sharing between VDE-TER and VDE-SAT DL [47]	FA-TDMA, FDMA	Sharing – also relevant to VDE-SAT

Table 4: Summary of access schemes considered for VDE-TER

Document	DL/ UL	Modulation Scheme(s)	Channel Coding Scheme(s)	Synchronisation, Channel Estimation & Equalisation	Comments
ENAV15-14.2.42 [5]	DL	$\pi/2$ BPSK, QPSK, 8-PSK, QAM (32 to 256)	Concatenated Low Density Parity Check (LDPC) + Bose, Chaudhuri and Hocquenghem (BCH) code	Repeated known symbols (e.g. pilots, preamble, post-amble). Sequence not specified.	Example based on DVB-S2X (digital video broadcast by satellite) standard [94]
DLR position on VDES [48]	DL	QPSK, 8-PSK, 16-QAM Optional OFDM	Turbo LDPC + BCH	Pilot insertion	Based on DVB (SH or S2X)
	UL	Spread spectrum	Turbo	Preamble and pilot insertion	Based on 3GPP W-CDMA / S-UMTS
e-Navigation Synchronization Design Considerations for VDES and ASM [91]		Low bit rate, highly robust for synchronisation component, e.g. BPSK Message modulation and coding specified via 'MODCOD' field	Message modulation and coding specified via 'MODCOD' field Strong coding scheme, e.g. Consultative Committee for Space Data Systems (CCSDS)	Predefined unique sync word/start flag Low temporal circular auto-correlation properties (e.g. Barker, Zadoff-Chu) Low temporal cross-correlation properties if multiple codes to be used in the future	
Design Consideration for VDE Satellite Down-Link [89]	DL	QPSK, 8-PSK, 16-QAM Message modulation and coding specified via 'MODCOD' field	Message modulation and coding specified via 'MODCOD' field Turbo	Pilot insertion Waveform customisation to reduce overhead	Based on DVB-SH-B (TDM mode) DVB-S2 also considered Simulation results included

Table 5: Summary of PHY components considered for VDE-SAT

Document	Access Scheme(s)	Comments
ENAV15-14.2.42 [5]	TDMA, FDMA, Full frequency reuse sharing	Sharing – also relevant to VDE-TER
DLR position on VDES [48]	Uncoordinated multiple access with interference cancellation at the receiver.	ETSI S-band Mobile Interactive Multimedia (S-MIM) standard [49].
Considerations on Terrestrial and Satellite Links Coexistence [93]	Comparison of TDMA, FDMA, Full frequency sharing, Partial frequency reuse	Sharing – also relevant to VDE-TER
Design Consideration for VDE Satellite Down-Link [89]	Alternatives for spectrum sharing with VDE-TER: 150 kHz channel shared with VDE-TER 50 kHz, exclusive to SAT downlink 3x 50 kHz channels: (1) exclusive to TER, (2) shared (3) exclusive to SAT	Sharing – also relevant to VDE-TER

Table 6: Summary of access schemes considered for VDE-SAT

8 Shortlisting Methodology

8.1 Waveform Performance Metrics and Test Methodologies

Suitable metrics are required to assess the VDES waveform and access scheme performance at each stage of the development and testing process, i.e. during:

- Candidate shortlisting – via analysis of published results
- Reference model implementation – via simulation, using appropriate channel models
- Testbed implementation – via bench tests, using a VHF channel emulator
- Field trials – via experiments at sea in real-world channels

It is typical for physical layer performance parameters, such as receiver sensitivity and co-channel selectivity, to be specified against a minimum packet error rate (PER) requirement, e.g. as specified for AIS [10].

Measurement of PER at the link layer allows the benefits of automatic repeat request (ARQ) mechanisms to be analysed. Measuring the rate of CRC failure (i.e. passed CRC for erroneous message, or erroneous CRC field for an error-free message) will allow CRC length to be optimised.

Some recommendations on testing digital communications systems in marine environments are provided in [95]. This document aims to address the challenge of comparing results for a wide range of different radio equipment being used by different administrations. Given the large variations in the probabilistic characteristics of radio channels in the maritime mobile service, the document recommends that the main parameter used to characterise the effectiveness of the equipment under test should be the gain in channel quality, relative to a reference system operated just before the start of each test. Measurement of character error probability is suggested as the test metric. Other indicators characterizing channel quality include mean link setting-up time and mean information transmission rate.

A description of trials of CCITT at VHF V.22bis (2400 bps QAM and 1200 bps PSK) is provided in [96]. Bit error rate was measured across blocks of length 10,000 bits.

A recent presentation on design considerations for VDES and ASM [91], suggests the following metrics:

- Channel symbol rate, bit rate, single user capacity
- Multiuser capacity (S/I required, channel 're-use' factors)
- Link parameters, E_b/N_0 , budget, worst case, noise consideration
- Near/far problem, spectral mask
- Amplifier cost, linearity requirements (price is approx. proportional to power squared)
- Adjacent channel interference, spectral mask, blocking
- Space issues, if different
- Receiver complexity

8.2 User Level Metrics and Test Methodologies

In order to help the VDES system designers assess how well the proposed waveforms and access schemes meet identified user needs a set of user level metrics needs to be defined. These may include the following:

- Maximum reliable communication range

- Guaranteed mean data rates in broadcast / addressed mode
- Maximum supported user density

The VDES literature [75], [91], [97] suggests the following user level metrics:

- Message loss rate
- Message latency and support for different message priorities
- Flexibility in rates and types of messages
- Use of non-patented intellectual property
- Power consumption requirements
- Cost of shore-based / ship-borne equipment and installation

Since potential applications of VDES include broadcasting of SBAS corrections [3], [31], it may also be appropriate to consider the four key performance metrics used in radionavigation and GNSS augmentation systems. These are as follows.

- **Positioning accuracy:** The degree of conformance between the estimated position of a platform and its true position; in the maritime sector this is usually specified as the horizontal position error not exceeded with a probability of 95%.
- **Integrity:** The ability of a system to provide timely warnings to users when the system should not be used for navigation; this is usually specified by the probability of an undetected failure occurring per hour of operation.
- **Availability:** A measure of the ability of the system to provide the required function and performance at the initiation of the intended operation; this is normally specified as the percentage of time that the system is available for use.
- **Continuity:** A measure of the capability of the system to perform its function without non-scheduled interruptions during the intended operation. It is specified by the probability that the system will remain available for the duration of a phase of operation (typically assumed 15 minutes), assuming that it was available at the beginning of that phase of operation.

The accuracy, integrity, availability and continuity performance requirements for radionavigation and augmentation systems used in the maritime sector are specified in IMO Resolution A.1046(27) [98]. The accuracy and integrity requirements may impose constraints on the minimum VDES SBAS message rate, maximum latency and integrity (see e.g. the CRC failure rate mentioned above). It would also seem desirable that the availability and continuity of the VDES SBAS broadcasts should be no worse than that required by A.1046. It is expected that the availability at a given range from a shore station will be driven by long-term diurnal / seasonal fluctuations in the received signal field strength. The continuity will presumably be affected by short-term effects such as multi-path fading and RF interference.

A description of end-to-end, user level, tests of VHF data communication equipment in the maritime environment is provided in [96]. A VHF data link was set up between a vessel sailing in the English Channel and a coast station. The radio link was extended via the PSTN to the vessel owner's office. An ARQ error correcting protocol was used. Data files from an office software package were transferred in both directions and the correct receipt and number of re-transmissions observed.

User level tests of prototype VDES equipment are described in reference [51]. Bench experiments were conducted using the ASM 1 and 2 channels, while also maintaining normal AIS operation. Each prototype VDES unit was connected to a PC running a file transfer application. Apart from providing the user interface, the application also performed

segmentation of the data files into messages suitable for transmission, error correction and throughput measurements. The measured throughput was compared against that of AIS.

9 Scope of VDES Waveform Study

The VDES Waveform Study will focus on:

- The physical and data link layers
- Terrestrial VDES functionality beyond the existing AIS, i.e. ASM and VDE-TER

The study will coordinate with:

- IALA VDES working groups to advance work on the PDNR for VDES (WG1), and to advance work on user requirements (WG2) [99].
- Developments in the satellite domain, especially with regard to spectrum sharing as discussed in Section 7.
- Programs that will also advance the development of VDES, such as the DMA-led EfficienSea2 project and ESA projects [97].

Scope of the VDES Waveform Study is highly scalable, according to available funding and further coordination with other studies in order to avoid duplication. An example work plan for the remaining phases of the study is provided in Section 10.

10 Proposed Work Plan

This section presents an example work plan for remaining phases, including key milestone review points and deliverables. The work plan is based upon the proposal provided in [2], and has been refined according to the scope of the study defined in Section 9. The scope and work plan will be further refined, and timelines will be estimated, upon determination of available funding. Further coordination with other programs will also be undertaken in order to ensure effective use of resources.

Phases may be carried out sequentially. However there is scope for some concurrency in phases 2-5. In particular, design components of Phase 3, 4 and 5 could occur prior to completion of the previous phase. There is also scope for some concurrency between individual work packages within each phase.

10.1 Phase 2 - Initial Candidate Shortlisting

The purpose of this work package is to agree upon a shortlist of candidate waveforms and access methods to be taken forward for implementation within the software reference model. Factors to be considered will include:

- Indicative implementation complexity
- Reported performance metrics in the existing literature
- Fit-for-purpose: likely to meet the identified user requirements and technical constraints

This phase of work will also develop the VHF channel and interference models to be implemented in the reference model.

10.1.1 Phase 2 Work Packages

10.1.1.1 WP 2.1 Channel Model

- Development of suitable models for the terrestrial VDES channels, i.e. ship-to-ship and ship-to/from-shore channels
- Based on existing models and maritime channel sounding studies discussed in Section 6, and interference considerations identified in Section 5.1

10.1.1.2 WP 2.2 Technical Requirements

- Derivation of technical requirements for ASM and VDE-TER
- Based on user requirements (coming from IALA VDES user requirements WG2 [99])
- Consideration for real world maritime channel effects based on WP 2.1
- Definition of requirements for parameters relevant to physical and link layers

10.1.1.3 WP 2.3 Test Plan

- Development of detailed test plan for evaluation of candidate waveforms

10.1.1.4 WP 2.4 Candidate Waveform Selection

- Consideration of top level waveform characteristics (e.g. single vs multicarrier) based upon channel model
- Trade-off analysis of waveform and access scheme methods, at waveform/link level and component level (e.g. modulation, synchronisation, channel coding, access method, ARQ).

- Preliminary performance analysis – mathematical analysis and/or existing results in the literature

10.1.2 Phase 2 Milestones

- Channel model complete
- Technical requirements complete
- Test plan and candidate waveform selection complete

10.1.3 Phase 2 Deliverables

- VHF channel model specification document
- Technical requirements document
- Test plan document
- Candidate waveform selection report, including candidate shortlist

10.2 Phase 3 - Reference Model Implementation and Simulation Study

This work package will develop a complete modular software reference model allowing rapid performance comparison of candidate waveforms, and tuning of waveform parameters.

This work package will also optimise the performance of selected candidate waveforms using reference model simulations as a design tool.

10.2.1 Phase 3 Work Packages

10.2.1.1 WP 3.1 Reference Model Overview Design

- Development of reference model architecture
- Selection of implementation framework (language, revision control and development environment). This will be done with the intention of sharing this framework as far as possible with the embedded system development in Phase 4.
- Specify coding standards and documentation standards
- Specify methodology for integration of reference model assets into embedded system testbed
- Specify user interfaces into reference model

10.2.1.2 WP 3.2 Reference Model Detailed Design

- Design of all software modules for each system component, including candidate transmitter and receiver modules, and channel model components
- Development of reference model test plan for unit, integration and acceptance testing

10.2.1.3 WP 3.3 Reference Model Implementation and Testing

- Development and module testing of all reference model software modules
- Integration and testing of full reference model

10.2.1.4 WP 3.4 Waveform Analysis

- Initial performance evaluation of each candidate waveform, following previously developed test plans
- Optimisation and selection of key waveform parameters (iterative optimisation using the reference model as an analysis tool)

- Develop recommendations for waveforms to be taken forward to field trial

10.2.1.5 WP 3.5 Access Scheme Analysis

- Initial performance evaluation of each candidate access scheme, following previously developed test plans
- Optimisation and selection of key access scheme parameters (iterative optimisation using the reference model as an analysis tool)
- Develop recommendations for access schemes to be taken forward to field trial

10.2.2 Phase 3 Milestones

- Overview design complete
- Detailed design complete
- Waveform and access scheme analysis complete

10.2.3 Phase 3 Deliverables

- Reference model architecture document
- Detailed design document
- Reference model test plan document
- Report on recommended waveforms and access schemes

10.3 Phase 4 - Testbed Implementation and Laboratory Performance Evaluation

This package of work will develop the hardware and embedded software systems (most likely based on a COTS software defined radio platforms) and test rigs to be used for field trials. Laboratory trials of the shortlisted candidate waveforms will be conducted (using a VHF channel emulator) to validate performance prior to field trials.

10.3.1 Phase 4 Work Packages

10.3.1.1 WP 4.1 Testbed Specification and Procurement

- Specification of testbed architecture including test rig automation requirements
- Hardware requirements, specification and procurement

10.3.1.2 WP 4.2 VDES System Development

- Development of modules for each system component, leveraging designs and implementations from WP 3.2 and WP 3.3
- Module testing, validation and calibration against reference model

10.3.1.3 WP 4.3 Testbed System Development

- Specification of data formats (to facilitate data access and use post field trials)
- Development of test rig automation, logging systems and post-processing data analysis tools
- End-to-end system testing

10.3.1.4 WP 4.4 Laboratory Performance Evaluation

- Laboratory-based performance evaluation of each waveform candidate, following previously developed test plans
- Representation of real world maritime channel via VHF channel emulator
- Documentation of findings

10.3.2 Phase 4 Milestones

- Testbed specification complete and system hardware procured
- Field trial ready system complete and tested in laboratory
- Laboratory performance evaluation candidate waveforms complete

10.3.3 Phase 4 Deliverables

- Testbed methodology and architecture design document
- Design documentation for all testbed modules
- Candidate waveform implementation performance results document
- Field trial ready system

10.4 Phase 5 - Field Trials

The objective of this final phase is to obtain performance results for the final set of waveform candidates in a variety of real-world marine environments.

It is preferable to be able to test all candidate waveforms simultaneously (as far as possible, while maintaining a controlled interference environment) for each location and test scenario.

It may be desirable for initial analysis of trial to be performed near-real-time (e.g. overnight) to allow adaptation of test plans and scenarios during the campaign.

It may also be desirable to stage the field trials into several discrete campaigns to allow the results from one campaign to inform the detailed design of the next campaign.

Small scale testing of candidate access schemes may be conducted in the field. Large scale tests, i.e. requiring large numbers of active nodes, may be examined using the reference model during Phase 3.

10.4.1 Phase 5 Work Packages

10.4.1.1 WP 5.1 Field Trial Preparation

- Identification of test scenarios and key performance metrics
- Selection of test sites
- Specification of testbed system configuration
- Development of test plan and schedule for each test scenario/site

10.4.1.2 WP 5.2 Field Trial Execution

- Execute field trials and capture data
- Perform preliminary analysis onsite during trial and adapt plan as required

10.4.1.3 WP 5.3 Field Trial Analysis

- Analyse field trial data sets

- Where required, investigate features or anomalies further within reference model
- Prepare preliminary results and recommendations
- Prepare final report and recommendations

10.4.2 Phase 5 Milestones

- Field trial preparation complete
- Field trials executed
- Analysis and recommendations complete

10.4.3 Phase 5 Deliverables

- Field trial test plan
- Field trial data sets
- Preliminary field trial report for sponsor review and comment
- Final report and recommendations

11 Conclusions and Recommendations

This report has presented a comprehensive review of literature relating to VDES development, drawn from sources including IALA, ITU and IMO, along with academic journals, related industry standards and reports. It has also captured the current state of design considerations for VDES waveform and access scheme development.

A number of existing studies have already been undertaken to develop user requirements for e-navigation and the VDES, and IALA are currently consolidating these requirements. During Phase 2 of the proposed VDES waveform study, these user requirements will be used as a basis to derive technical requirements for development and testing.

Past studies have developed several models for terrestrial propagation, typically in the context of land mobile radio applications. Recent channel sounding studies conducted at sea have identified a need to refine these models for maritime environments. Phase 2 of the proposed study will produce an appropriate terrestrial maritime channel model for simulation and laboratory channel emulation.

Physical layer design for ASM has received recent attention from several studies. The use of differential PSK modulation is typical. Coding schemes and synchronisation mechanisms are still to be determined. Support for multiple modulation and coding schemes has been proposed, allowing the link to adapt to channel conditions. The proposed VDES waveform study will compare ASM waveform candidates for terrestrial use.

Waveform design for satellite VDE has received considerable attention. Several waveform designs currently under development and test are based upon the DVB-S family of standards. Customisation of these waveforms for VDES applications and the VDE-SAT channel has recently begun. The design of satellite VDE waveforms is outside of scope of the proposed study. However, coordination with VDE-SAT developments will be maintained, as noted in Section 9.

Waveforms proposed for terrestrial VDE have been derived from TETRA. Recent maritime channel sounding campaigns have identified several differences between land and maritime propagation conditions. A key requirement for VDES is to minimize the complexity of the ship-borne equipment. One study has identified that there is not a significant difference in equaliser computational complexity between multicarrier and single carrier schemes at VDES data rates. Several studies have also noted that the use of multicarrier modulation requires a power amplifier capable of significantly higher output power than is required when using single carrier modulation. VDES channels are narrow and support low signal bandwidth. This results in a fading profile that is typically flat across the channel, with multipath components that are not resolvable. The proposed study will use the maritime channel model to compare trade-offs between single and multicarrier waveforms. This will allow the design of the VDE-TER waveform be customised for optimal performance in maritime environments and minimal complexity.

There has been consideration to date on the allocation of channel resources at a top level e.g. between terrestrial and satellite components. However, design of the VDES link layer operation requires significant further study to ensure efficient access and ARQ mechanisms. The proposed study will investigate efficient link layer techniques for terrestrial VDES.

The proposed VDES waveform study (Section 10) will develop and compare ASM and VDE-TER waveform and access scheme candidates via simulation and testing, in the laboratory and in the field. Each phase of the study will narrow the field of consideration for waveform design in order to deliver a system that exploits and customises modern communication techniques for VDES application. The channel used for testing at each stage will be consistent with real world maritime conditions.

12 Publications

This report is available as Input Document Number **TBD** to the meeting of the IALA ENAV Committee Working Group 3, ENAV 16, Saint-Germain-en-Laye, 20th to 24th April 2015. It will also be distributed through the normal R&RNAV report distribution system.

A Summary of Previous User Requirements Studies

This appendix reviews previous studies of user requirements for e-navigation and the VDES. The document sources are listed in chronological order.

- *Communications for e-Navigation [15]*

This study examined the range of possible applications that would need to be supported by the maritime communication infrastructure in a future e-navigation environment (considering 2020+). The applications were broken down into three areas: safety related; operationally related; and commercial. An overview of the applications considered is shown in Table 7.

The study then assessed the likely data levels that would be typical in two busy coastal areas around the UK, the Solent and the Dover Straits, resulting from future vessel and communication traffic. The process is illustrated pictorially in Figure 7 and the same method could be suitable for determining data requirements for VDES.

Within the study scenario analysis, in both scenarios, the levels of safety related data that needed to be passed from ships to shore and shore to ships were found to be negligible (sub 10 kbit/s in either direction on average) when compared to potential VDES data link capacity. Operationally related data levels were more significant, but again within the reach of VDES communications (up to a 100 kbit/s in either direction on average). However, the possible commercial applications of communications were found to have the potential to provide large levels of data traffic which cannot be entirely accommodated by the VDES.

The study was conducted in 2009 and the GLA have recently commissioned work to update the report (results expected by end of March 2015).

Safety	Operational	Commercial
AIS position reports	Weather data	Voyage orders
AIS AtoN (Aid-to-Navigation)	Ship reporting	Commercial port services
Digital Selective Calling	Notifications to coastal states	Operational reports
Long Range Identification and Tracking (LRIT)	Port arrival notification	Crew personal communications
Differential GNSS	IALA Maritime Information Objects	Crew e-training
NAVTEX	Port & VTS surveillance feeds	Cargo telemetry
VTS Coordination	Electronic chart updates	Passenger Internet access
Emergency SAR	Access to vessel & equipment manuals	Point of Sale
	Remote maintenance & service	
	Telemedicine	

Table 7: Overview of maritime communication applications by type [15]

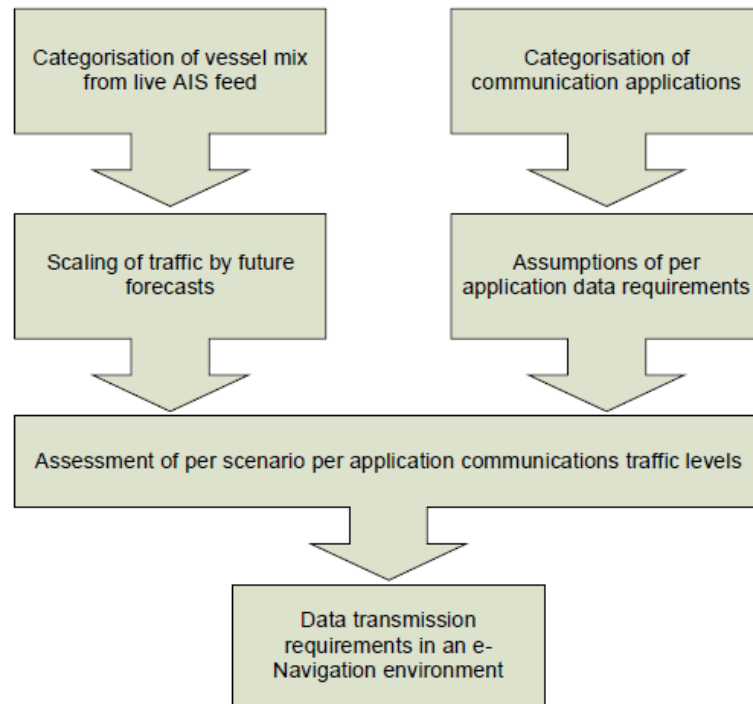


Figure 7: Overview of the scenario process [15]

- *Guidance on the Use of Application-Specific Messages, IMO SN.1/Circ.289 [18]*

This IMO document provides an overview of the purpose and scope of AIS ASMs. The messages described in this document are recommended for broad international use.

The document identifies 22 applications/message types, such as: Met/Hydrological data, Dangerous cargo indication, Number of persons on-board, etc. In addition to the IMO defined messages, IALA also maintains a list of ASM definitions defined by national administrations which is available at <http://www.e-navigation.nl/asm>. These lists can be used to determine data requirements for ASM applications.

The following functional requirements for AIS ASM are stated in the document:

- AIS ASMs may be either addressed or broadcasted.
- The transmission of any addressed AIS ASM prompts a system acknowledgement on the VDL by the receiving AIS station. This acknowledgement should not be confused with a user acknowledgment.
- To obtain a high probability for reception, message transmissions should be made with access method Fixed Access Time Division Multiple Access (FATDMA) in reserved time slots (see ITU-R Recommendation M.1371 [10]). IALA Recommendation A-124 Ed. 1.3 *On AIS Shore Station and Networking Aspect relating to the AIS Service* recommends FATDMA allocations not exceeding 3 consecutive slots.
- It should also be possible to interrogate a ship for a specific message and automatically receive the requested information, provided that the ship has the appropriate equipment installed.

- *IALA Maritime Radio Communication Plan, Edition 2 [27]*

The Maritime Radio Communications Plan (MRCP) was developed by IALA to assist in the selection of radio communication systems required to support e-navigation.

The e-navigation communication requirements presented in the document are based on report [15]. Reference is also made to the IMO/ITU Joint Experts Group which states that data rates higher than 200 kbit/s will be required for e-navigation.

The plan anticipates that the implementation of e-navigation will result in a continuing, but declining need for voice communications on VHF, and an increasing need for data communications.

New applications/uses of AIS are expected to emerge, such as:

- Navigational and environmental warnings
- Ship reporting
- Repeater stations
- Satellite detection of AIS
- Personal Locating Beacon (PLB) based on the AIS-SART technology
- Position, Navigation and Timing (PNT) by means of AIS ranging

Table 8, adapted from the MRCP, then gives some indication of the possible future applications for the different components of the VDES.

The MRCP also identifies some functional requirements for an integrated e-navigation communications system (of which VDES would presumably be a part):

- 'An ideal e-navigation communications system would operate automatically, selecting the best communications technology, channel, and characteristics in accordance with the ship's location, and the type of data to be exchanged. This automatic process would be managed in accordance with rules and the needs of the mariner that might include the following:
 - Need to avoid latency – such as when exchanging safety and navigation data with other vessels or receiving it from electronic systems ashore or on the water surface;
 - Ability to delay the sending or receipt of data – such as the sending of non-urgent administrative data, or the receipt of chart corrections for the current voyage, a subsequent voyage or for a port to be visited later in the present voyage;
 - Value / Cost of communications;
 - Importance of the data for commercial services on board;
 - Rate of data transfer (capacity of transmission).
- Some of the rules managing this seamless data communications would be programmed into the system, for example those concerned with safety of navigation. Other rules might be set by the ship's operator in accordance with their procedures and the operator's commercial model. Further rules might be adjusted, from time to time, by the ship's crew. Such an automatic, seamless management of e-navigation communications appears to be essential in the future.'

	ASM	VDE	AIS for safety of navigation	AIS long range
Functionality	Marine safety information Marine security information Short Safety related Messages (SSRMs) General purpose information communication	General purpose data exchange Robust high speed data exchange VDE satellite communications	Safety of navigation Maritime locating devices	Satellite detection of AIS Possible support of future SAR
Sub functionality	Area warnings and advice Meteorological and hydrographic data Traffic management Ship-shore data exchange Channel management	High message payload Satellite communications	Ship to ship collision avoidance VTS Tracking of ships Locating in SAR VDL control (by Base Station)	Detection of vessels by coastal states beyond range of coastal AIS base stations
Message types for AIS protocol	IMO SN.1/ Circ.289 international ASMs Regional ASMs Base Station		Vessel identification Vessel dynamic data Vessel static data Voyage related data Aids to Navigation Base Station	Satellite detection of AIS Possible support of future SAR

Table 8: VDES communications including AIS, ASM, and VDE [27]

The Plan also states that:

- 'Legacy AIS functionality will be maintained.
- AIS channel management, using Channel 70, already available internationally, should be maintained until it is replaced by another internationally agreed method of channel management.'

The Plan assumes that AIS and digital VHF data coverage will be available anywhere within the GMDSS Sea Area A1 (typically up to 20 NM to 30 NM from the coast; see Table 1 in the MRCP).

- *Report from the JCG Workshop on International Standardization of Next Generation AIS [43]*

At this workshop, the following definition of the VDES was agreed:

'The VHF Data Exchange System (VDES) is a VHF maritime data communication system that includes the functions of AIS, facilitates e-navigation, supports GMDSS modernization and general maritime communication'.

The following functional requirements for VDES were identified:

- use high level interface (e.g. IEC 61162-450);
- use common phrase of communication;
- permit text message;

- use S-100 and Common Maritime Data Structure (CMDS);
- use common templates;
- use automatic timing based on events;
- use machine to machine communication;
- use user-friendly human interface;
- provide multiple access to information network amongst ships and shore users;
- have the ability to cross check multiple sources of critical navigation information;
- use a standard management method for incorrect data;
- use automation in action, integrity and interface;
- enable automatic updates based on events;
- access the update status by globally available means;
- use short text message
- use additional data beyond voice communication (machine to machine communication);
- prioritize SAR message in slot management;
- enable gathering necessary information from different data sources shore and onboard;
- provide efficient remote access to ship owners;
- provide an automated record of data transfer;
- use automatic selection of access means;
- use automatic exchange of data and information;
- use automated access to shore based data base of information regarding navigation and others (e.g. metrological, hydrographical, traffic);
- use automated broadcast of information regarding navigation and other;
- use automatic and autonomous data communication;
- use automatic and accurate logging of data communication;
- provide an acknowledgement of messages;
- use self-diagnostic and heartbeat function;
- use Recommendation ITU-R M.1842-1 (update);
- have secure communication capability.

Further, the following GMDSS-specific functional requirements for VDES were identified:

- include alerting function with nature of distress using existing message;
- include acknowledgement using existing message;
- be able to receive distress alert and acknowledgement;
- include reliability on latency of the data being transmitted;
- include locating and identification capability;
- include data communication capability between ship - ship, ship - shore and ship - SAR aircraft and support subsequent communication;
- include MSI promulgation;
- be capable of urgency and safety alerting/acknowledging and communication;
- be capable of transmitting messages with the priority of distress, urgency, safety and general;

- provide access to data or data base to assist SAR automatically and autonomously.
- *Additional Considerations for VDES Design [73]*

This IALA ENAV meeting working document contains some additional requirements to be considered in the design of VDES:

- Protection / increase of the receive capacity of the AIS shore stations when VDE is collocated: The trigger to ask for additional frequencies was that the AIS VDL was getting too crowded for the AIS shore stations to obtain adequate target reception and much slot reuse was witnessed. Since the impact of an overloaded AIS VDL are much more important for shore stations than for ship stations, **the additional frequencies should help preserve or increase the reception capacity of shore-based AIS stations first and foremost.**
- Requirements for a satellite downlink and uplink: Requirements should consider the capacity of acknowledgment of messages received from the satellite and request for information from the satellite may also be required.
- If compromises need to be made in the VDES design, they should consider the current e-navigation user requirements which can be roughly estimated at (numbers from Canadian user requirements matrix and may be very different with other applications, e.g. MONALISA):
 - 80% of bandwidth will be required for shore-to-ship communications (including satellite downlink);
 - 17% of bandwidth for ship-to-shore communications (including satellite uplink);
 - 3% of bandwidth for ship-to-ship communications.
- The limitation and practicality on on-board and on-shore installations and radio capabilities must always be considered. Specifically with respect to the interaction between AIS/VDE/ASM/SAT/voice, etc.
- *Maritime Safety Information Dissemination in the Arctic as a Use Case for the VDES Satellite Component [38], [39], [42]*

This IALA ENAV Communications WG meeting input document presents an analysis of an example application (MSI dissemination in the Arctic) for VDE-SAT.

Two services were considered and the following user requirements were assumed:

- Service 1 – Ice Maps
 - Maps encoded using ASMs
 - Data volume: 8 kB/day
 - Latency: 30 min to 120 min
- Service 2 – MSI Hazards
 - Hazards bulletins and charts encoded as ASMs
 - Data volume: 30 kB/day
 - Max. latency 30 min
- General
 - It shall be possible to authenticate the source to prevent spoofing by other VHF sources.

The analysis showed that:

- The VDE-SAT has the capability to disseminate between 20 MBytes (worst case) and 34 MBytes (best case) per day to every location within the Arctic.
- More than 85% of the Arctic region will receive a broadcast message within 30 minutes. After a few hours, 100% of the Arctic region will have received this message. This is with a single satellite.
- *User Requirements for VDES [100]*

This IALA ENAV Communications WG meeting output document collates user and data-related requirements for VDES that were identified as of August 2013.

Annex 2 maps user needs identified by IMO to different VDES components.

Annex 3 contains example services/use cases for SAT VDES, incl. latency, refresh rate and estimated data rate requirements. The selection of services appears to be based on the prioritised e-navigation solutions and includes: MSI, Reports from ship, SAR, Satellite based augmentation systems (SBAS).

Annex 4 contains results of a study into e-navigation user needs conducted by the Canadian Coast Guard (CCG). This later became the basis for the VDES User Needs Template [101] maintained by IALA ENAV Communications WG.

The CCG study covered 6 geographical areas within the CCG service area; these were divided into sub-areas such as coastal, major ports, etc.

The selection of services was based on e-navigation solutions identified by IMO. The following 3 services were considered:

- Environmental Information
- Waterways Management
- Emergency

The services were broken down into categories and further into individual data items. It was assumed that the data would be transmitted as ASMs. For each data item the following parameters are listed:

- Data source and format
- Refresh rate
- No. of ASMs per cycle
- Transfer per day per site (kB)

Priority for each data item/area combination is also included.

The studies included in this document provide estimated data rate requirements per data item but the overall data requirements for real-world scenarios were not determined.

- *Report of the Ninth Meeting of the Joint IMO/ITU Experts Group on Maritime Radiocommunication Matters, IMO NCSR 1/17 [25]*

This IMO document discusses, among other things, the role of AIS/VDES in the modernisation of GMDSS. It was recognised that AIS/VDES has the potential to contribute to meeting the following functional requirements for GMDSS:

- Transmit ship-to-shore distress alerts by at least two separate and independent means, each using a different radio communication service;
- Transmit and receiving ship-to-ship distress alerts;
- Transmit and receive SAR coordinating communications;

- Transmit and receive on-scene communications;
- Transmit and receive signals for locating;
- Receive MSI; there is a need for machine-readable MSI, that can readily be displayed on navigational systems.

The document also states that 'Digitization should not interfere with global use of VHF channels 16 and 70. Elements operating satisfactorily should remain in place'.

- *IALA Guideline No. 1108 on The Challenges of Providing AtoN Services in Polar Regions [35]*

This IALA Guideline mentions VDES as one of the technologies that could enhance communications with ships operating in the polar areas and identifies the following e-navigation information services that could benefit navigation in the Polar Regions:

- MSI
- Sea Traffic Management – dynamic route planning, QA for hydrographic data, global sharing of maritime information, for example user-shared ice-routing
- Virtual AtoN

References are also made to the Maritime Cloud and ArcticWeb projects.

- *An Overview of the 'Maritime Cloud' – Proposed Information Exchange Infrastructure for e-Navigation [36]*

This IALA ENAV Communications WG meeting input document provides an overview of the Maritime Cloud concept, including a description of key anticipated services, contributions to e-navigation, and relation to the GMDSS.

The document claims that the Maritime Cloud (and through it potentially also the VDES) has the potential to contribute to all the five IMO prioritised e-navigation solutions (S1 to S4, S9 [28]). Some examples are included below.

- S2: Means for Standardized and Automated Reporting - FAL Reporting

The Convention on Facilitation of International Maritime Traffic (FAL Convention) includes a list of documents which public authorities can demand of a ship. IMO has developed standardized forms for seven of these documents, which are (see IMO FAL.5/Circ.40 [30]):

- IMO General Declaration (FAL form 1)
- Cargo Declaration (FAL form 2)
- Ship's Stores Declaration (FAL form 3)
- Crew's Effects Declaration (FAL form 4)
- Crew List (FAL form 5)
- Passenger List (FAL form 6)
- Dangerous Goods (FAL form 7)

Today the required information is still often printed off and submitted in paper form, only to be re-entered manually at the other end. e-Navigation solution S2 is specifically targeted towards enabling automated electronic exchange of such information, based on the recommendations of the IMO FAL. The Maritime Cloud/VDES could provide mechanisms to enable such an electronic exchange.

- S4: Integration and Presentation of Available Information in Graphical Displays Received via Communication Equipment

- An MSI or Weather Information Service based on Geocasting (MSP⁸ 5, MSP 15)

The 'Geocast' capability of the Maritime Cloud will be particularly useful for providing a quality assured, standardised MSI or Weather service, based on S-100 [102] standardized information services. This service can extend the existing coordinated broadcast service, providing quality assured delivery of MSI to all ships inside a given area, or make available to a ship MSI or Weather data relevant to an intended voyage.

Such a Geocast MSI service will enable a complementary service based on existing commercially available data links as well as ASMs that can carry S-100 standardised data messages displayable on e-navigation enabled display systems such as an upgraded ECDIS. This will facilitate a transition from the existing NAVTEX and SafetyNet systems under the current GMDSS, towards new communication systems such as NAVDAT or VDES.

- S9: Improved Communication of the VTS Service Portfolio

- VTS Information Service (MSP 1)

Existing VTS information services available in a particular VTS area, such as weather or oceanographic data, traffic, special restrictions, etc., may be made automatically available in a standard format (S-100).

The chosen communication system may however impose restrictions to the level of detail that can be contained in the VTS information service. Different versions (with different levels of detail) of the same information service, may thus be implemented.

- Navigational Assistance Service and Traffic Organisation Service (MSP 2 & MSP 3)

Will require, in some cases, assurance of authenticity of the communicating parties. The identify mechanisms of the Maritime Cloud will support authenticated and secure communication.

- Vessel Shore Reporting (MSP 8)

It is expected that most of the mandatory reporting information related to VTS reporting lines can be derived from information provided by systems already available on-board. Creating a local ship-borne collection of such information and automation of the mandatory reporting process will reduce the need for extensive use of voice communication for manual and repeated reporting.

In the short term, mandatory reporting information might be encapsulated into ASMs.

The Maritime Cloud could also support the future GMDSS. The key GMDSS-related applications would be expected to include MSI dissemination in machine readable data formats, and communications for SAR coordination.

The Maritime Cloud assumes a shipside component that will provide an abstraction layer to communication, encapsulating the complexities of communication roaming. The component is envisaged to be part of the Integrated Navigation System (INS), and will

⁸ Maritime Service Portfolio; see the IMO e-Navigation Strategy Implementation Plan [28].

need to function as a local information hub, connected with relevant sensors, navigation displays and communication equipment (such as the VDES transceiver). It is assumed that this component will address the following tasks:

- Interface different communication systems;
 - Provide a resilient connection to external information services for relevant user interfaces and display systems related to navigation;
 - Perform 'least cost route' selection of communication links, based on user defined rules;
 - Assume responsibility for regular reconnect or position update to the Maritime Cloud Maritime Messaging Service (implementing the LRIT⁹ functionality as a side effect);
 - Hold a store-and-forward prioritized queue of outbound messages from ship to other actors, in case of an outage in communication;
 - Perform system acknowledge of received maritime messages that request system acknowledge and hold them in a store-and-forward inbound queue until delivered to relevant user systems;
 - Hold and regularly update the local copy of 'The Almanac'¹⁰, and make it available to relevant user systems;
 - Handle public-key infrastructure and the ship's certificates;
 - Hold a list of updated information relevant for automated reporting.
- *A Vision for the Operational Context of VDES [37]*

This IALA ENAV Communications WG meeting input document describes the potential role of the VDES within the concept of the Maritime Cloud.

VDES is seen as one of a number of data links providing access to the Maritime Cloud. It is expected that VDES will be globally standardised and free of charge for the mobile user.

Applications of VDES highlighted in the document include:

- MSI dissemination
- Improved provision of VTS Services and Local Port Services,
- Automated reporting.

Several functional requirements for VDES were identified in the document, which include:

- VDES should be designed to give priority to communication as defined by the GMDSS (Distress \ Urgency \ Safety \ Routine communication). It was proposed that this may be implemented by reserving time slots for different priorities.
- In relation to GMDSS, the document also proposes that VDES satellites could be used for monitoring of Ch 70.
- In order to enable advanced information services to evolve for the future, it is recommended that IPv6 protocol is applied, rather than building on the AIS protocol using static definitions of Application Specific Messages. The Maritime

⁹ Long Range Identification and Tracking

¹⁰ Offline version of the public part of the Maritime Identity Registry and the Maritime Service Portfolio Registry, acting as a 'yellow pages phone book' [36].

Cloud will provide higher-layer mechanisms to ensure authenticity, integrity and confidentiality of transferred information, where appropriate.

- *Report to the Maritime Safety Committee, NCSR 1/28, Annex 7 [28]*

Annex 7 of this IMO document contains the approved e-Navigation Strategy Implementation Plan (SIP).

The SIP focuses on 5 prioritised e-navigation solutions:

- S1: Improved, harmonized and user-friendly bridge design;
- S2: Means for standardized and automated reporting;
- S3: Improved reliability, resilience and integrity of bridge equipment and navigation information;
- S4: Integration and presentation of available information in graphical displays received via communications equipment; and
- S9: Improved communication of VTS Service Portfolio (not limited to VTS stations).

As part of each one of the above prioritized e-navigation solutions, several sub-solutions were identified in the SIP, which could provide a basis for defining user requirements for the VDES. Only one of the solutions (S2) explicitly mentions the VDES, although most of the remaining (sub-)solutions can also be considered relevant to the AIS/VDES development.

ID	Identified Services
MSP1	VTs Information Service
MSP2	Navigational Assistance Service (NAS)
MSP3	Traffic Organization Service (TOS)
MSP4	Local Port Service (LPS)
MSP5	Maritime Safety Information Service (MSI)
MSP6	Pilotage service
MSP7	Tugs Service
MSP8	Vessel Shore Reporting
MSP9	Telemedical Assistance Service (TMAS)
MSP10	Maritime Assistance Service (MAS)
MSP11	Nautical Chart Service
MSP12	Nautical Publications Service
MSP13	Ice Navigation Service
MSP14	Meteorological Information Service
MSP15	Rea-time Hydrographic and Environmental Information Service
MSP16	Search and Rescue Service

Table 9: Proposed MSP [28]

As part of the improved provision of services to vessels through e-navigation, Maritime Service Portfolios (MSPs) have been identified as the means of providing electronic information in a harmonized way, which is part of solution 9. The proposed list of MSPs is presented in Table 9. Further information about MSPs is set out in Annex 2 of the SIP. MSPs could also provide a basis for defining user requirements for VDES.

The following six areas have been identified for the delivery of MSPs:

1. Port areas and approaches;
2. Coastal waters and confined or restricted areas;
3. Open sea and open areas;
4. Areas with offshore and/or infrastructure developments;
5. Polar areas; and
6. Other remote areas.

These area categories could be used as a basis for organising VDES use cases/scenarios and planning of sea trials.

As mentioned earlier, the SIP endorses the VDES and Maritime Cloud concepts.

- *Design Considerations for VDES [63]*

This IALA ENAV meeting working document summarises functional requirements for VDES and its components that were identified by the Communications WG as of October 2014 and presents some design considerations.

The following general requirements for VDES were identified:

- VDES shall protect AIS integrity for collision avoidance and identification purposes;
 - Consider scheduled AIS transmissions;
 - Consider slot selection rules of AIS to avoid the loss of near targets on AIS.
- VDES shall have similar service area as AIS (power 12.5 W, sensitivity);
- The duty cycle of any given transmission shall respect AIS and voice communications;
 - Limit length of ASM and VDE transmissions;
 - Limit amount of ASM and VDE transmissions per minute (mobile, base station), may be adapted dynamically depending on channel load.
- The transition period between having a VDES service and capabilities available on ships shall be carefully considered;
 - Existing AIS equipment may not receive on ASM and VDE;
 - Interference with current VHF voice communications;
 - There will be a transition period where ASMs will be on AIS and/or ASM.

The following ASM-related requirements were identified:

- The ASM channels shall, to the extent that is practical, support all ASM formats;
- The ASM component shall protect AIS integrity for collision avoidance and identification purposes;
- The ASM shall protect AIS integrity for shore side monitoring and control purposes (cargo type, etc.);
- The duty cycle of any given ASM transmission must respect AIS and voice communications, and if practical VDE;
- The ASM modulation may be variant on a per slot basis; (one modulation scheme for ASM only)
- The ASM shall use an efficient modulation scheme, not necessarily GMSK;
- The ASM shall provide a robust link, e.g. FEC;
- The ASM shall support differentiated priority of message transmissions as described in the GMDSS;
- All ASM transmissions must have a unique identity (MMSI, MAC, etc.);
- The ASM should maximize, to the extent that is practical, satellite reception; (e.g. FEC);
- The ASM channels do not need to duplicate transmissions on both channels, two independent data channels;

- It shall be possible to manage the capacity and use of the ASM channels from the shore side;
 - Set limits for the amount of ASM messages per ASM channel per unit;
 - Different limits for ASM 1 and ASM 2;
 - Allow for reservation of slots.
- The ASM link shall support a maximum control range of TBD with considerations for authentication;
- The ASM link may support at a minimum line of sight communications;
- Synchronisation: either UTC direct or derived from received AIS messages.

The following VDE-related requirements were identified:

- The VDE shall support differentiated priority of message transmissions as described in the GMDSS;
- The VDE shall provide a robust link, e.g. FEC;
- The VDE medium access schemes and waveform may include multiple modulation and encoding schemes as dictated by the link requirements;
- The VDE shore side may support full duplex operation;
- The VDE shall support semi duplex operation;
- The VDE shall support a satellite sharing scheme (freq. and/or time);
- The VDE transmissions shall have a unique identity;
- The duty cycle of any given VDE transmission shall respect AIS, ASM, and voice communications;
- It shall be possible to manage the capacity and use of the VDE channels from shore side;
- The VDE link shall support a maximum control range of TBD with considerations for authentication;
- The VDE link may support a minimum terrestrial service range within line of sight at a lower quality of service;

- *Draft IALA Recommendation On Introduction of VDES and Protection of the AIS [13]*

This IALA ENAV meeting working document contains rationale for recommending a transition period to handle the introduction of ASMs. It should be noted that there may be a need for “VDES” ASMs to coexist with “legacy” GMSK ASM transmissions on ASM 1 and ASM 2 in some parts of the world during the transition period.

- *IALA VDES User Needs Template [101]*

This IALA ENAV meeting working document contains estimated data transfer requirements for selected e-Navigation services. The document is based on the Canadian Coastguard User Needs study (see above).

Five services were considered: those from the CCG study plus SBAS (S3; see also the GLA proposal [31]) and Report from ship (S2).

Four service areas: Port, Coastal, Satellite, and Ship-to-Ship communications.

The services are broken down into categories and further into individual data items. For each data item the following parameters are included: Data source; Format.

For each data item/area type combination the following information fields are included:

- Priority
- Unicast/multicast/broadcast
- Encrypted
- Reporting interval
- Size of information packets – In the CCG study this was no. of ASMs per cycle! Needs to be reviewed.
- Transfer per day per site (kB)

The document is work in progress and needs to be developed further.

- *Draft IALA Guideline On VHF Data Exchange System (VDES) [6]*

Annex B of this IALA Guideline describes a set of scenarios/use cases used as a basis for the selection of the proposed VDES Channel Plan A.

Six scenarios were explored:

- SAR Communication;
- Broadcast of MSI and Temporary and Preliminary Notice to Mariners;
- Automated Reporting (IMO FAL Forms);
- VTS Service Portfolio;
- Download of updated digital publication;
- Route Exchange (Ship-Ship);

with a number of variants considered, e.g. coastal waters vs. remote areas (SAT coverage), small data packages (<10 kB) vs. medium data packages (10 kB – 100 kB), ASM vs. VDE use. These could be used as a basis for determining the overall data requirements for VDES.

- *Report from the 3rd JCG Workshop on International Standardization of VDES [68]*

Annex 15 of this report contains a *Working Document toward Draft Recommendation on Performance Standards for Ship-borne VHF Data Exchange System (VDES)* developed by the workshop participants.

The working document identifies the following functional requirements for VDES:

- The VDES should be capable of coordinating with respect to AIS in the following modes:
 - an “autonomous” mode for operation in all areas;
 - a “controlled” mode where the transmission may be controlled by a competent authority.
- The VDES should comprise:
 - antenna(s), capable of transmitting and receiving data through terrestrial and satellite link;
 - an AIS part complying with the performance standards for AIS as set out in resolution MSC.74(69) [103], ANNEX 3;
 - a multi-function data communication process for coordinating AIS, ASM and VDE;

- a multi-function transmitter, capable of operating over a range of maritime frequencies for AIS, ASM and VDE;
- multi-function receivers, capable of operating over a range of maritime frequencies, simultaneously for AIS, ASM and VDE;
- a means to automatically input data from other sources;
- a means to automatically output data to other [devices];
- a means of ensuring the integrity of the data;
- a means to automatically or manually update the device as needed;
- built in test equipment (BITE).
- The VDES should:
 - not harm VHF voice communication by ships from communication method of VDES;
 - give a higher priority to AIS;
 - automatically schedule the transmission of data by its priority;
 - automatically select the operation mode described above by a reception of a message from a competent authority;
 - send an acknowledgement as required;
 - send addressed or broadcast data.
- To input and output data, the VDES should be provided with an interface conforming appropriate international marine interface standards.
- For the purpose of ship and message identification, an appropriate unique identifier should be used.

The following data related requirements were identified:

- The data provided by the VDES should include :
 - time stamp;
 - unique identifier;
 - message identifier.
- As a minimum, the VDES should support the following:
 - AIS data;
 - distress and urgency communication related data;
 - search and rescue co-ordinating communications related data;
 - on-scene communications related data;
 - position related data;
 - maritime safety information (MSI) related data;
 - security and safety information related data;
 - VTS related data:
 - [e-navigation related data]
 - general radiocommunications related data;
 - bridge-to-bridge communications related data;
- The data provided by the VDES should be prioritized as follows:
 - Global Maritime Distress and Safety System (GMDSS) related data (distress, urgency, emergency, MSI);
 - AIS data;
 - security and safety related data;

- e-navigation related data;
- others.
- A security mechanism should be provided:
 - to detect disabling data;
 - to prevent unauthorized alternation of input or transmitted data;
 - to conceal necessary data such as security related data; and
 - when possible, to notify.

Other points of interest in the report include:

- A review of AIS channel management capability at ITU is required as the use of regional AIS channels is no longer recommended.
- There is an interest in the U.S. to use AIS/VDES for distress alerting but regulatory changes are required to allow that; ITU developed a draft report on this subject.
- IEC is developing a standard for the integrated communication system for GMDSS, which should have the capability of automatic selection of the appropriate communication channel

- *VDES Role in e-Navigation, a Canadian Perspective [62]*

Canada completed a study to quantify the risks of interference from the VDES for the proposed channel plans A, B and C [44] (see Section 5.1.3). This IALA ENAV Communications WG input document complements the conclusions of the study. The document also contains information on the forecasted usage of VDES in Canada.

It is expected that the most frequent use cases will be the transfer of safety related data from shore to ship:

- Met/hydro information
- Water levels, actual and predicted
- Recommended ice routes
- Ice maps
- Shoals
- Notices to mariners

Canada evaluated that to achieve these most frequent use cases, a bandwidth of less than 100 kbit/s would be required. This assumes that the information is broadcasted to all ships and repeated at appropriate time intervals.

The document also describes the 3 phases of the concept of operation for e-navigation developed by Canada (Figure 8). Canada believes that Phase II is where VDES will be required to fill the existing gap in communications. VDES VHF should be used for coastal waters and inland waterways. VDES SAT, should be used for high seas areas, including the Arctic. Although the Internet could be used in some cases for Phase II, Canada generally believes that when it comes to time-sensitive safety related information, it is preferable to push the data to the users using a private network with appropriate service levels such as VDES rather than rely on the user to pull the data from the Internet.

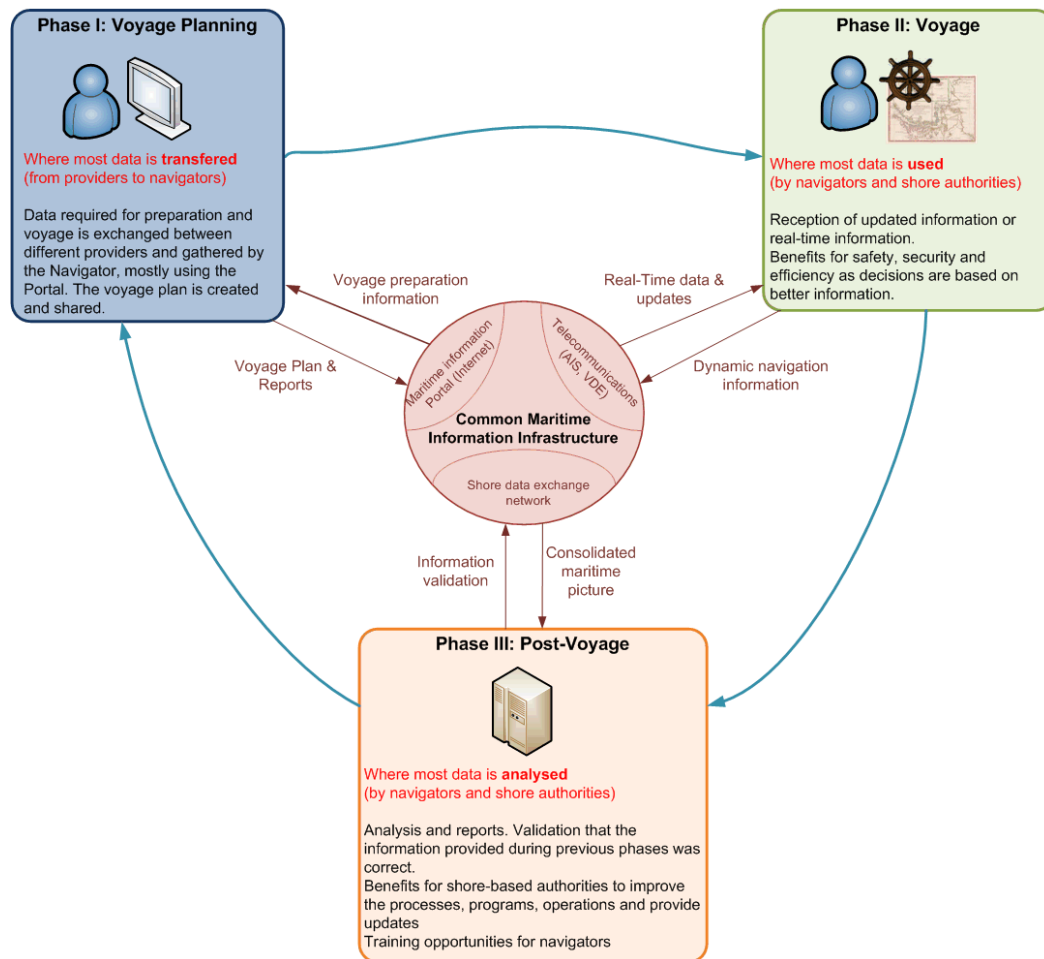


Figure 8: Canada's e-navigation concept

- **User Requirement Document [3]**

This IALA ENAV Communications WG working document provides the user requirements for the development of the VDES. It is a primary input to the technical development of the primary specification of the VDES and provides criteria against which the system will be evaluated. The document also provides useful general guidance on development of user requirements.

Section 1 (Introduction) and Section 2 (General Description) recycle information provided in references [5], [68], [104] summarised elsewhere in this Scoping Document.

Section 3 contains the specific requirements for the VDES identified by the WG as of February 2015.

Section 3.1 describes 7 use cases, including example scenarios:

1. SAR Communications
2. MSI / Safety Information
3. Ship Reporting
4. VTS
5. Updated Charts and Publications
6. Route Exchange

7. Logistics / Services

Section 3.2 lists some user requirements derived from the use cases; the group also developed a user requirements spread sheet [105]. 11 essential requirements have been identified so far.

B Overview of Cooperative Intelligent Transportation Systems

B.1 System and Applications

Road transport and maritime use cases share similar challenges in the areas of safety, efficiency and environmental sustainability. In the case of road transport, Cooperative Intelligent Transport Systems will contribute to future solutions by equipping vehicles and traffic management systems with the capacity to:

- Cooperate, via vehicle-to-vehicle and vehicle-to-infrastructure communications,
- Operate intelligently, using on board sensors, processors and control mechanisms,
- Perform system optimisation and control, using real-time information from vehicles.

This allows vehicles and infrastructure to interact with each other in a cooperative manner to deliver road safety and efficiency benefits.

The automotive industry, in partnership with equipment manufacturers, road authorities, government agencies and research partners are in the final stages of large-scale field trials of cooperative intelligent transport systems. These trials (and projects extending back over the last decade) are intended to prove the concept of operations, validate the technology and standards, demonstrate the applications and evaluate the benefits of these systems. Car manufacturers have publicly committed to production vehicles in 2015, and after-market devices are already available.

C-ITS systems combine reliable, low-latency wireless connectivity, accurate positioning (via global positioning satellites and vehicle dead-reckoning) and an on-board applications processor to allow vehicles to communicate directly to each other (vehicle-to-vehicle, or V2V links), and to road-side units (vehicle-to-infrastructure or V2I). The components of a typical on-board unit are shown in Figure 9. Roadside units have a similar architecture, replacing the link to the vehicle control system with appropriate links to roadside infrastructure (e.g. traffic signals).

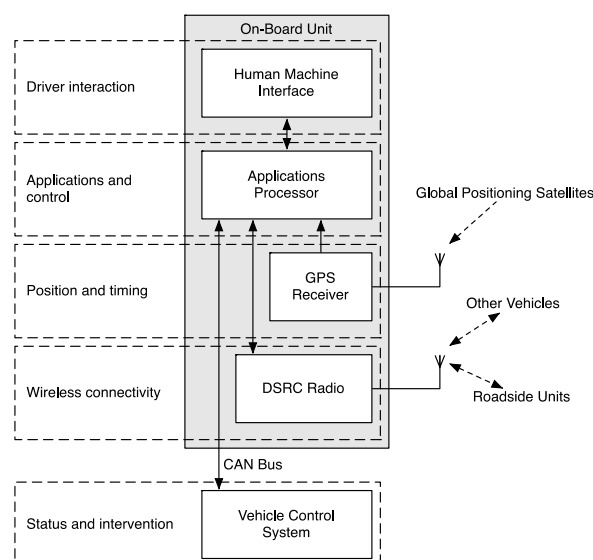


Figure 9: Cooperative intelligent transport Systems On-board Unit

Equipped vehicles periodically broadcast basic safety messages, nominally ten times per second. These wireless messages are one instance of cooperative awareness messages. They contain detailed dynamic information including latitude, longitude, speed, heading, four-way acceleration, brake status, steering wheel angle, throttle position, and vehicle size. Vehicles receiving basic safety messages from surrounding vehicles build up a detailed model of the location and predicted trajectories, which enables cooperative collision avoidance applications, such as intersection collision warning, forward collision warning and do not pass warning. Upon detection of a collision threat, the system can warn the driver. Figure 10 illustrates the intersection collision warning V2V application that provides a (possibly directional) warning to the driver of a potential collision at an intersection (e.g. due to failure to give way). On board units can also assist the driver or take automatic intervention, via interface to the vehicle control system (using the standard controller area network, or CAN bus), e.g. to automatically increase brake pressure.

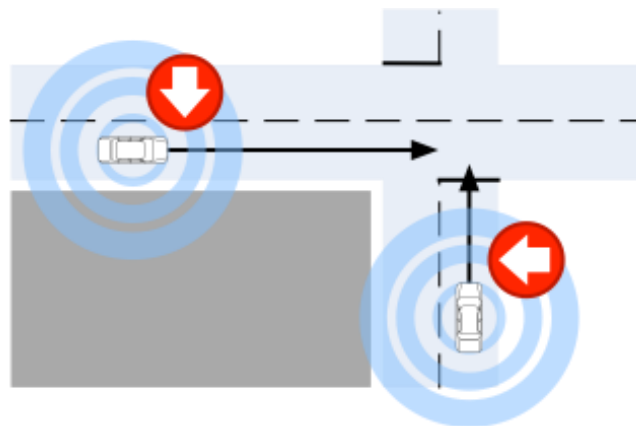


Figure 10: Intersection Collision Warning

Vehicles and infrastructure can also broadcast decentralized environmental notification messages (DENM), which are event-triggered in response to certain hazards, such as emergency braking, signal violation, roadwork warning, weather conditions or icy conditions. Figure 11 shows how V2I communications at a signalized intersection enables green wave and signal violation warning applications.

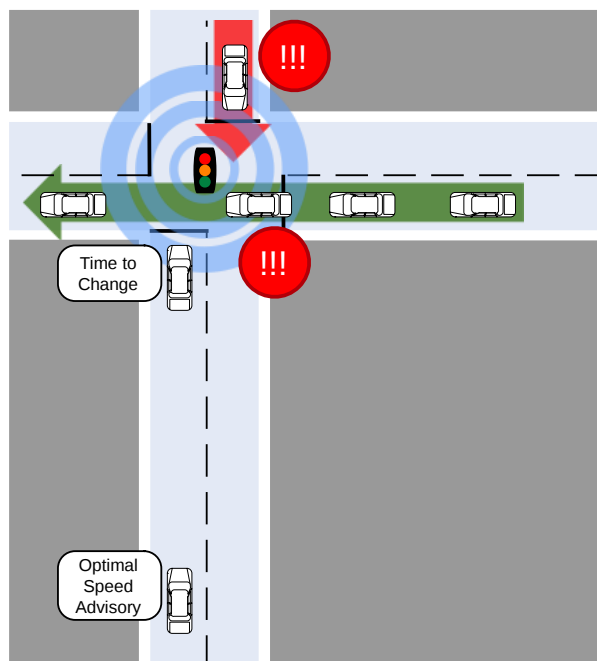


Figure 11: Vehicle to infrastructure communications at a signalized intersection

B.1.1 Spectrum

Protection from interference is critical for road safety applications. Safety systems should also not have to compete for channel access with other applications. These considerations have driven the allocation of dedicated spectrum in the 5.9 GHz band the United States and Europe. This band is particularly suited to short-range (hundreds of meters up to kilometer) communications. Vehicles typically only need communication with other surrounding vehicles or with nearby roadside infrastructure. For these scenarios, short range is actually an advantage, as it allows spatial re-use of radio channels.

Figure 12 shows the band plan specified for the United States. Channels are 10 MHz wide, with an option to combine channels to provide 20 MHz channels. A special control channel (CCH) is intended to be the channel where devices advertise services. The services themselves are offered on service channels (SCH). Devices regularly check the control channel, and then switch to the relevant service channel to receive those services.

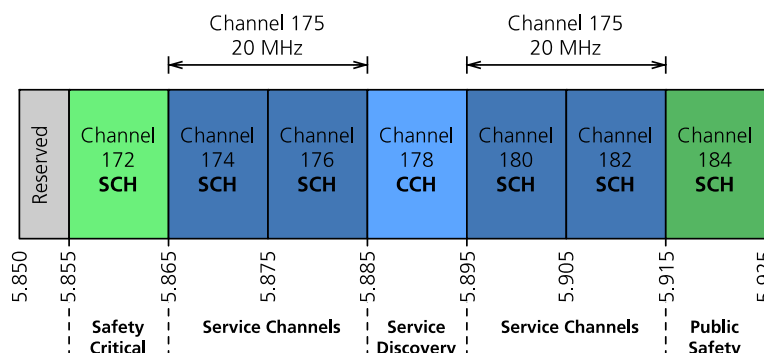


Figure 12: United States 5.9 GHz band plan

In order to avoid contention between safety-critical and other services, safety related messages are transmitted on their own channel. The Federal Communications Commission (FCC) has designated Channel 172 for this purpose. Channel 184 is designated for exclusive use for high-power, long-distance applications and would typically be used by public safety agencies and road authorities.

B.1.2 Communication Standards

Dedicated Short Range Communications (DSRC), also referred to as Wireless Access in Vehicular Environment (WAVE) is a family of standards developed by the Institute of Electrical and Electronic Engineers for low-latency vehicle-to-vehicle and vehicle-to-infrastructure communications. Figure 13 shows the DSRC/WAVE communications stack. These standards have been ratified, and products are already available and are in trial use worldwide. High-level overviews of these standards can be found in [53], [106].

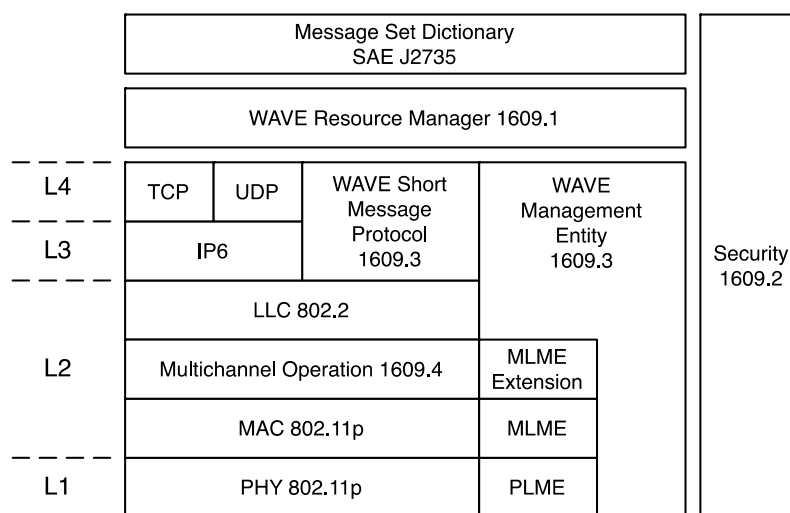


Figure 13: DSRC/WAVE protocol stack.

The wireless air interface is IEEE 802.11p [107], which is a variant of the standard used for Wi-Fi. This standard covers the physical layer, the medium access control layer and link layer control. The radio channel is shared using carrier sense with collision avoidance. Anonymity is built in to the standard, via frequent randomization of the MAC address. IEEE 802.11p is the basis of the European ITS-G5 [108].

IEEE have also developed the IEEE 1609 set of standards for networking and security aspects, including support for very low-latency vehicle-to-vehicle connection. This is critical for safety applications.

In contrast to standard infrastructure-based Wi-Fi (where communications is mediated by one or more access points), vehicle-to-vehicle DSRC communications takes place directly between vehicles. Basic safety messages are broadcast using the WAVE Short Message Protocol, which allows for very low latency transmission. Acknowledgements are not used, since each vehicle is transmitting its current position 10 times per second. Occasional missed messages are quickly superseded. Higher layer protocols such as TCP/IP are also possible, allowing session-based communications and standard Internet applications.

Extensive safety demonstrations have verified that DSRC indeed provides the required low latency and high reliability [109].

If the proposed use of 802.11ac proceeds in the 5.9 GHz band, coexistence mechanisms will be required. This should be possible, due to the fact that .11ac and .11p come from the same family of standards and use similar access methods. Coexistence methods have already been identified [55].

Optional multichannel operation is supported by IEEE 1609.4. All on-board units must monitor channel 172 for safety-related messages. If units also wish to discover other services, they need to also monitor the control channel 178. This requires two radios, one permanently tunes to channel 172, and another that according to IEEE 1609.4 switches between CCH and other SCH channels.

IEEE 1609.3 covers networking services, and defines the WAVE Short Message (WSM) Protocol for low-latency communications. It also defines the WAVE Service Announcement (WSA) for advertising services.

Security services are standardized in IEEE 1609.2. This standard specifies authentication and encryption for messages such as WSM and WSA. This provides authentication for basic safety messages, which are carried inside WSMs. In addition to providing authentication and encryption, the standard incorporates privacy mechanisms. For example, each security certificate is used for a short period of time (minutes). The vehicle also regularly changes its MAC address. This is intended to prevent unauthorized tracking of vehicles.

When low latency is not required, existing cellular communications systems such as 3G or LTE can be used for vehicle-to-infrastructure communications. These systems already provide wide-area coverage in many countries and may be more suited to “infotainment” applications. While cellular is a good option for high-bandwidth Internet applications, it is unable to provide sufficient capacity or sufficiently low latency for vehicle-to-vehicle safety messages [110]. One of the main issues is that communication between two nearby vehicles using 3G or LTE is actually indirect. All cellular communication is mediated by several other network nodes (base stations and other nodes in the core network) even if the two vehicles are in the same cell. Cellular devices are also switched to an idle mode when not active. Returning to active mode can take up to 2.5 seconds, which further negatively impacts the ability to offer low latency.

Cellular technologies are complementary to DSRC/WAVE and are being considered as part of the emerging technology landscape for cooperative intelligent transport systems. The ISO TC204 Working Group 16 are developing a set of standards and frameworks for cooperative intelligent transport systems that support the use of multiple different air interfaces, including WAVE and Cellular. Building on this, a European view of the communications architecture has been developed by ETSI [111]. A similar concept of operations combining multiple communications bearers is being developed in the United States [25].

A dictionary of messages has been standardized by the Society of Automotive Engineers under SAE J2735 [52]. This provides the common language whereby vehicles can understand each other. In addition to basic safety messages and other specific applications (intersection collision warning, lane change warning, forward collision warning to name just a few), this standard defines messages for notification of approaching emergency vehicles and roadworks, as well as messages that allow traffic signals to communicate their state to vehicles (including time to change and the presence of pedestrians). Probe vehicle data messages have been defined which allow vehicles to transmit information about their driving history in support of active traffic management applications. Many other messages have been defined, as well as generic, extensible messages to provide for future applications.

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