ENAV18-11.16.2

RESEARCH & RADIONAVIGATION
GENERAL LIGHTHOUSE AUTHORITIES
United Kingdom and Ireland

VDES Waveform Technical Requirements

Report

Report No: RPT-02-JSa-16

Report Version: 1.0

Report Version Date: 19/01/2016

R&RNAV Contact	Reviewer	Approved for Release
Jan Safar	Nick Ward	Martin Bransby
R&D Engineer	Research Director	R&RNAV Manager
JS	NW	MB

Please make comments in this box:

Executive Summary

The VHF Data Exchange System (VDES) is potentially one of the key elements supporting 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 technical requirements study conducted by the General Lighthouse Authorities of the United Kingdom and Ireland (GLA) and the Institute for Telecommunications Research (ITR) at the University of South Australia (UniSA). The technical requirements study is a component of Phase 2 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

The VDES waveform study will contribute to the development of Application-Specific Message (ASM) and terrestrial VHF Data Exchange (VDE-TER) waveforms and access schemes via simulation and testing, in the laboratory and in the field.

This report maps the existing base of user requirements for e-navigation onto the ASM and VDE-TER waveform descriptions from the current draft VDES recommendation and identifies any gaps for future consideration. It also uses results from a recent maritime channel sounding study to derive a terrestrial maritime channel model. The model is then used to analyse waveform operating requirements and expected performance.

Results from the performance analyses show that all modulation and coding schemes currently proposed provide reliable communication (PER $\leq 10^{-2}$) for almost all scenarios examined in the channel sounding study. Equivalent link layer performance has also been modelled assuming the use of transmission retries. By allowing a single transmission retry, a significant performance improvement was observed when compared to the physical layer PER. The technique was also combined with existing models for average power prediction in order to predict performance at increased range.

Document Disclaimer

This document is uncontrolled when removed from iManage (either electronic or printed)

Document Information

Client	GLA
Project Title	VDES Development
Deliverable Number	M011/2014
Report Title	VDES Waveform Technical Requirements
Report Identifier	RPT-02-JSa-2016
Report Version	1.0
Report Version Date	19/01/2016
Lead Author	David Haley
Contributing Author(s)	Khoa Nguyen Rick Luppino Jan Safar Nick Ward
R&RNAV Contact Information	Jan Safar GLA Research and Radionavigation The Quay, Harwich, Essex, CO12 3JW, UK, T: +44-1255-245145 F: +44-1255-245038 E: jan.safar@gla-rrnav.org W: www.gla-rrnav.org
iManage Location	
Circulation	1. Client 2. Project Files (hard copy) 3. R&RNAV Distribution List 4. R&RNAV Team

Contents

List of Figures

List of Tables

1 Introduction

The VHF Data Exchange System (VDES) is seen as one of the potential key elements supporting 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.

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

The VDES waveform study will contribute to the development of Application-Specific Message (ASM) and terrestrial VHF Data Exchange (VDE-TER) waveforms and access schemes via simulation and testing, in the laboratory and in the field.

Following on from the VDES Waveform Scoping Study [3] this report presents the results of a technical requirements study conducted as a component of Phase 2 of the VDES Waveform study.

This report maps the user requirements for e-navigation [4], [5] onto the ASM and VDE-TER waveform descriptions from the current VDES recommendation [6] and identifies any gaps for future consideration. It also draws upon results from a recent maritime channel sounding study [7] to produce a terrestrial maritime channel model. The model is then used to analyse waveform operating requirements and expected performance.

2 Key Concepts and Input Document Sources

This report considers the technical requirements for ASM and VDE-TER waveforms at the physical and data link layers. A basic channel model is developed, based on maritime channel sounding results. This is then used to characterise the relationships between communications range, data rate, and link margin (transmit power and receive sensitivity) requirements.

The technical requirements for ASM and VDE-TER include those driven by coexistence with AIS. This report focuses on terrestrial VDES and flags potential requirements for coexistence with the satellite VDES (VDE-SAT) functions for future consideration against VDE-SAT study outcomes [8].

Key input documents include:

- *User Requirement Document* [4] *and spread sheet* [5]:
  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.
- *Technical Characteristics for a VHF Data Exchange System in the Maritime Mobile Band ITU-R M.[VDES]* [6]:
  This ITU recommendation contains the most recent specification for VDES. It also includes historical background on VDES development.
- *Technical Characteristics for an Automatic Identification System Using Time Division Multiple Access in the VHF Maritime Mobile Frequency Band, ITU-R M.1371-5* [9]:
  This ITU recommendation provides the latest version of the AIS specification.
- *VHF Data Exchange System Channel Sounding Campaign* [7]:
  This ITU-R WP5B report presents the results of a VDES channel sounding campaign, supported by the administrations of the United Kingdom and Australia.
- *VDES Waveform Scoping Study* [3]:
  This report presents the results of the VDES Waveform Scoping Study. It provides a comprehensive literature review and work plan proposal for the VDES Waveform Study.

3 User Requirements Drivers

This section summarises technical requirements relating to the terrestrial VDES physical and link layers driven by the user requirements identified by the IALA ENAV Communications WG [10] [4] [5]. These technical requirements are then mapped to the current VDES recommendation [6] in the following categories:

- Coexistence
- VDES station identification and channel access
- Message scheduling and prioritisation
- Communications integrity and link adaptation
- Use case requirements

Where appropriate, the source user requirement identifier has been provided for reference. These identifiers have the form VDES-TEC-# for technical requirements, and VDES-OPS-# for operational requirements [10].

A summary of gaps identified between the current set of user requirements and the VDES recommendation is provided in Section 7.2.

3.1 Coexistence

3.1.1 Coexistence with AIS

Requirement: The VDES shall operate in a manner that respects existing operational and functional requirements of AIS in support of safety of navigation, and gives a higher priority to the transmission of AIS [10, Sec. 2.6] and requirement VDES-TEC-001.

Mapping onto Current VDES Recommendation [6]:

One of the characteristics common to all elements of VDES is that AIS position reporting and safety related information be given the highest priority of all VDES communications (Annex 1 Section 1, Annex 6 Section 2.2 and Annex 7 Section 2). This is confirmed in Annex 2 Section 3.3.1.1, which states that the ASM system must give priority to AIS when accessing the physical data link.

Figure A1-1 (Annex 1 Section 2) presents the frequency usage of the VDES and shows that ASM and VDE communications will use different physical channels to those used for AIS. The proposed ASM channels (ASM1 and ASM2) are immediately adjacent to the two AIS channels AIS1 and AIS2). The VDES transmitter specifications must ensure that transmissions will not interfere with AIS reception, e.g. through transmitter frequency error, frequency drift, or spurious emission.

Table A1-7 (Annex 1 Section 3.9.1) provides specifications for VDES ship station transmitters, including constraints on frequency error, transmit power and spurious emissions. Table A2-2 (Annex 2 Section 2.2) provides additional specifications for ASM transmitters, including a slotted modulation mask and spurious transmission constraint. Table A3-1 (Annex 3 Section 3.2) specifies the same parameter set as those provided in Table A1-7, in this case for shore station VDE-TER transmitters. These specifications are in place to limit VDES transmissions from increasing the noise floor of existing AIS receivers (hence resulting in decreased receiver sensitivity).

As discussed in Section 3.1.2, a recent study has recommended a tightening of the spurious emission requirement, from -36 dBm to -46 dBm, in order to reduce potential interference from

VDES into other GMDSS systems [11]. Similar arguments may apply if considering separate but closely located AIS and VDE-TER/ASM systems. Hence the recommended tightening of the spurious emission requirement will also improve AIS coexistence. The AIS receive sensitivity requirement is 20% PER at -107 dBm [9]. Applying the same approach taken in [11], the required spurious/noise level to avoid degradation at the AIS receiver is therefore -117 dBm (assuming 10 dB co-channel selectivity [9]). This implies a required attenuation between VDE/ASM transmit and AIS receive antennas of 71 dB in order to avoid any degradation of receiver sensitivity. These levels are equivalent to those provided for the analysis of VHF telephony and the expected effects on receive sensitivity for varying attenuation between antennas presented in Table 9 of [11]. Thus similar effects on AIS receive sensitivity may be expected.

If receiver desensitisation is not acceptable then an alternative approach may be to limit the useable timeslots of VDE and ASM transmissions [9], potentially in coordination with the AIS slot map. The use of transmit filtering is also analysed in [12].

3.1.2 Coexistence with VHF DSC and Radiotelephony

Requirement: The VDES shall operate in a manner that does not prevent existing VHF DSC communications or existing maritime VHF radiotelephony [10, Sec. 2.6].

Mapping onto Current Draft VDES Recommendation:

As discussed in Section 3.1.1, the recommendation includes specifications for (among other things) transmit power and spurious emissions of VDES transmitters.

A recent study has considered the co-existence of VDES specifically with digital selective calling (DSC) and VHF radiotelephony [11]. The study includes analysis of required antenna separation and examines the associated effects on receiver sensitivity. The study recommended a tightening of the spurious emission requirement, from -36 dBm to -46 dBm, in order to reduce potential interference from ASM and VDE transmissions. It was noted that this would allow a DSC and voice communication range of greater than 20 NM (assuming the free space path loss model and an attenuation from antenna separation of at least 30 dB) even in the presence of permanent VDE transmission at 25 W. With a more realistic path loss model, such as the ITU-P.1546 model [13], the DSC and voice communication range could be significantly lower than that predicted in [11] . Since the spurious emission interference is still significantly higher than typical noise floor, further tightening the spurious emission requirement could be useful to maintain the performance of DSC. Potential VDES impacts on analogue voice and DSC also motivated a previous study on the use of transmit filtering [12].

3.1.3 Summary of Physical Layer Risks and Mitigations

Study [14] assessed the main risks pertaining to the physical layer of the VDES. The following general risks were considered:

- Co-channel interference;
- Adjacent channel interference;
- Blocking interference and spurious response;
- Receiver desensitisation by transmitter wideband noise;
- Intermodulation product interference.

Eleven specific risks were identified as affecting the IALA proposed Channel Plan A (which has become the basis for the current draft VDES Recommendation) and some mitigations were proposed in [14]. Table 1 below details the main physical layer risks related to the terrestrial component of VDES, together with the mitigations included in the current draft VDES Recommendation, and other proposed mitigation measures that may be considered in the development of VDES. The risks related to the satellite component of VDES are not discussed in this document.

In addition to the risks shown in Table 1, the following intermodulation risks were identified in study [14]:

- Use of two co-sited 50 kHz VDE channels (either on the ship or shore) could generate intermodulation products falling within the receiving bandwidth of VDE and AIS.
- Simultaneous operation of AIS1, ASM1 and Ch. 16 (Voice) or Ch. 70 (DSC) can generate products falling within the VDE receiving bandwidth at the ship station.
- Simultaneous operation of AIS1/ASM1 and AIS2/ASM2 channels can generate interference on the ASM2/AIS1 channel.

The following mitigations were proposed [14]:

- VDES should not support two co-sited 50 kHz VDE channels;
- VDES RF frontends to be all linear to minimise intermodulation products.

		Receive (Interfered Station)						
		AIS	**ASM**	**VDE-TER Shore**	**VDE-TER Ship**	**Voice Shore**	**Voice Ship**	**DSC**
Transmit (interfering Station)	**AIS**	**Risks** -	**Risks** Receiver blocking, at the ship and at the shore station. Adjacent channel interference. **Current Mitigations** Transmitter specifications (Table 5, § 2.2, Annex 2, M.1371; Table 35, § 4.2.2.1, Annex 7, M.1371). Limit duty cycle of AIS transmissions. Use FEC and ARQ in ASM (§ 3.5, Annex 1). **Proposed Mitigations** Co-site interference cancellation (Fig. 20, Fig. 21 in ref. [14])	**Risks** Receiver blocking at the shore station. Receiver desensitization by transmitter wideband noise, at the shore station. **Current Mitigations** Transmitter specifications (Table 5, § 2.2, Annex 2, M.1371; Table 35, § 4.2.2.1, Annex 7, M.1371). Limit duty cycle of AIS transmissions. Use FEC and ARQ in VDE (§ 3.5, Annex 1). **Proposed Mitigations** Antenna separation (Fig. 3, Fig. 4 in ref. [14]). High Q cavity multi-couplers would allow a sharp rejection of the AIS transmitter signal (Fig. 5, Fig. 19 in ref. [14]). Co-site interference cancellation (Fig. 20, Fig. 21 in ref. [14]).	**Risks** Receiver blocking at the ship station. Receiver desensitization by transmitter wideband noise, at the ship station. **Current Mitigations** Transmitter specifications (Table 5, § 2.2, Annex 2, M.1371; Table 35, § 4.2.2.1, Annex 7, M.1371). Limit duty cycle of AIS transmissions. Use FEC and ARQ in VDE (§ 3.5, Annex 1). **Proposed Mitigations** Antenna separation (Fig. 3, Fig. 4 in ref. [14]). Co-site interference cancellation (Fig. 20, Fig. 21 in ref. [14]).	**Risks** Receiver blocking at the shore station. Receiver desensitization by transmitter wideband noise, at the shore station. **Current Mitigations** Transmitter specifications (Table 5, § 2.2, Annex 2, M.1371; Table 35, § 4.2.2.1, Annex 7, M.1371). Limit duty cycle of AIS transmissions. Antenna separation. **Proposed Mitigations** -	**Risks** Receiver blocking at the ship station. Receiver desensitization by transmitter wideband noise, at the ship station. Adjacent channel interference, at the ship: satellite AIS uplink Ch. 75, 76, interfering with Ch. 16 (sat. AIS transmissions are infrequent and short but may unsquelch Ch. 16 receiver). **Current Mitigations** Transmitter specifications (Table 5, Annex 2, § 2.2, M.1371; Table 35, Annex 7, § 4.2.2.1, M.1371). Limit duty cycle of AIS transmissions. Antenna separation. **Proposed Mitigations** -	**Risks** Receiver blocking. Receiver desensitization by transmitter wideband noise. **Current Mitigations** Transmitter specifications (Table 5, § 2.2, Annex 2, M.1371; Table 35, § 4.2.2.1, Annex 7, M.1371). Limit duty cycle of AIS transmissions. Antenna separation. **Proposed Mitigations** -
	ASM	**Risks** Receiver blocking at the ship and at the shore station. Adjacent channel interference. **Current Mitigations** Transmitter specifications (Table A1-7, § 3.9.1, Annex 1; Table A2-2, § 2.2, Annex 2). ASM channel access scheme takes account of the AIS slot usage map (§ 1, Annex 1; § 2.2, Annex 6; § 2.3, Annex 6; § 2, Annex 7; § 3.3.1.1, Annex 2; § 3.3.1.2, Annex 2). **Proposed Mitigations** Strengthen the spurious emission requirement from -36 dBm to -46 dBm [11]. Limit the duty cycle of ASM transmissions [11]. Reduce VDES transmit power [11]. Co-site interference cancellation (Fig. 20, Fig. 21 in ref. [14]).	**Risks** -	**Risks** Receiver blocking at the shore station. Receiver desensitization by transmitter wideband noise, at the shore station. **Current Mitigations** Transmitter specifications (Table A1-7, § 3.9.1, Annex 1; Table A2-2, § 2.2, Annex 2). Use of FEC and ARQ in VDE (§ 3.5, Annex 1). **Proposed Mitigations** Strengthen the spurious emission requirement from -36 dBm to -46 dBm [11]. Limit the duty cycle of ASM transmissions [11]. Antenna separation (Fig. 3, Fig. 4 in ref. [14]). High Q cavity multi-couplers would allow a sharp rejection of the ASM transmitter signal (Fig. 5, Fig. 19 in ref. [14]). Co-site interference cancellation (Fig. 20, Fig. 21 in ref. [14]).	**Risks** Receiver blocking at the ship station. Receiver desensitization by transmitter wideband noise, at the ship station. **Current Mitigations** Transmitter specifications (Table A1-7, § 3.9.1, Annex 1; Table A2-2, § 2.2, Annex 2). Use of FEC and ARQ in VDE (§ 3.5, Annex 1). **Proposed Mitigations** Strengthen the spurious emission requirement from -36 dBm to -46 dBm [11]. Limit the duty cycle of ASM transmissions [11]. Antenna separation (Fig. 3, Fig. 4 in ref. [14]). Co-site interference cancellation (Fig. 20, Fig. 21 in ref. [14]).	**Risks** Receiver blocking at the shore station. Receiver desensitization by transmitter wideband noise, at the shore station. **Current Mitigations** Transmitter specifications (Table A1-7, § 3.9.1, Annex 1; Table A2-2, § 2.2, Annex 2). Antenna separation. **Proposed Mitigations** Strengthen the spurious emission requirement from -36 dBm to -46 dBm [11]. Limit the duty cycle of ASM transmissions [11].	**Risks** Receiver blocking at the ship station. Receiver desensitization by transmitter wideband noise, at the ship station. **Current Mitigations** Transmitter specifications (Table A1-7, § 3.9.1, Annex 1; Table A2-2, § 2.2, Annex 2). Antenna separation. **Proposed Mitigations** Strengthen the spurious emission requirement from -36 dBm to -46 dBm [11]. Limit the duty cycle of ASM transmissions [11].	**Risks** Receiver blocking. Receiver desensitization by transmitter wideband noise. **Current Mitigations** Transmitter specifications (Table A1-7, § 3.9.1, Annex 1; Table A2-2, § 2.2, Annex 2). Antenna separation. **Proposed Mitigations** Strengthen the spurious emission requirement from -36 dBm to -46 dBm [11]. Limit the duty cycle of ASM transmissions [11]. Specify that there must be no spurious on Ch. 70 [11].

	VDE-TER Shore-to-Ship	**Risks** Receiver blocking at the shore station. Receiver desensitization by transmitter wideband noise, at the shore station. **Current Mitigations** Transmitter specifications (Table A3-1, § 3.2, Annex 3). **Proposed Mitigations** Strengthen the spurious emission requirement from -36 dBm to -46 dBm [11]. Limit the duty cycle of VDE transmissions [11]. Antenna separation (Fig. 3, to Fig. 5 in ref. [14]). Co-site interference cancellation (Fig. 19 to Fig. 21 in ref. [14]).	**Risks** Receiver blocking at the shore station. Receiver desensitization by transmitter wideband noise, at the shore station. **Current Mitigations** Transmitter specifications (Table A3-1, § 3.2, Annex 3). Use of FEC and ARQ in ASM (§ 3.5, Annex 1). **Proposed Mitigations** Strengthen the spurious emission requirement from -36 dBm to -46 dBm [11]. Limit the duty cycle of VDE transmissions [11]. Antenna separation (Fig. 3, to Fig. 5 in ref. [14]). Co-site interference cancellation (Fig. 19 to Fig. 21 in ref. [14]).	**Risks** Receiver blocking at the shore station. Receiver desensitization by transmitter wideband noise, at the shore station. **Current Mitigations** Transmitter specifications (Table A3-1, § 3.2, Annex 3). **Proposed Mitigations** Strengthen the spurious emission requirement from -36 dBm to -46 dBm [11]. Limit the duty cycle of VDE transmissions [11]. Duplexer (analogical to Fig. 4 in ref. [14]). Antenna separation and transmit\receive cavity filters (Fig. 5, Fig. 19 in ref. [14]). Co-site interference cancellation (Fig. 20, Fig. 21 in ref. [14]).	**Risks** Co-channel interference when more than one coastal station is in the same area, when the ship is located on the overlap zone, that is within coverage of two coastal stations or more. **Current Mitigations** ? **Proposed Mitigations** ?	**Risks** Receiver blocking at the shore station. Receiver desensitization by transmitter wideband noise, at the shore station. **Current Mitigations** Transmitter specifications (Table A3-1, § 3.2, Annex 3). Antenna separation. **Proposed Mitigations** Strengthen the spurious emission requirement from -36 dBm to -46 dBm [11]. Limit the duty cycle of VDE transmissions [11]. Transmit filtering ([12], Fig. 5 in ref. [14]).	**Risks** **-**	**Risks** Receiver blocking at the shore station. Receiver desensitization by transmitter wideband noise, at the shore station. **Current Mitigations** Transmitter specifications (Table A3-1, § 3.2, Annex 3). Antenna separation. **Proposed Mitigations** Strengthen the spurious emission requirement from -36 dBm to -46 dBm [11]. Limit the duty cycle of VDE transmissions [11]. Transmit filtering ([12], Fig. 5 in ref. [14]). Specify that there must be no spurious on Ch. 70 [11].
	VDE-TER Ship-to-Ship	**Risks** Receiver blocking at the ship station. Receiver desensitization by transmitter wideband noise, at the ship station. **Current Mitigations** Transmitter specifications (Table A1-7, § 3.9.1, Annex 1). VDE Ship-to-Ship channel access scheme takes account of the AIS slot usage map (§ 2.3, Annex 6). **Proposed Mitigations** Strengthen the spurious emission requirement from -36 dBm to -46 dBm [11]. Limit the duty cycle of VDE transmissions [11]. Antenna separation (Fig. 3, Fig. 4 in ref. [14]). Co-site interference cancellation (Fig. 20, Fig. 21 in ref. [14]).	**Risks** Receiver blocking at the ship station. Receiver desensitization by transmitter wideband noise, at the ship station. **Current Mitigations** Transmitter specifications (Table A1-7, § 3.9.1, Annex 1). Use of FEC and ARQ in ASM (§ 3.5, Annex 1). **Proposed Mitigations** Strengthen the spurious emission requirement from -36 dBm to -46 dBm [11]. Limit the duty cycle of VDE transmissions [11]. Antenna separation (Fig. 3, Fig. 4 in ref. [14]). Co-site interference cancellation (Fig. 20, Fig. 21 in ref. [14]).	**Risks** -	**Risks** Co-channel interference in ship-to-ship mode with nearby coastal station. **Current Mitigations** ? **Proposed Mitigations** ?	**Risks** -	**Risks** Receiver blocking at the ship station. Receiver desensitization by transmitter wideband noise, at the ship station. **Current Mitigations** Transmitter specifications (Table A1-7, § 3.9.1, Annex 1). Antenna separation. **Proposed Mitigations** Strengthen the spurious emission requirement from -36 dBm to -46 dBm [11]. Limit the duty cycle of VDE transmissions [11].	**Risks** Receiver blocking at the ship station. Receiver desensitization by transmitter wideband noise, at the ship station. **Current Mitigations** Transmitter specifications (Table A1-7, § 3.9.1, Annex 1). Antenna separation. **Proposed Mitigations** Strengthen the spurious emission requirement from -36 dBm to -46 dBm [11]. Limit the duty cycle of VDE transmissions [11]. Specify that there must be no spurious on Ch. 70 [11].

	VDE-TER Ship-to-Shore	**Risks** Receiver blocking at the ship station. Receiver desensitization by transmitter wideband noise, at the ship station. **Current Mitigations** Transmitter specifications (Table A1-7, § 3.9.1, Annex 1). Frequency separation (§ 2.1.3.1, Annex 1: "Shipborne VDES receivers are on the upper legs of RR Appendix 18, 4.6 MHz above the lower legs, which facilitates protection by filtering from receiver blocking by ships VHF radios.") VDE Ship-to-Shore channel access scheme **may** take account of the AIS slot usage map (§ 3.9, Annex 3; § 2.1, Annex 6; § 2.2, Annex 6) **Proposed Mitigations** Strengthen the spurious emission requirement from -36 dBm to -46 dBm [11]. Limit the duty cycle of VDE transmissions [11]. Antenna separation (Fig. 3, Fig. 4 in ref. [14]). Co-site interference cancellation (Fig. 20, Fig. 21 in ref. [14]).	**Risks** Receiver blocking at the ship station. Receiver desensitization by transmitter wideband noise, at the ship station. **Current Mitigations** Transmitter specifications (Table A1-7, § 3.9.1, Annex 1). Frequency separation (§ 2.1.3.1, Annex 1: "Shipborne VDES receivers are on the upper legs of RR Appendix 18, 4.6 MHz above the lower legs, which facilitates protection by filtering from receiver blocking by ships VHF radios.") Use of FEC and ARQ in ASM (§ 3.5, Annex 1). **Proposed Mitigations** Strengthen the spurious emission requirement from -36 dBm to -46 dBm [11]. Limit the duty cycle of VDE transmissions [11]. Antenna separation (Fig. 3, Fig. 4 in ref. [14]). Co-site interference cancellation (Fig. 20, Fig. 21 in ref. [14]).	**Risks** -	**Risks** Receiver blocking at the ship station. Receiver desensitization by transmitter wideband noise, at the ship station. **Current Mitigations** Transmitter specifications (Table A1-7, § 3.9.1, Annex 1). Frequency separation (§ 2.1.3.1, Annex 1: "Shipborne VDES receivers are on the upper legs of RR Appendix 18, 4.6 MHz above the lower legs, which facilitates protection by filtering from receiver blocking by ships VHF radios.") Use of FEC and ARQ in VDE (§ 3.5, Annex 1). **Proposed Mitigations** Strengthen the spurious emission requirement from -36 dBm to -46 dBm [11]. Limit the duty cycle of VDE transmissions [11]. Duplexer (Fig. 4 in ref. [14]). Co-site interference cancellation (Fig. 20, Fig. 21 in ref. [14]).	**Risks** -	**Risks** Receiver blocking at the ship station. Receiver desensitization by transmitter wideband noise, at the ship station. **Current Mitigations** Transmitter specifications (Table A1-7, § 3.9.1, Annex 1). Antenna separation. **Proposed Mitigations** Strengthen the spurious emission requirement from -36 dBm to -46 dBm [11]. Limit the duty cycle of VDE transmissions [11].	**Risks** Receiver blocking at the ship station. Receiver desensitization by transmitter wideband noise, at the ship station. **Current Mitigations** Transmitter specifications (Table A1-7, § 3.9.1, Annex 1). Antenna separation. **Proposed Mitigations** Strengthen the spurious emission requirement from -36 dBm to -46 dBm [11]. Specify that there must be no spurious on Ch. 70 [11].
	Voice Shore	**Risks** Receiver blocking at the shore station. Receiver desensitization by transmitter wideband noise, at the shore station. **Current Mitigations** Transmitter specifications [15], [16]. Antenna separation. **Proposed Mitigations** -	**Risks** Receiver blocking at the shore station. Receiver desensitization by transmitter wideband noise, at the shore station. **Current Mitigations** Transmitter specifications [15], [16]. Antenna separation. Use of FEC and ARQ in ASM (§ 3.5, Annex 1). **Proposed Mitigations** -	**Risks** Receiver blocking at the shore station. Receiver desensitization by transmitter wideband noise, at the shore station. **Current Mitigations** Transmitter specifications [15], [16]. Antenna separation. Use of FEC and ARQ in VDE (§ 3.5, Annex 1). **Proposed Mitigations** -	**Risks** -	**Risks** -	**Risks** -	**Risks** Receiver blocking at the shore station. Receiver desensitization by transmitter wideband noise, at the shore station. **Current Mitigations** Transmitter specifications [15], [16]. Antenna separation (if external DSC unit used). **Proposed Mitigations** -

	Voice Ship	**Risks** Receiver blocking at the ship station. Receiver desensitization by transmitter wideband noise, at the ship station. **Current Mitigations** Transmitter specifications [15], [16]. Antenna separation. Frequency separation (§ 2.1.3.1, Annex 1: "Shipborne VDES receivers are on the upper legs of RR Appendix 18, 4.6 MHz above the lower legs, which facilitates protection by filtering from receiver blocking by ships VHF radios.") **Proposed Mitigations** Transmit filtering [12].	**Risks** Receiver blocking at the ship station. Receiver desensitization by transmitter wideband noise, at the ship station. **Current Mitigations** Transmitter specifications [15], [16]. Antenna separation. Frequency separation (§ 2.1.3.1, Annex 1: "Shipborne VDES receivers are on the upper legs of RR Appendix 18, 4.6 MHz above the lower legs, which facilitates protection by filtering from receiver blocking by ships VHF radios.") Use of FEC and ARQ in ASM (§ 3.5, Annex 1). **Proposed Mitigations** Transmit filtering [12].	**Risks** -	**Risks** Receiver blocking at the ship station. Receiver desensitization by transmitter wideband noise, at the ship station. **Current Mitigations** Transmitter specifications [15], [16]. Antenna separation. Frequency separation (§ 2.1.3.1, Annex 1: "Shipborne VDES receivers are on the upper legs of RR Appendix 18, 4.6 MHz above the lower legs, which facilitates protection by filtering from receiver blocking by ships VHF radios.") Use of FEC and ARQ in VDE (§ 3.5, Annex 1). **Proposed Mitigations** Transmit filtering [12].	**Risks** -	**Risks** -	**Risks** Receiver blocking at the ship station. Receiver desensitization by transmitter wideband noise, at the ship station. **Current Mitigations** Transmitter specifications [15], [16]. Antenna separation (if external DSC unit used). **Proposed Mitigations** -
	DSC	**Risks** Receiver blocking at the ship and at the shore station. Receiver desensitization by transmitter wideband noise. **Current Mitigations** Transmitter specifications [17], [18]. Antenna separation. Frequency separation (§ 2.1.3.1, Annex 1: "Shipborne VDES receivers are on the upper legs of RR Appendix 18, 4.6 MHz above the lower legs, which facilitates protection by filtering from receiver blocking by ships VHF radios.") Limit duty cycle of DSC transmissions. **Proposed Mitigations** Transmit filtering [12].	**Risks** Receiver blocking at the ship and at the shore station. Receiver desensitization by transmitter wideband noise. **Current Mitigations** Transmitter specifications [17], [18]. Antenna separation. Frequency separation (§ 2.1.3.1, Annex 1: "Shipborne VDES receivers are on the upper legs of RR Appendix 18, 4.6 MHz above the lower legs, which facilitates protection by filtering from receiver blocking by ships VHF radios.") Use of FEC and ARQ in ASM (§ 3.5, Annex 1). Limit duty cycle of DSC transmissions. **Proposed Mitigations** Transmit filtering [12].	**Risks** Receiver blocking at the shore station. Receiver desensitization by transmitter wideband noise, at the shore station. **Current Mitigations** Transmitter specifications [17], [18]. Antenna separation. Use of FEC and ARQ in VDE (§ 3.5, Annex 1). Limit duty cycle of DSC transmissions. **Proposed Mitigations** -	**Risks** Receiver blocking at the ship station. Receiver desensitization by transmitter wideband noise, at the ship station. **Current Mitigations** Transmitter specifications [17], [18]. Antenna separation. Frequency separation (§ 2.1.3.1, Annex 1: "Shipborne VDES receivers are on the upper legs of RR Appendix 18, 4.6 MHz above the lower legs, which facilitates protection by filtering from receiver blocking by ships VHF radios.") Use of FEC and ARQ in VDE (§ 3.5, Annex 1). Limit duty cycle of DSC transmissions. **Proposed Mitigations** Transmit filtering [12].	**Risks** Receiver blocking at the shore station. Receiver desensitization by transmitter wideband noise, at the shore station. **Current Mitigations** Transmitter specifications [17], [18]. Antenna separation (if external DSC unit used). Limit duty cycle of DSC transmissions. **Proposed Mitigations** -	**Risks** Receiver blocking at the ship station. Receiver desensitization by transmitter wideband noise, at the ship station. **Current Mitigations** Transmitter specifications [17], [18]. Antenna separation (if external DSC unit used). Limit duty cycle of DSC transmissions. **Proposed Mitigations** Transmit filtering [12].	**Risks** -

Table 1: Summary of Main Physical Layer Risks and Mitigations (Assuming IALA Channel Plan A).

3.2 VDES Station Identification and Channel Access

3.2.1 Unique Identification of VDES Stations

Requirement: The system shall use unique identifiers for each VDES station [10, Sec. 4.2] (VDES-OPS-012).

Mapping onto Current Draft VDES Recommendation:

Section 3.1 of Annex 1 states that all VDES stations (ASM, VDE-TER and VDE-SAT) shall be uniquely and automatically identified using an appropriate numerical identifier e.g. a Maritime Mobile Service Identity (MMSI).

In relation to ASM specifically, Section 3.3.5.2 of Annex 2 presents a message structure that is compatible with ITU-R M.1371. This Link Layer structure contains a *User ID* field, which is a unique identifier of 30 bits in length.

In relation to VDE-TER specifically, Section 3.9 of Annex 3 presents the structure of the physical layer slot for each of the three bandwidth cases (25kHz, 50kHz and 100kHz). The structure contains a *Data* field (i.e. the Link Layer message) the contents of which are listed in Section 4.2. Included in this list are a *Destination* field (which is stated as optional) and a *Source ID* field, both of which can be used to uniquely identify the source and destination of an individual packet. Although not stated explicitly in this section, these identifiers may be set to the MMSI of the destination and source stations respectively, according to Section 3.1 of Annex 1.

3.2.2 Communication Direction and Casting

Requirement: The VDES will support all communications directions - shore-ship; ship-shore; ship-ship [10, Sec. 4.3] (VDES-TEC-004).

The VDES will support transmission from a VDES station to [10, Sec. 4.3]:

- Another VDES station (point to point) (VDES-TEC-012)
- A group of VDES stations (fleet or group notification) (VDES-TEC-011)
- A specified geographic area (area notification) (VDES-TEC-010)
- All other stations in range (general broadcast) (VDES-TEC-013)
- A combination of the above (VDES-TEC-014)

Mapping onto Current Draft VDES Recommendation:

Sections 2.1.1 and 2.1.3.3 of Annex 1 provide details on the use of the VDES frequency spectrum (as depicted in Figure A1-1 of Annex 1) and map specific channels to directions of communication. That is, the recommendation states that frequency channel VDE1-A shall be used for ship-to-shore communications while channel VDE1-B shall be used for shore-to-ship and ship-to-ship communications. In the case of ASM, Figure A1-1 illustrates support for the three required directions of communication (ship-to-shore, shore-to-ship and ship-to-ship).

Section 4.9 of Annex 3 provides additional information (for VDE-TER) on the three directions of communication and how they operate in relation to the frequency allocation. Section 4.12 of Annex 2 details how the logical channels of communication are utilized for different types of traffic. For example, Section 4.12.5 specifies how the Random Access Channel (RAC) is to be used under different scenarios.

Sections 4.12.3 and 4.12.4 of Annex 3 describe two types of traffic to be supported by VDE-TER at the Link Layer, namely Multicast and Unicast. While the recommendation states that Multicast traffic can be used to send messages to a large number of ships (defaulting to a general broadcast i.e. all stations), it does not provide detail on how this traffic type may be used to restrict the ships that are to receive the message. That is, it does not specify how this traffic type could be used to send messages to a specific group of stations, either by geographic location or other means of identification. For the Unicast traffic type, the recommendation is clear that this is used for direct station-to-station communication.

At the Network Layer, Section 5.1 of Annex 3 provides a list of the types of transmissions that should be supported for VDE-TER, including Unicast and Multicast traffic and the corresponding directions of communication.

Two different ASM traffic types are supported, namely point-to-point (i.e. addressed messages) and general broadcast. These are discussed in Section 5.2 of Annex 2 (Transport Layer), however as is the case for VDE-TER, the recommendation does not provide detail on how the broadcast traffic type could be used to send messages to a specific group of stations.

3.2.3 Mesh Networking

Requirement: The VDES shall provide mesh network support and allow routing between VDES transceivers for seamless end-to-end application connectivity [4, Sec. 4.1.10].

Mapping onto Current Draft VDES Recommendation:

As discussed in Section 3.2.1, every ASM and VDE-TER message includes an identifier for the source station and in some cases the destination station.

Although the recommendation does not specifically state that a mesh network topology (i.e. message routing) should be supported, it may be possible given the message structures presented in Section 3.3.5.2 of Annex 2 and Sections 3.9 and 4.2 of Annex 3. As a simplistic example, if the message received by a particular station contains a destination MMSI that does not match its own, then that station could simply transmit that same packet (i.e. forward it) to the additional stations within its range. A mechanism should also be included to avoid collisions and network flooding, potentially requiring each station to maintain a network map.

3.2.4 Use of Time Division Multiple Access

Requirement: The system should use TDMA for terrestrial links [10, Sec. 4.3] (VDES-TEC-003).

Mapping onto Current Draft VDES Recommendation:

The following sections of the recommendation indicate clearly that TDMA will be used for both ASM and VDE-TER at the Link Layer.

- Annex 2: Sections 1, 1.2.2.3, 3.1, 3.3.1 and 3.3.4
- Annex 3: Section 4.1

The recommendation also specifies the various types of TDMA that are to be supported. For ASM, these are Incremental TDMA (ITDMA), Random Access TDMA (RATDMA), Fixed Access TDMA (FATDMA) and Slot Carrier Sense TDMA (SCTDMA) – as stated in Sections 3.3.1 and 3.3.4 of Annex 2. The latter of these is intended for use only with VDES-SAT. Note that ASM as defined for ITU-R M.1371 supports Self Organising TDMA (SOTDMA), however SOTDMA is not supported in the VDES recommendation.

Section 4.1 of Annex 3 identifies the specific types of TDMA that are to be supported by VDE-TER. These are as per those identified for ASM, with the exception of SCTDMA (as this is intended for use only in VDES-SAT).

The recommendation states, in Section 3.3 of Annex 1, that the slot and frame structures defined in ITU-R M.1371 will be used in the TDMA access schemes for both ASM and VDE-TER. Section 4.8 of Annex 3 provides more detail on the frame hierarchy to be employed for VDE-TER (although a similar hierarchy does not appear for ASM in Annex 2 of the recommendation).

In Section 3.3.1 of Annex 2 (ASM), the recommendation states that the type of TDMA used at any given time is dependent on the application and current mode of operation (Section 3.3.2 of Annex 2). However, the recommendation does not clearly state which TMDA access scheme is used for each mode of operation. Furthermore, it does not state explicitly which TDMA scheme should be used at station power on (Section 3.3.3 of Annex 2), however Section 3.3.4.4 suggests that either ITDMA or RATDMA may be used at power on.

For VDE-TER specifically, Sections 4.10 and 4.12 of Annex 3 provide some detail over which type of TDMA access scheme should be used under different scenarios.

3.2.5 Multi-mode Support

Requirement: The system should be capable of various modes of operation, including the autonomous, assigned and polled modes [10, Sec. 2.4]. The VDES shall operate in a manner that is capable of automatically selecting the most efficient operation of autonomous or controlled mode by reception of a message from a competent authority [10, Sec. 2.6].

Mapping onto Current Draft VDES Recommendation:

Section 3.3.2 of Annex 2 identifies three different modes of operation for ASM, namely:

- Autonomous: station determines its own schedule
- Assigned: station transmits according to an assigning message
- Polled: station automatically responds to interrogation messages

Autonomous mode is stated as the default mode of operation and a station may switch to/from other modes. While the recommendation does not explicitly state how the change in modes occurs, it can be deduced (from the text in Sections 3.3.2.1 to 3.3.2.3) that a station would switch to Polled mode on the reception of an interrogation message. Similarly, a station would switch to Assigned mode on the reception of a schedule assigning message.

The recommendation does not identify any specific modes of operation for VDE-TER. It also does not specify that the most efficient mode of operation should be automatically selected based on the reception of a message from a competent authority, or provide detail on how this should be achieved.

3.3 Message Scheduling and Prioritisation

3.3.1 Transmit Scheduling

Requirement: The VDES will support automated, delayed, and scheduled transmission in long and short timeframes [10, Sec. 4.2] (VDES-OPS-018).

Mapping onto Current Draft VDES Recommendation:

The recommendation does not provide any details on how VDES transmissions may be scheduled (i.e. automated, delayed or scheduled) and does not state that the priority of the message may be used to schedule transmissions automatically.

Transmit scheduling is typically handled at the higher layers in the protocol stack (i.e. Network or Transport Layer).

3.3.2 Message Prioritisation

Requirement: The VDES will support priority of transmission (distress, urgency, safety, other) [10, Sec. 4.2] (VDES-OPS-019).

Mapping onto Current Draft VDES Recommendation:

Section 3.3.4.5 of Annex 2 identifies the four different priority levels for ASM as follows:

- Priority 1 (highest): Critical link management messages
- Priority 2: safety related messages
- Priority 3: Interrogation and responses to interrogation
- Priority 4 (lowest): All other messages

The recommendation does not identify priority levels for VDE-TER.

Section 3.3.2 of Annex 1 and Sections 1.2.3 and 4 of Annex 2 both state that the assignment and management of message priorities are the responsibility of the Network Layer, and hence out of the scope of this report. However, the description of the Network Layer (for both ASM and VDE-TER) in the recommendation does not yet provide detail on how message priorities are to be assigned and managed.

3.3.3 Message Lifetime

Requirement: VDES information items contain a property indicating the lifespan of the information item [4, Sec. 4.1.5].

Mapping onto Current Draft VDES Recommendation:

The recommendation does not specify the inclusion of a lifespan property for ASM or VDE-TER messages. This would normally be included in the higher layers of the protocol stack i.e. above the Link Layer. For example, TCP/IP packets include a Time to Live (TTL) field at Layer 3.

3.4 Communications Integrity and Link Adaptation

3.4.1 Data Verification

Requirement: The VDES will ensure integrity of data transmitted [10, Sec. 4.2] (VDES-OPS-016).

Mapping onto Current Draft VDES Recommendation:

There are two mechanisms specified in the recommendation to improve and manage data integrity, namely Forward Error Correction (FEC) and Cyclic Redundancy Check (CRC).

FEC increases physical layer reliability by allowing errors introduced during transmission to be corrected at the receiver. The recommendation describes the structure of the turbo encoder to be used and defines the constituent codes and the interleaver. A number of code rates are specified in the recommendation to allow for rate adaptation.

The use of a CRC in the transmitted messages will allow the receiver to identify packets that have been received in error and thus to take appropriate action. A 32-bit CRC (calculated in accordance with ITU-T V.42) is appended to the last segment of each transmitted datagram.

The recommendation specifies the use of FEC in the Physical Layer of both ASM (Section 2.8 of Annex 2) and VDE-TER (Section 3.9.6 Annex 3). The use of a CRC is specified in the Link Layer of ASM (Section 3.2.3 of Annex 2), and for the VDE-TER packet structure (as defined in Sections 4.2 and 4.3 of Annex 3).

3.4.2 Acknowledgment

Requirement: The VDES shall operate in a manner that is able to send an acknowledgement to a message, if required [10, Sec. 2.6].

Mapping onto Current Draft VDES Recommendation:

Section 3.2.1 of Annex 1 states that the Transport Layer is responsible for ensuring that messages are reliably transferred between stations, including segmentation and acknowledgement. This applies to both ASM and VDE-TER and is confirmed in Section 5 of Annex 2 and Section 4.5 of Annex 3 of the recommendation respectively.

In the case of ASM specifically, Section 5.2 of Annex 2 identifies two types of transmissions, namely addressed messages and broadcast messages. In the case of addressed messages, the recommendation states that the receiver may acknowledge the reception of a transmitted packet, and in the event that the acknowledgement is not received, the packet may be retransmitted.

The recommendation does not provide any further detail on how the acknowledgement of messages is handled for VDE-TER.

3.4.3 Transmission Retries

Requirement: The VDES system shall be designed to allow (implementation dependent) mechanisms that can use multiple transmissions of exactly the same information to correct bit errors [4, Sec. 4.5.1].

Mapping onto Current Draft VDES Recommendation:

As stated in Section 3.4.2, the Transport Layer (ASM and VDE-TER) has the responsibility of ensuring that messages are transferred reliably between stations.

In the case of ASM, Section 5.2.1 of Annex 2 states that when an acknowledgement is required but is not received for a particular message, that exact message may be retransmitted by the source station. If the receiving station did receive the message but bit errors were present, it may choose to not send an acknowledgement (or send a negative acknowledgement) back to the transmitting station to prompt it to retransmit that same message.

In the case of VDE-TER, Section 4.4 of Annex 3 describes that automatic repeat request (ARQ) may be used (depending on the application) to request the retransmission of a lost data segment. In addition to this, Sections 4.6 and 4.7 describe the use of end of delivery notifications (EDN) and end of delivery failures (EDF) to indicate when the destination station has or has not (respectively) received a particular datagram. The EDF is sent to the source once the retry limit/timeout has been exhausted.

3.4.4 Link Adaptation

Requirement: The system should allow adapting some parameters of the transmission (robustness or capacity) [10, Sec. 2.4].

Mapping onto Current Draft VDES Recommendation:

The Physical Layer waveform design for ASM and VDE-TER includes Forward Error Correction (FEC), as specified in Section 3.5 of Annex 1 of the recommendation. Section 3.5.4 of Annex 1 lists the various code rates that should be supported and shows that these code rates are generated by adjusting the puncturing rate of the encoder output.

The modulation scheme used for ASM is π/4-QPSK (Annex 2, Section 2.3) and FEC code rates of ½, ¾, 5/6 and 1 are supported (Annex 2, Section 2.6). The code rate used for a specific Physical Layer packet is identified in the Signal Information field of that packet (Figure A2-2).

For VDE-TER, the recommendation lists three (and reserves 13 for future use) Modulation and Coding Schemes (MCS) which specify the modulation type and code rate used for a particular packet (Annex 3, Section 3.4.1). Each MCS results in a different throughput rate, as shown in Table A3-2 of Annex 3 and is also mapped to a unique Channel Quality Indicator (CQI) value. The CQI value is included in each VDE-TER transmission to allow a VDES shore station to select the highest throughput format (i.e. MCS) with adequate link margin, thus maximising spectral efficiency (Annex 3, Sections 3.5, 4.12.2 and 4.12.4).

The recommendation does not currently specify a protocol for rate adaption in response to changes in link quality.

4 Application Requirements

4.1 Use Case Requirements

This section inspects physical layer and data link layer technical requirements that are driven by the following 27 specific use cases described in the user requirements spread sheet [5]. Further detail on each use case can be found in [10].

Use Case 1: Search and Rescue (SAR) Communications

UC-1.1 Distress Communications - Mayday Relay: Text / standard format [DSC/SafetyNet]

UC-1.2 SAR Operations - initiate search / response: Search plan (waypoints) / text / some standard format / case specific

UC-1.3 SAR Operations - information exchange: Text / updated plan / images / case specific

UC-1.4 Telemedical: Text / images / video / telematics / need for voice in addition to digital data exchange

UC-1.5 MEDEVAC: Text / images / video / telematics / need for voice in addition to digital data exchange

Use Case 2: Maritime Safety Information

UC-2.1 Meteorological Services and Warnings / Navigational Warnings: Wind / sea state / temperature / pressure / forecast for set time frame - Text / images / weather maps

UC-2.2 Weather Observations (from ships): Text (standard format) / images

UC-2.3 Ice Maps: Text / image

UC-2.4 Notices to Mariners: Status of aids to navigation, including input from remote monitoring. Status of hydrographic information - tides / currents.

UC-2.4 SBAS Corrections: Examples of such situations include during close-quarter precision navigation and when calibrating inertial navigation equipment.

UC-2.5 Crowd-sourced Information: Text / images

Use Case 3: Ship Reporting

UC-3.1 Submit Arrival Notice: Text

UC-3.2 Submit Updated Information: Text / image

UC-3.3 Provide Initial Report to Shore (prior to departure): Text

UC-3.4 [Encrypted] Ship Reporting: Text

UC-3.5 Danger Message: Text / image

Use Case 4: Vessel Traffic Services

UC4.1 Waterway Monitoring: Text

UC-4.2 Information Service: Text

UC-4.3 Navigational Assistance Service: Text

UC-4.4 Traffic Organisation Service: Text

Use Case 5: Charts and Publications

UC-5.1 Updates Linked to Ship Route: Text / images (S-100 series)

Use Case 6: Route Exchange

UC-6.1 Ship to Ship Route Exchange: Text

UC-6.2 Ship to Shore Route Exchange: route /waypoints (specific area of the route to be defined - i.e. the coming X nm); included speed of vessel along the route; intentions

UC-6.3 Shore to Ship Route Exchange: Text / images

UC-6.4 Navigational Disruption: Text / images

Use Case 7: Logistics

UC-7.1 Logistic Services - Ship to Shore: Text

UC-7.2 Logistic Services – Shore to Ship: Text / image

4.2 Estimated Data Size

A data size requirement range is estimated for each use case. Observing all use cases the following ranges are present:

- Small, 32 B to 1 kB: Use cases UC-1.1 and UC-2.5
- Large, 10 kB to 1 MB: Use case UC-2.3
- Medium, 1 kB to 10 kB: All remaining (24) use cases.

The current VDES recommendation specifies that an ASM packet will be π/4-QPSK modulated with a data portion of maximum length 380 (uncoded) message bits, i.e. 47.5 Bytes ([6] Annex 2, Section 3.2.2.1). The most robust ASM packet will have rate ½ coding applied, and therefore be able to carry 190 message bits, i.e. 23.75 Bytes.

The ASM function will be well suited to applications that use small messages. However the majority of use cases require a medium size data transfer of at least 1 kB. Considering the highest throughput case, if the channel could support uncoded communication this would require at least 22 ASM packets. The duration of this transfer would be lower bounded by 22 slot durations (assuming uninterrupted transmission) i.e. 586 ms. This duration could place stress on some applications that have high latency sensitivity. Less favourable channel conditions would require coding (and potentially transmission retries) and hence additional packets/time. Therefore, use of ASM communication for applications that require medium sized data transfer (1 kB to 10 kB) should be considered on a case by case basis, depending on likelihood of operation at the lower end of the transfer requirement, latency requirements, and message priority.

VDE-TER offers higher data rate communication than ASM, with raw throughput ranging from 38.4 kbps (25 kHz channel, π/4-QPSK) to 307.2 kbps (100 kHz channel, 16QAM) ([6] Annex 3, Section 3.4.1). Considering the proposed VDE-TER modulation, coding schemes and slot structure, the number of data bits (not including the 32 bit CRC) supported by each VDE-TER packet variant is provided in Table 2.

The 25 kHz channel VDE-TER is well suited to applications that use small messages. In the case where SNR is sufficient to support MCS-5 each packet can carry 158 message bytes. Medium sized messages are better suited to either the 50 kHz or 100 kHz channels. In the case of the 100 kHz channel, the most robust MCS-1 supports 220 message bytes and can therefore carry a 1 kB message in 4.5 packets. The highest throughput is provided by MCS-5 on the 100 kHz channel, with each packet carrying 668 message bytes. In this case a 10 kB message may be carried using 15 packets. In order to carry 1 MB for the most demanding use case (UC-2.3) this scheme would require 1,498 packets to be successfully received.

	Data Field Length in Bits (Bytes)		
MCS \ Channel	**25kHz**	**50kHz**	**100 kHz**
MCS-1 (π/4-QPSK, CR=1/2)	400 (50)	864 (108)	1760 (220)
MCS-3 (8PSK, CR=3/4)	940 (117.5)	1984 (248)	4000 (500)
MCS-5 (16QAM, CR=3/4)	1264 (158)	2656 (332)	5344 (668)

Table 2: VDE-TER Packet Data Length.

4.3 Surety of Delivery

The surety of delivery requirement is defined in [5] as the confidence factor that the traffic will be delivered, according to the following levels:

- High: Machine to machine (M2M) acknowledgement of delivery required
- Medium: machine confirms transmit in time range
- Low

The required surety of delivery is summarised for all use cases in Table 3, sorted from most demanding to least demanding, and noting that some use cases require a range of support depending on the particular application being used.

Surety of delivery is investigated further via the packet error rate (PER) metric for the different ASM and VDE-TER modulation and coding schemes in Section 6.

Use Case	Title	High	Medium	Low
UC-1.1	Distress Communications - Mayday Relay			
UC-1.2	SAR Operations - initiate search / response			
UC-1.3	SAR Operations - information exchange			
UC-1.4	Telemedical			
UC-1.5	MEDEVAC			
UC-3.5	Danger Message			
UC4.1	Waterway Monitoring			
UC-4.3	Navigational Asisstance Service			
UC-4.4	Traffic Organisation Service			
UC-6.1	Ship to Ship Route Exchange			
UC-6.3	Shore to Ship Route Exchange			
UC-6.4	Navigational Disruption			
UC-2.1	Meteorological Serv & Warn / Navigational Warnings			
UC-2.4	Notices to Mariners			
UC-3.1	Submit Arrival Notice			
UC-3.2	Submit Updated Information			
UC-5.1	Updates Linked to Ship Route			
UC-7.1	Logistic Services - Ship to Shore			
UC-7.2	Logistic Services –Shore to Ship			
UC-2.2	Weather Observations (from ships)			
UC-4.2	Information Service			
UC-2.3	Ice Maps			
UC-2.5	SBAS Corrections			
UC-2.6	Crowd-sourced Information			
UC-3.3	Provide Initial Report to Shore (prior to departure)			
UC-3.4	[Encrypted] Ship Reporting			
UC-6.2	Ship to Shore Route Exchange			

Table 3: Use Case Surety of Delivery Requirements

4.4 Importance

The message delivery importance requirement is defined in [5] according to the following levels:

- High: delivery in low time range
- Medium: delivery in acceptable time range
- Low: If not met in the time range then discard message

The required message delivery importance is summarised for all use cases in Table 4, sorted from most demanding to least demanding, and noting that some use cases require a range of support depending on the particular application being used.

As Importance requirements reflect latency they are also related to priority and quality of service (QoS), as discussed in Section 4.5.

4.5 Priority

The message delivery priority requirement is defined in [5] according to the following levels:

- 1: Distress
- 2: Safety
- 3: Urgent
- 4: Other

Required message priority is summarised for all use cases in Table 5, sorted from most demanding to least demanding, and noting that some use cases require a range of support depending on the particular application being used.

As discussed in Section 3.3.2 four priority levels are currently defined for ASM, although they are not given the same labels as in [5]. Priority levels are not currently defined for VDE-TER messages.

The network layer is responsible for the management of priority assignments ([6] Annex 2, Section 1.2.3). Suitable QoS mechanisms should be designed in order to allow high priority messages to be queued ahead of less important data, e.g. for a new Telemedical message (UC-1.4) to interrupt the transmission of previously queued crowd sourced information (UC-2.6). Moreover, an application may need to interrupt transmission based on latency requirements according to the importance criteria discussed in Section 4.4. For example, a digital voice transmission (UC-1.5) requiring low latency, may need to transmit ahead of data queued for less delay sensitive Logistics Services (UC-7.1). These QoS mechanisms may also require link layer components and protocols to be considered during the design phase.

Use Case	Title	High	Medium	Low
UC-1.1	Distress Communications - Mayday Relay			
UC-1.2	SAR Operations - initiate search / response			
UC-1.3	SAR Operations - information exchange			
UC-1.4	Telemedical			
UC-1.5	MEDEVAC			
UC-2.5	SBAS Corrections			
UC-3.5	Danger Message			
UC-4.3	Navigational Assistance Service			
UC-4.4	Traffic Organisation Service			
UC-6.1	Ship to Ship Route Exchange			
UC-6.3	Shore to Ship Route Exchange			
UC-6.4	Navigational Disruption			
UC-2.1	Meteorological Serv & Warn / Navigational Warnings			
UC-2.2	Weather Observations (from ships)			
UC-2.4	Notices to Mariners			
UC-4.2	Information Service			
UC-2.3	Ice Maps			
UC-3.1	Submit Arrival Notice			
UC-3.2	Submit Updated Information			
UC-3.3	Provide Initial Report to Shore (prior to departure)			
UC-3.4	[Encrypted] Ship Reporting			
UC4.1	Waterway Monitoring			
UC-6.2	Ship to Shore Route Exchange			
UC-7.1	Logistic Services - Ship to Shore			
UC-7.2	Logistic Services – Shore to Ship			
UC-5.1	Updates Linked to Ship Route			
UC-2.6	Crowd-sourced Information			

Table 4: Use Case Message Delivery Importance Requirements

Use Case	Title	Distress	Urgent	Safety	Other
UC-1.1	Distress Communications - Mayday Relay				
UC-1.2	SAR Operations - initiate search / response				
UC-1.3	SAR Operations - information exchange				
UC-1.4	Telemedical				
UC-1.5	MEDEVAC				
UC-2.4	Notices to Mariners				
UC-6.4	Navigational Disruption				
UC-2.2	Weather Observations (from ships)				
UC-2.1	Meteorological Serv & Warn / Nav Warn				
UC-2.5	SBAS Corrections				
UC-3.5	Danger Message				
UC-4.3	Navigational Assistance Service				
UC-4.4	Traffic Organisation Service				
UC-5.1	Updates Linked to Ship Route				
UC-6.1	Ship to Ship Route Exchange				
UC-6.3	Shore to Ship Route Exchange				
UC-3.2	Submit Updated Information				
UC-4.2	Information Service				
UC-2.3	Ice Maps				
UC-2.6	Crowd-sourced Information				
UC-3.1	Submit Arrival Notice				
UC-3.3	Initial Report to Shore (prior to depart)				
UC-3.4	[Encrypted] Ship Reporting				
UC4.1	Waterway Monitoring				
UC-6.2	Ship to Shore Route Exchange				
UC-7.1	Logistic Services - Ship to Shore				
UC-7.2	Logistic Services – Shore to Ship				

Table 5: Use Case Message Priority Requirements

4.6 Affected System Elements

A list of affected system elements for each use case is provided in [5], indicating the direction of communication and multicast characteristics according to the following:

- Unicast
    - Ship to ship (individual)
    - Ship to Coastal Radio Station (Terrestrial)
    - Coastal Radio Station to Ship (individual) Terrestrial
- Multicast / Geocast
    - Ship to ship (group)
    - Ship to ship (area)
    - Coastal Radio Station to Ship (group) Terrestrial
    - Coastal Radio Station to Ship (area) Terrestrial

Figure 1 illustrates the affected system elements and corresponding links to support all use cases that require unicast communications. The use case colour scheme shown is consistent with [5]. More than half of all use cases require bidirectional communications between ship and shore.

Figure 2 illustrates the affected system elements and links to support all use cases that require multicast and/or geocast communications. Geocast communication is required by 17 use cases, and multicast communication is required by 6 use cases. As discussed in Section 3.2.2 the current VDES recommendation does not yet provide details for multicast and geocast communication mechanisms.

The figures in this section provide a graphical aid to ensuring coverage of affected system elements and directional links when selecting appropriate design reference applications in Section 4.8.

Communication range for the shore to ship link is investigated further for different ASM and VDE-TER modulation and coding schemes in Section 6.

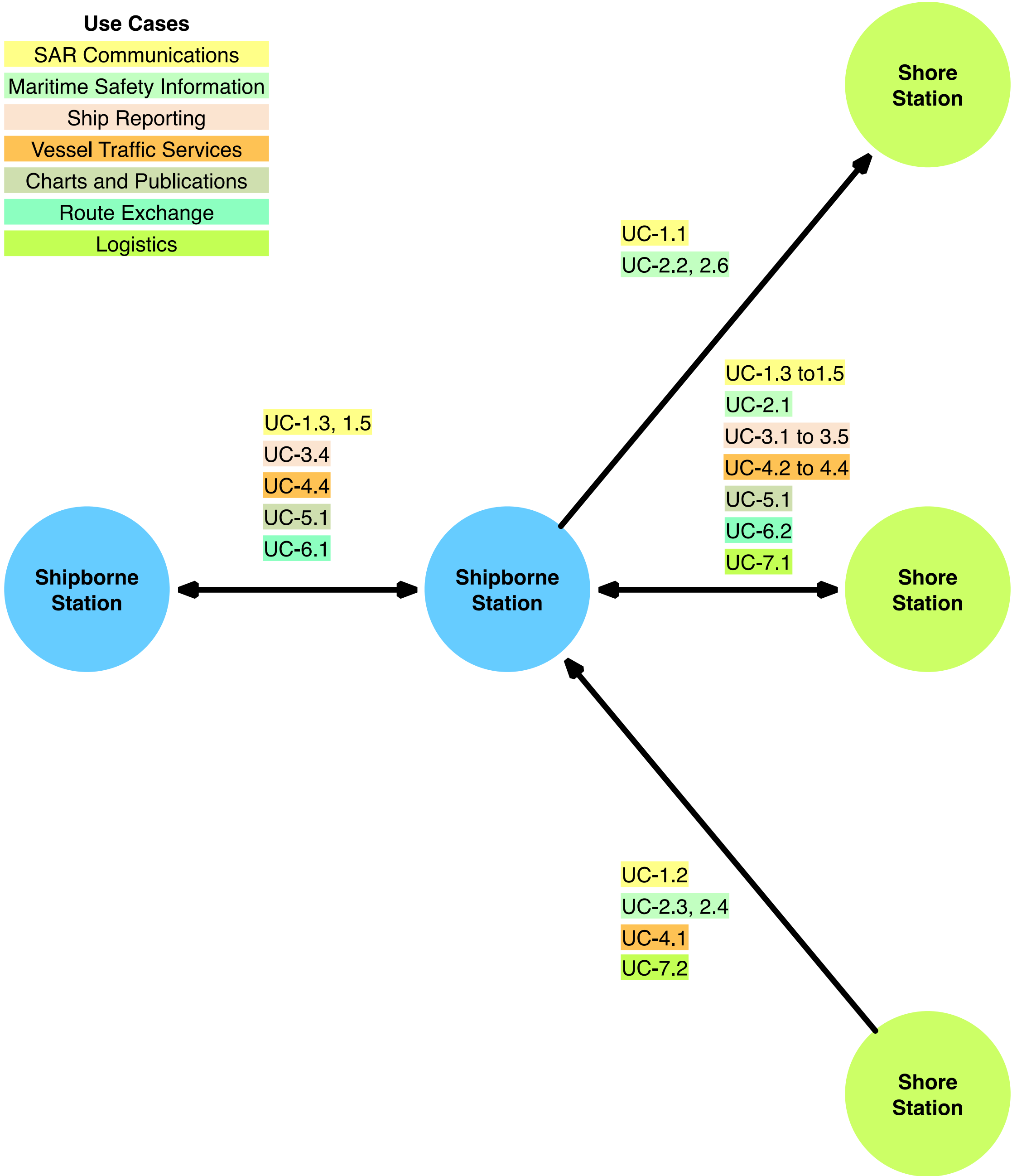

Figure 1: Directional Links for Unicast Communication

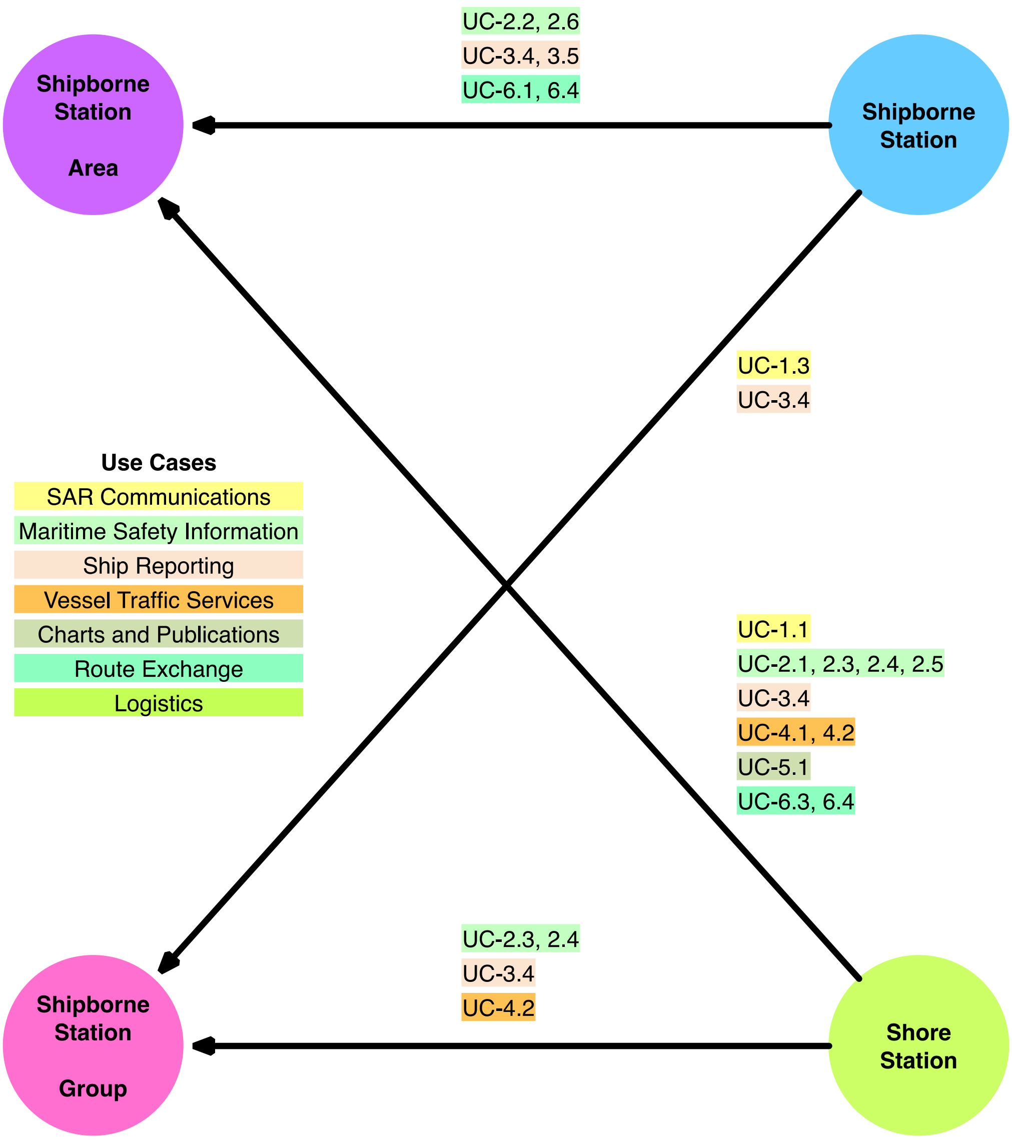

Figure 2: Directional Links for Multicast/Geocast Communication

4.7 Proposed Method

One or more communication methods are proposed in [5] for each of the use cases. Observing all use cases the following methods are proposed:

- Any available: Proposed for use cases UC-1.1 and UC-1.3
- VDE / ASM / AIS: Proposed for all Vessel Traffic Services cases (UC-4.1 to UC4.4)
- VDE / ASM: Proposed for all 21 remaining use cases.

In many applications ASM may not present an effective method given its lower capacity than VDE-TER, as described in Section 4.2. For example, ASM is currently a proposed method for Ice Map delivery (UC-2.3) which has a data carriage requirement of 10 kB to 1MB.

For applications that require data transfer at the lower end of the medium scale (i.e. closer to 1 kB) ASM may provide a suitable fall-back for transfer of medium sized messages of high priority (e.g. distress and safety) if the VDE-TER channel is not available.

Consideration (and simulation) of a multi ship scenario would allow the effects of collisions and network congestion to be observed. This would provide valuable input into the selection of appropriate communication methods beyond the link level data size comparisons provided in Section 4.2.

4.8 Design Reference Applications

In this section a set of use cases are selected from which design reference applications may be chosen as candidates for simulation, lab testing, field trials and demonstration. Use cases have been selected to enable coverage of technical requirements by testing a subset of all use cases. At least one use case has been selected from every use case group, in order to exercise the following requirements:

- Each system element and link (see Section 4.6), i.e. each unicast link, multicast link, and geocast link
- A range of
    - Data size (<1kB, 1kB to 10kB, 10kB to 1 MB)
    - Surety of delivery (high, medium, low)
    - Delivery importance (high, medium, low)
    - Priority (Distress, Urgent, Safety, Other)

Considering the analysis presented throughout Sections 4.1 to 4.7, Table 6 lists the proposed set of design reference applications. When combined, the set covers the full range of each of the requirements listed above. Testing the application set in parallel will allow importance and priority interrupt performance to be assessed.

Use Case	Title	Link(s) Exercised	Data Size	Surety of Delivery	Delivery Importance	Priority
UC-1.1	Distress Communications - Mayday Relay	Ship-Shore Unicast	Less than 1 kB	High	High	Distress
UC-2.3	Ice Maps	Shore-Ship Unicast Shore-Ship Multicast Shore-Ship Geocast	10 kB to 1 MB	Medium	Medium	Other
UC-3.4	[Encrypted] Ship Reporting	Ship-Ship Unicast Ship-Shore Unicast Shore-Ship Unicast Ship-Ship Multicast Ship-Ship Geocast	1 kB to 10 kB	Medium	Medium	Other
UC-4.2	Information Service	Shore-Ship Unicast Ship-Shore Unicast Shore-Ship Multicast Shore-Ship Geocast	1 kB to 10 kB	High, Medium, Low	High, Medium, Low	Safety, Other
UC-5.1	Updates Linked to Ship Route	Ship-Ship Unicast Ship-Shore Unicast Shore-Ship Geocast	1 kB to 10 kB	High, Medium	Medium Low	Safety
UC-6.4	Navigational Disruption	Ship-Ship Geocast Shore-Ship Geocast	1 kB to 10 kB	High	High	Urgent, Safety
UC-7.2	Logistic Services – Shore to Ship	Shore-Ship Unicast	1 kB to 10 kB	High Medium	Medium	Other

Table 6: Proposed Set of Design Reference Applications

5 Maritime Channel Model

This section derives a channel model for use in requirements analysis and future design phases. The model is developed using shore-to-ship data captured during an on-sea VDES channel sounding campaign, conducted by the GLA and ITR [7].

Due to multipath propagation and mobility of ships and surrounding objects, the received signal strength varies with time. Characterising the distribution of the received signal power is an important step toward determining the communication reliability. Let P_{av} be the average received power, then the instantaneous power is $P_r = X^2 P_{\mathrm{av}}$ where X is a random variable with $E[X^2] = 1$. Here the instantaneous received power is separated into two components, the average received power P_{av}, which is typically predicted using propagation path loss models, and the random fluctuation gain X, whose distribution is characterised subsequently.

In many scenarios, X follows a Rician distribution with probability density function (pdf) [19]

$$f_X(x; K) = 2x(K+1)e^{(-K-(K+1)x^2)} I_0\left(2x\sqrt{K(K+1)}\right), x \geq 0 \qquad (1)$$

where K is the Rician factor. K characterises the ratio of the direct (or specular) power to scattered power, and $I_0(x)$ is the zeroth-order modified Bessel function of the first kind [20]. To characterise the distribution of the received power, the mean received power P_{av} and Rician factor K are estimated using the empirical data. Finally, the obtained distribution is visually compared to the empirical distribution, to determine whether the Rician distribution is a suitable match to the trial results.

The maximum likelihood estimator[1] [21] is used to estimate the distribution parameters P_{av} and K. The estimation results in the Rician distribution that maximizes the likelihood of the empirical data. In other words, let $\hat{P}_r(i), i = 1, \dots, M$ denote the empirical received power of M packets in a trial, then the maximum likelihood estimator gives

$$(\hat{P}_{\mathrm{av}}, \hat{K}) = \underset{(P,K)}{\operatorname{argmax}} \prod_{i=1}^{M} f_X\left(\sqrt{\frac{\hat{P}_r(i)}{P}}; K\right), \qquad (2)$$

where $\hat{P}_{\mathrm{av}}$ and $\hat{K}$ denote estimates of P_{av} and K for the trial respectively. The technique is illustrated here for the channel sounding Trial 1504 at Sunk Deep Water Anchorage. The maximum likelihood estimator gives

$$\hat{P}_{\mathrm{av\_dBm}} = 10\log_{10}(\hat{P}_{\mathrm{av}}) = -101.3 \text{ dBm}$$

$$\hat{K} = 26.3.$$

The empirical distribution of $\hat{X}$ obtained from $\hat{X}(i) = \sqrt{\frac{P_r(i)}{\hat{P}_{\mathrm{av}}}}$ for $i = 1, 2, \dots$ and the estimated Rician pdf $f_X(x; \hat{K})$ for Trial 1504 at Sunk Deep Water Anchorage is illustrated in Figure 3.

---

[1] One can also analytically obtain the parameter estimation by matching the second and fourth moment of the Rician distribution with that of the empirical data. In these trials, the moment matching method and the maximum likelihood estimator give similar distribution parameters. However, the maximum likelihood estimator is generally more rigorous. The algorithm can be implemented with the command *mle* in the Matlab statistical toolbox.

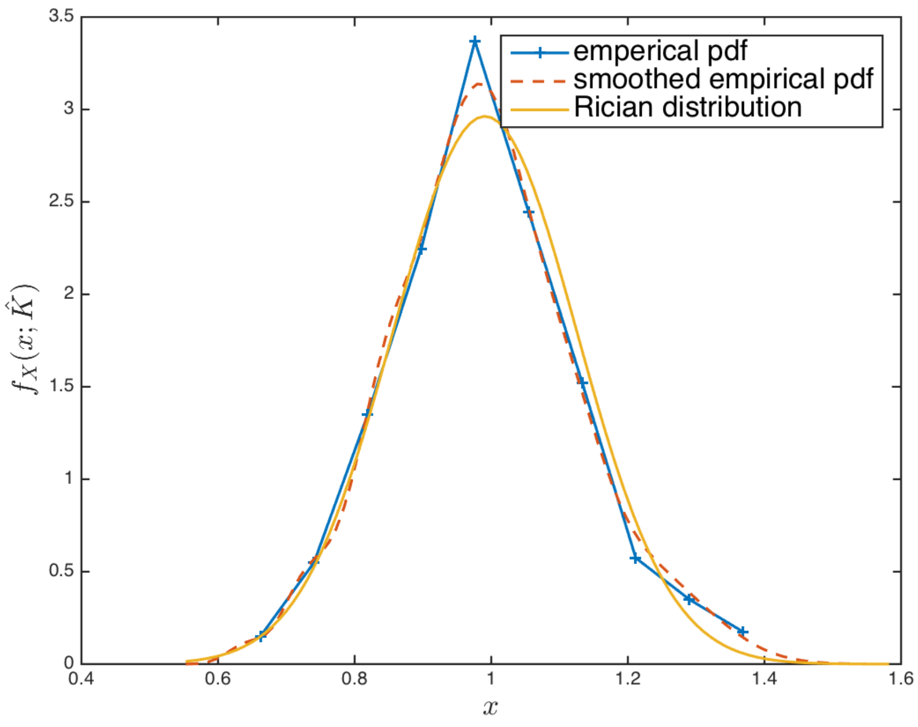

Figure 3: Empirical distribution of X and its Rician estimation for Trial 1504 at Sunk Deep Water Anchorage

In Figure 3, the crossed solid line denotes the empirical pdf obtained from the histogram of X; the dashed line represents a smoothed version of the empirical pdf obtained by kernel density estimation; and the solid line represents the Rician approximation. The figure shows a close match between the Rician distribution and the empirical distribution. The relatively high Rician factor $\widehat{K}$ indicates that this propagation environment is not rich scattering. This observation is consistent with the Sunk Deep Water Anchorage site being in LOS of the transmitter.

The estimation technique has also been applied to data captured during other trials from the VDES channel sounding campaign [7]. The average power P_{av} and the Rician factor K for the channel fading gain X is summarised in Table 7[2]. Plots that compare the Rician distribution approximations to the empirical distributions obtained from the captured data are provided in Appendix A.

The study shows that under LOS and near LOS conditions and relatively calm sea the channel exhibits a high K factor and the channel fading gain X is highly concentrated around 1. This can been seen for trials 1629 (Figure 12), 1647 (Figure 17) and 1129 (Figure 13). In these cases the channel approaches a non-fading AWGN channel. On the other hand, as identified in [7], ship rocking in rough sea conditions causes polarisation mismatch and the instantaneous received power fluctuates significantly around the mean value. This can been seen for trials 1504 (Figure 3) and 1227 (Figure 16). The effect of ship rocking on received power was also studied analytically in [22]. The effect leads to a reduction of the K factor as observed in trials 1504 and 1227. Trial 1504 exhibits a higher K factor than Trial 1227, although

---

[2] Table 7 contains revised values of P_{av}, after identifying and correcting a miscalculation in the channel sounding report ITU-R M.2317-0 [7]. A revision to ITU-R M.2317 is in progress.

both trials were conducted on the same day in very similar sea state conditions. This is because the effect of ship rocking is less severe at larger transmitter-receiver separation [22]. Low K factors are also observed in NLOS conditions, as in trial 1542 (Figure 14) and the trials in Ipswich (see Figure 15, Figure 18 and Figure 20).

It should be noted that the Rician distribution does not provide a good fit for all trials in [7]. Examples include trials where the ship moves or rotates during captures (Harwich Approach) and the trial adjacent to rotating windmill blades (Gunfleet Sands).

Location	Recorded Sea State	Propagation	Trial ID	Channel	P_{av} (dBm)	K factor
Harwich Harbour	3 (slight)	LOS	1629	VDE100	-43	178
			1647	VDE50	-44	106
			1725	ASM1	-45	29
Gunfleet Sands	3-4 (slight to moderate)	Near LOS	1129	VDE100	-84	148
		NLOS	1542	VDE100	-97	20
Sunk Deep Water Anchorage	4-5 (moderate to rough)	LOS	1504	VDE100	-101	26
Ipswich	1-2 (calm to smooth)	NLOS	1226	VDE100	-96	11
			1247	VDE50	-96	5.5
			1309	ASM1	-96	11
Harwich Approach	4-5 (moderate to rough)	LOS	1227	VDE100	-77	10

Table 7: Channel Parameters for VDES sounding trials

6 Expected Performance

This section presents the expected performance for communication over the channels derived in Section 5. The performance is measured in terms of average packet error rate (PER), as well as the signal-to-noise ratio (SNR) margin for a given target average PER. Section 6.1 summarises the methodology for computing the average PER. Section 6.2 reports the average PER predictions for the trials presented in Table 7. Finally, the long range PER for the PHY and link layer are predicted in Sections 6.3 and 6.4.

6.1 Methodology

The average PER can be computed by averaging the instantaneous PER, which is a function of the instantaneous SNR and the modulation and coding scheme, over the distribution of the received power. The instantaneous SNR is the ratio between instantaneous received symbol energy E_s and the noise spectral density N. The receive symbol energy is computed from the instantaneous received power P_r characterised in Section 5, the receiver antenna gain G_R, the cable loss L_c, and the symbol duration. The noise spectral density includes the thermal noise, the receiver noise figure NF, and has also been used to account for the implementation margin IM. Finally, given the instantaneous SNR, the instantaneous PER can be computed as follows:

- The instantaneous PER is computed assuming that signal acquisition is always successful.
- For uncoded transmission, the instantaneous PER can be derived from the instantaneous symbol error rate and the frame length.
- For coded transmission, the instantaneous PER is computed under the assumption of ideal error correcting codes and infinite packet length. Under this assumption, the instantaneous PER is 1 whenever the instantaneous SNR is below the SNR requirement, and is 0 otherwise. The SNR requirement is a function of the MCS. The loss due to using a practical coding scheme is assumed to be absorbed into the implementation margin.

Further detail on the derivation of average PER is provided in Appendix B.

In the remainder of this section the average PER is computed for the system parameters summarised in Table 8 [6]. Furthermore, the receiver is assumed to have the following characteristics

- Receiver noise figure $\mathrm{NF} = 12$ dB
- Implementation margin $\mathrm{IM} = 2$ dB
- Receiver antenna gain $G_R = 2.15$ dBi
- Cable loss $L_C = 1.2$ dB.

Channel	Bandwidth (kHz)	Frame length	Rolloff factor α	MCS
VDE100	100	1792	0.3	QPSK[3], R=0.5 8-PSK, R=0.75 16-QAM, R=0.75
VDE50	50	896		
VDE25	25	432		
ASM	25	380	0.35	QPSK (R=1/2, 3/4, 5/6)

Table 8: VDE-TER and ASM physical layer parameters

6.2 Scenario based PER

This section illustrates the expected PER performance for the channel models summarised in Section 5. In cases of practical interest, the average PER performance of each trial depends on the channel parameters in the following ways:

- A larger average received power P_{av} leads to smaller average PER.
- A larger K factor induces a smaller average PER since the instantaneous SNR is more tightly concentrated around the mean value.

The expected PER performance is studied for the VDE100 trials summarised in Table 7. A combination of high average SNR and large K values lead to very low average PER for trials 1629 and 1129. For clarity Figure 4 only shows the expected PER for the 4 remaining VDE100 trials. Given a target average PER requirement at the physical layer, the supported MCS can be read from the figure. For example, at a target PER 10^{-2}, trial 1504 supports up to 8PSK, R=0.75; trial 1542 supports up to uncoded (R=1) QPSK; trial 1226 supports up to 16QAM, R=0.75; and trial 1227 supports all MCS, including the uncoded schemes.

Figure 4 also shows that although the channels observed during trials 1542 and 1226 have similar average received power P_{av}, they predict significantly different PER performances. This is the result of the different K factors associated with the two trials. In trial 1542 a larger Rician factor ($K = 20$) leads to a lower average PER compared to that of trial 1226 ($K = 11$). The figure also shows that the uncoded schemes are always inferior compared to the coded schemes.

[3] The results in this section are derived for uniform QPSK constellations, which hold for the $\pi/4$-QPSK modulation scheme recommended in [6]. For generality and brevity of notation, the acronym QPSK will be used throughout this section.

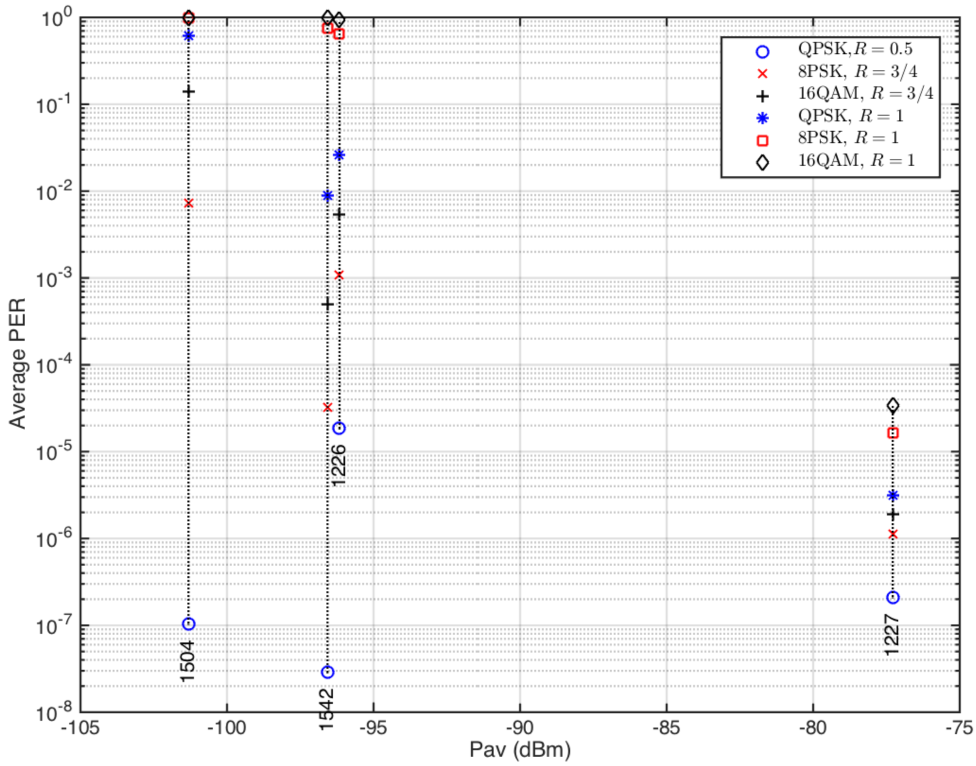

Figure 4: Expected PER for VDE100 trials

Another performance measure is the SNR margin, which characterises how much the average received power can be reduced while maintaining a target average PER. The SNR margin can be used to accommodate additional losses that have not been captured in the trials, such as additional shadowing or unexpected interference. For each trial, the SNR margin depends on the chosen modulation and coding scheme, and the target average PER. The method to compute the SNR margin is described in Appendix B.

Table 9 summarises the SNR margin for the trials presented in Table 7 when targeting a PER of 10^{-2}. For the VDE channels, moving from QPSK, R=0.5 to 8PSK, R=0.75 reduces the SNR margin by 7 dB, and moving from 8PSK to 16-QAM at R=0.75 reduces the SNR margin by 2.1 dB. For the ASM channels, increasing rate from 0.5 to 0.75 and from 0.75 to 0.83 reduces the SNR margins by 3.2 dB and 1.2 dB respectively. A similar generalisation is not apparent for uncoded (R=1) transmission.

Trial	VDE100			VDE50			ASM			
	QPSK $R=\frac{1}{2}$	8PSK $R=\frac{3}{4}$	16QAM $R=\frac{3}{4}$	QPSK $R=\frac{1}{2}$	8PSK $R=\frac{3}{4}$	16QAM $R=\frac{3}{4}$	$R=\frac{1}{2}$	$R=\frac{3}{4}$	$R=\frac{5}{6}$	$R=1$
1629	67.5	60.5	58.4							
1129	26.2	19.2	17.1							
1227	28.4	21.3	19.2							
1226	9.9	2.9	0.8							
1542	11.4	4.4	2.3							
1504	7.2	0.2	-1.9							
1647				69.6	62.6	60.5				
1451				44.7	37.7	35.5				
1247				9.3	2.3	0.1				
1725							70.2	67.0	65.8	59.6
1309							16.0	12.8	11.6	5.7

Table 9: SNR margin for target average PER 10^{-2}.

Table 9 shows that all modulation and coding schemes can be supported by all channels, with the exception of the 16QAM scheme in trial 1504. This agrees with the average PER results illustrated in Figure 4. However, some differences can be observed between the SNR margin and average PER predictions. For example, while trial 1129 has a much lower average PER, its SNR margins are smaller than that of trial 1227. Trial 1129 exhibits a low average PER due to its high Rician K factor, however it has smaller P_{av}, and thus a smaller SNR margin, when compared to trial 1227.

6.3 PER at Range

For each channel type the expected PER is predicted at distance $d = 20, 30$ and 40 nautical miles (NM), or equivalently 37 km, 55.5 km and 74 km. Channel conditions at these distances are modelled as follows:

- The average received power P_{av} is predicted using a propagation path loss model.
- The Rician factor $K = 26$, as observed in trial 1504 at distance 31 km, is chosen for all ranges.

Either the John-Egli model [23] or the ITU-P.1546 model [13] is used to predict the average received power P_{av} at various transmitter-receiver separation. The VDES channel sounding campaign [7] shows that up to $d = 31$ km, the measured average received power is bounded from above and below by the ITU-R P.1546 and John-Egli models, respectively. The result is illustrated in Figure 5. The figure shows that the two propagation path loss models converge at large distance. Furthermore, the trial data converges to the John-Egli model at 31 km. For the longer ranges (≥ 37 km) studied in this section, and under the system deployment described in [7], the PER performance is therefore expected to be closer to that predicted using the John-Egli model than that predicted by the ITU-R P.1546 model.

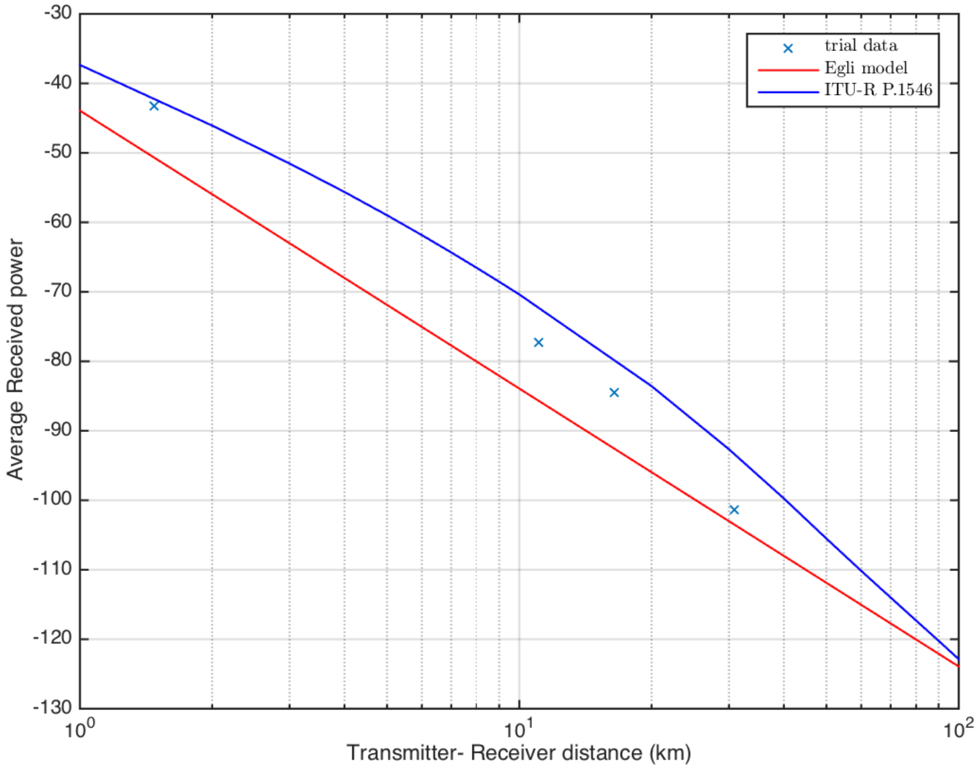

Figure 5: Average Received Power vs Distance Predicted by John-Egli and ITU-R P.1546 Models

Using the approach described above, the expected PERs at large distances are plotted in Figure 6 (for VDE100), Figure 7 (for VDE50), Figure 8 (for VDE25) and Figure 9 (for ASM). Each vertical line represents the range of the expected PER for a given MCS, where the upper point represents the average PER predicted by the John-Egli model and the lower point represents the average PER predicted by the ITU-R P.1546 model. For example, for QPSK, R=0.5 transmission over VDE100 at 20 NM, the average PER is predicted to be within the range 2×10^{-9} and 5×10^{-4}.

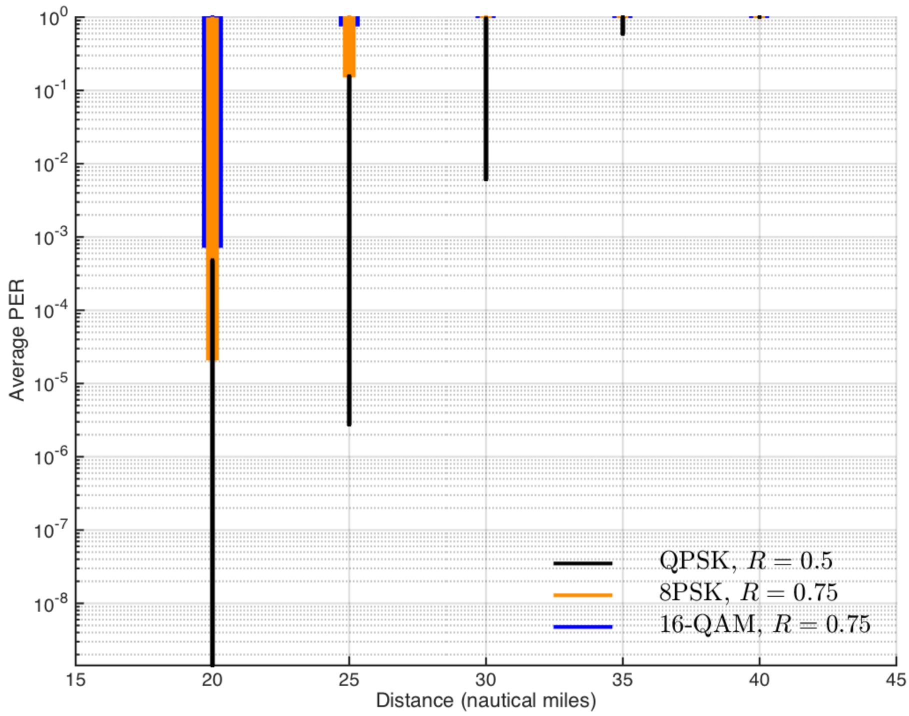

Figure 6: VDE100 PER Performance at Range

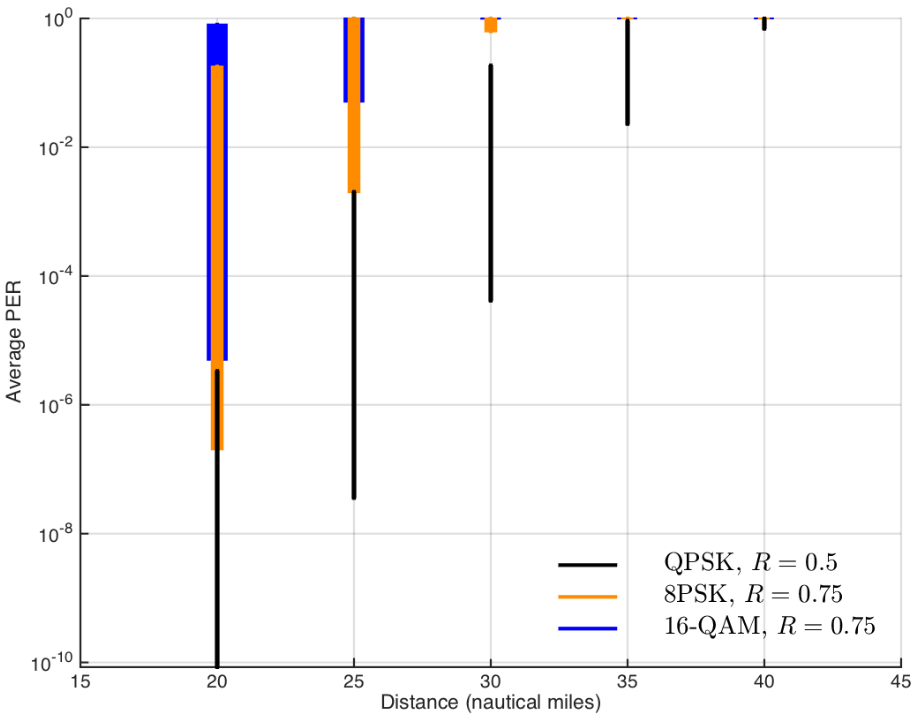

Figure 7: VDE50 PER Performance at Range

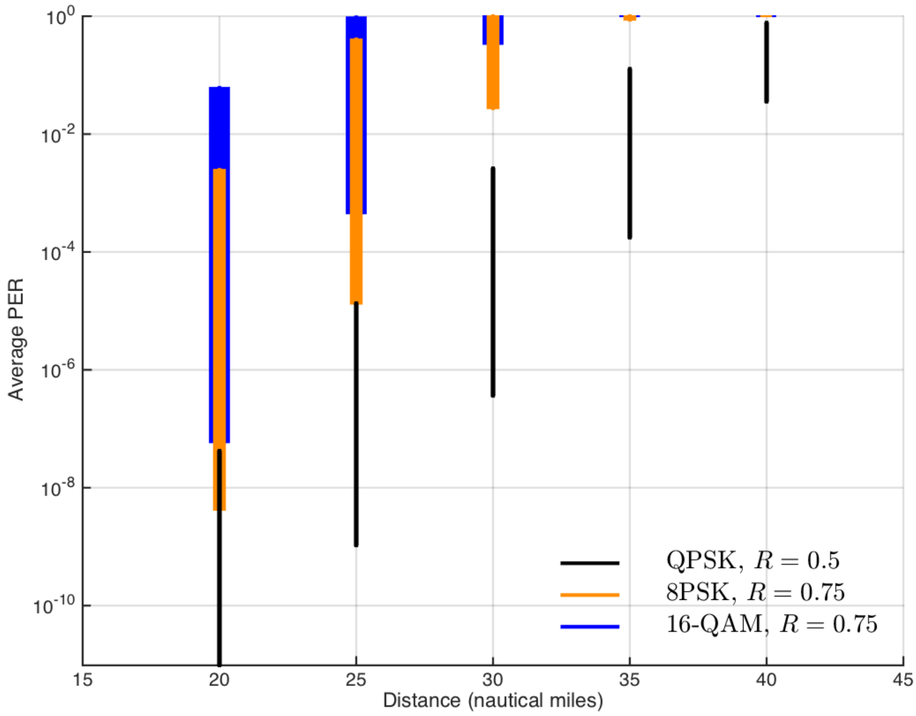

Figure 8: VDE25 PER Performance at Range

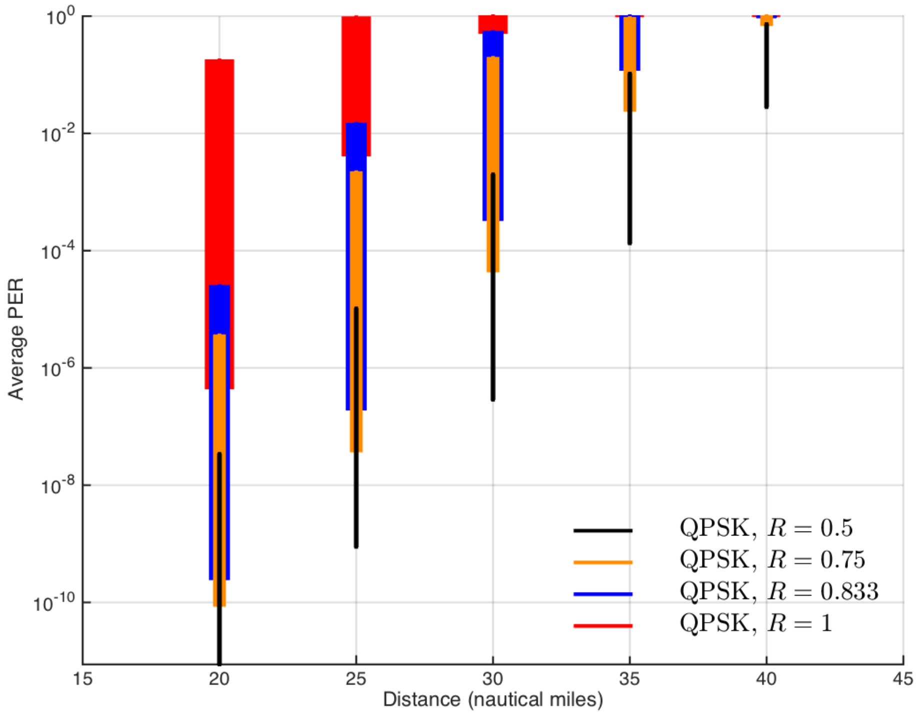

Figure 9: ASM PER Performance at Range

As discussed above, the John-Egli model provides a closer match to trial results at long distances. The remainder of this section therefore assumes the John-Egli model. The MCS that supports a particular PHY PER can be readily obtained from the above figures. For example if the required PHY PER is 10^{-2}, communication is not supported at distance 35 NM and beyond. For distance below 30 NM, at least one MCS can support the target PER. MCS support when targeting PER $\leq 10^{-2}$ at the PHY is summarised in Table 10.

Channel	20NM	25NM	30NM
VDE100	QPSK, R=0.5		
VDE50	QPSK, R=0.5	QPSK, R=0.5	
VDE25	QPSK, R=0.5 8PSK, R=0.75	QPSK, R=0.5	QPSK, R=0.5
ASM	QPSK R=0.5, 0.75, 0.83	QPSK R=0.5, 0.75	QPSK, R=0.5

Table 10: Supported MCS at Range

At each distance, halving the channel bandwidth increases the SNR by 3 dB. Therefore, VDE25 supports higher order modulation and code rate compared to VDE50 and VDE100. However, the smaller channel bandwidth results in lower symbol rate and thus lower throughput. Finally, the additional options of QPSK, R=0.75 and QPSK, R=0.83 modulation and coding schemes allow the ASM to support larger throughput than the VDE25 channel in some cases.

6.4 PER at Link Layer

An automatic-repeat-request (ARQ) scheme can be employed to improve PER performance. As discussed in Section 3.4 and specified in the current draft VDES recommendation [6], the receiver can use the CRC to detect errors and invoke retransmission of erroneously received datagrams. As stated in Section 3.4.2, the Transport Layer (ASM and VDE-TER) has the responsibility of ensuring that messages are transferred reliably between stations. This section considers the case when the CRC is evaluated on a per-packet basis, and evaluates the equivalent link layer performance assuming that transmission retries are enabled.

Error detection and retransmission can provide a significant reduction in PER at the link layer. Assume that T transmissions (at most $T-1$ retransmissions) are permitted, and that the retransmissions are sufficiently separated in time such that they experience independent fading gains. Then the PER at the link layer is

$$\mathrm{PER}_{\mathrm{link}} = \mathrm{PER}_{\mathrm{phy}}^{T}, \qquad (3)$$

where $\mathrm{PER}_{\mathrm{phy}}$ is the packet error probability at the physical layer presented in Sections 6.2 and 6.3.

Equation (3) suggests that increasing the number of retransmission can quickly reduce the link layer PER. When the physical layer PER of 10^{-2} is satisfied, the link layer PER is at most

10^{-2T}. Thus an ARQ protocol will significantly improve the reliability of the link. However, the choice of T is constrained by the latency requirement of the applications.

The average PER for an ARQ scheme with one retransmission is illustrated in Figure 10 for the VDE channels and Figure 11 for the ASM channel. In these figures, only the modulation and coding schemes that support an average physical layer PER of 10^{-2} are included (as summarised in Table 10). The figures show that an ARQ scheme reduces the PER at the link layer to less than 10^{-5}. Note that since the physical layer PER is assumed to be 10^{-2}, at most 1% of the packets will require retransmission, and thus the ARQ protocol will not severely impact the overall throughput.

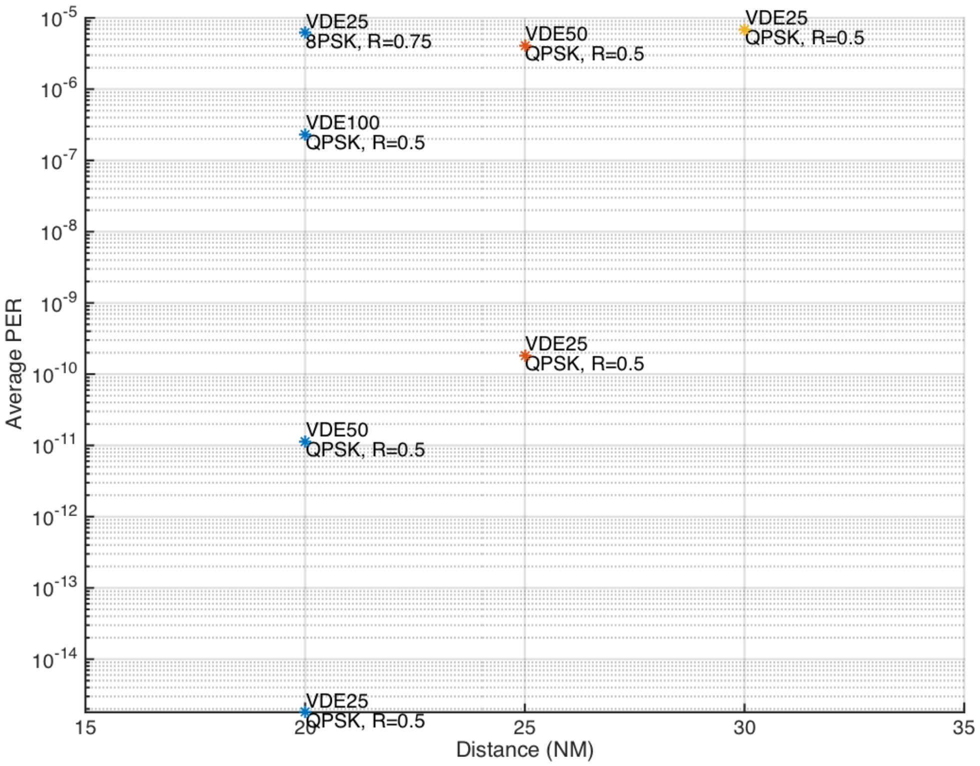

Figure 10: Equivalent Link Layer PER of VDE Channels, Allowing One Retransmission

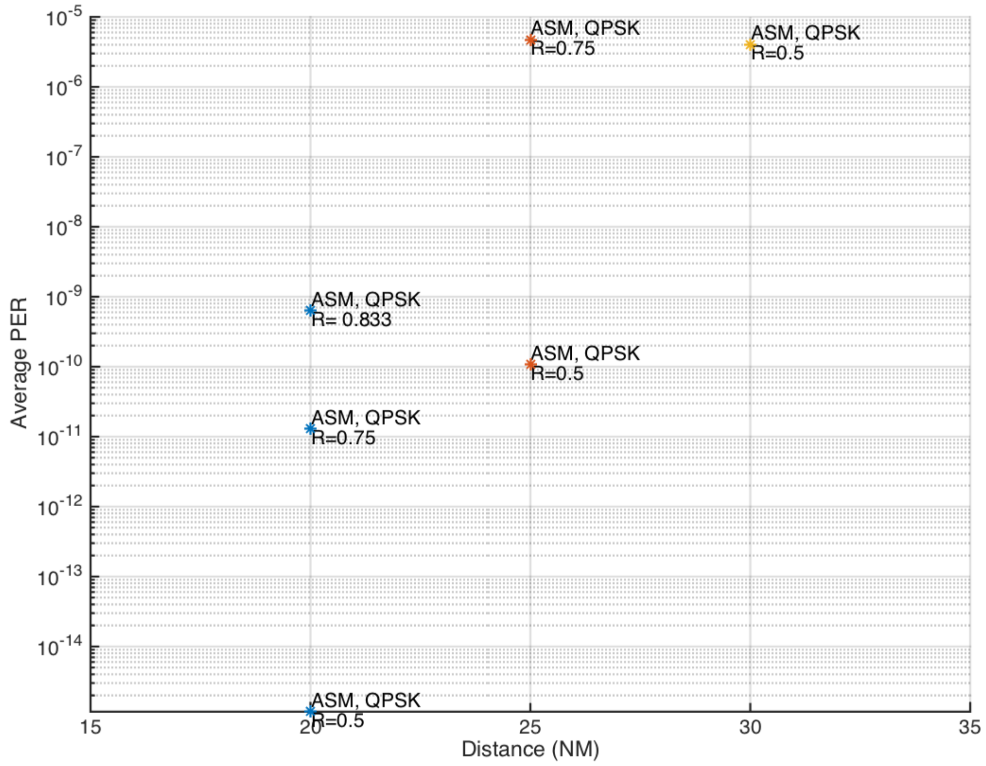

Figure 11: Equivalent Link Layer PER of ASM Channel, Allowing One Retransmission

7 Conclusions and Recommendations

This study has traced VDES user requirements that relate to physical and link layers forward into the current VDES recommendation, identifying any potential gaps that currently exist. The set of user applications have also been analysed in order to propose a set of design reference applications that provide full coverage of key physical and link layer requirements.

Using data obtained from on-sea trials, a set of channel models were developed and used to predict the expected VDES physical layer performance. Results show that all modulation and coding schemes currently proposed provide reliable communication (PER $\leq 10^{-2}$) for almost all trial scenarios, with the only exception being a PER of 0.1 for the R=0.75 16QAM scheme in the Sunk Deep Water Anchorage scenario. Equivalent link layer performance has also been modelled assuming the use of transmission retries. By allowing a single transmission retry, a significant performance improvement was observed when compared to the physical layer PER. The technique was also combined with existing models for average power prediction in order to predict performance at increased range.

7.1 Considerations for Co-existence with VDE-SAT

The scope of this report is limited to terrestrial ASM and VDE functions. However, it is essential that these functions can co-exist with satellite VDE functionality. The following points are noted for consideration on this topic:

Common Components: Annex 1, Section 3, of the current recommendation specifies common elements of VDES. Continuing with this approach will be critical in order to ensure that the terrestrial and satellite subsystems can coexist, and that components such as error control codecs can be reused across the two functions. Reuse of common components will also reduce testing requirements for simulation, development, and ultimately production.

Coexistence: As discussed in Section 3.1.1 the recent study regarding VDES coexistence with DSC and VHF voice communications has recommended a change to the spurious emission requirements for VDES [11]. Similar experiments in the context of the coexistence of terrestrial and satellite VDES functions would allow any potential desensitisation of VDE-SAT reception to be characterised.

Satellite AIS Reception: A previous study has noted that Doppler induced carrier frequency offsets of up to +/- 4 kHz that can occur during low earth orbit satellite reception should be considered in the specification of ASM waveforms [24]. It was recommended that the ASM data rate be limited to 19.2 kbps, in order to reduce occupied bandwidth, and avoid collision between AIS and ASM packets when received at a satellite. The current ASM data transmission bit rate specification ([6] Annex 2, Section 2.4) appears to be consistent with this recommendation. The ASM slotted modulation mask ([6] Table A2-2) may be tightened to reflect the occupied bandwidth for $\pi/4$ QPSK modulation described in [24].

7.2 Gaps between Current User Requirements and VDES Recommendation

The remainder of this section summarises existing gaps that have been identified during this study. Several of these may lead to future studies that could add value to the development of VDES. It is recognised that the current VDES recommendation is under development. With this in mind, this section is intended to assist in linking remaining efforts to the set of user requirements that have been identified to date.

Coexistence: As discussed in Section 3.1.1 the recent study regarding VDES coexistence with DSC and VHF voice communications has recommended a change to the spurious emission requirements for VDES [11]. Similar analysis and experiments may also be worthwhile in the context of AIS coexistence.

Terminology: Key terms such as message, frame, slot, packet, segment, datagram and fragment should be well defined and used consistently across all components of the VDES recommendation. Providing a set of definitions and a hierarchy figure in Annex 1 of the recommendation would help make these concepts clear.

Multicast/Geocast Communications: As discussed in Section 4.6, 23 of the use cases identified in [10] require multicast and/or geocast communications. However, as noted in Section 3.2.2, the recommendation does not yet specify how to address a group of stations (VDES-TEC-011) or a specific geographic area (VDES-TEC-010) for ASM or VDE-TER messages

Mode Dependent TDMA Selection: The ASM recommendation states that the type of TDMA (VDES-TEC-003) to be used is application and mode dependent (see Section 3.2.4). However, the recommendation does not yet clearly state which TDMA access scheme is to be used for each mode of operation.

Multimode Operation and Selection: As discussed in Section 3.2.5 the recommendation describes multi-mode support for ASM but not VDE-TER. It also does not specify how the most efficient mode of operation should be automatically selected.

Transmit Scheduling: As discussed in Section 3.3.1 the recommendation does not yet describe how automated, delayed, and scheduled transmissions will be supported (VDES-OPS-018).

Transmit Priority: As discussed in Section 3.3.2 the recommendation defines four ASM priority levels, although not given the same labels as those provided in the corresponding user requirement (VDES-OPS-019). Priority levels are not currently defined for VDE-TER messages. The recommendation does not yet describe methods for priority assignment and management.

Message Acknowledgment: The current recommendation describes a message acknowledgement protocol for ASM but does not yet provide the equivalent level of detail for VDE-TER (see Section 3.4.2,).

Adaptive Modulation and Coding: As discussed in Section 3.4.4 the recommendation clearly defines a set of modulation and coding schemes for both ASM and VDE-TER. However it does not yet describe a protocol for transmit rate adaption in response to changes in link quality.

Specification of Pulse Shaping Filter: This report assumes the use of root raise cosine pulse shaping filters. The current recommendation specifies roll offs for ASM and VDE-TER of 0.35 and 0.3 respectively, without stating the filter type.

Quality of Service: mechanisms to provide the QoS necessary to meet message importance (latency) and priority requirements may require further consideration (see Sections 4.4 and 4.5). Assignment and management of message priorities are currently the responsibility of the Network Layer. QoS mechanisms may also require link layer components and protocols to be considered during the design phase.

Proposed VDE Methods: ASM is currently proposed as a suitable method for all application use cases [5]. The lower capacity of ASM, when compared to VDE-TER, makes it better suited to applications that require either small (<1 kB) data transfer, or data transfer at the lower end of the medium scale, as discussed in Section 4.7.

A multi-ship simulation study would allow analysis of the effects on VDES capacity when large numbers of vessels are collocated, and could assist in the allocation of appropriate communications methods to each application. Such a model could also be used to observe any potential VDES impacts to or from AIS, VHF telephony, and DSC.

Synchronisation and Signal Field Performance: In order for a packet to be decoded, the signal field must itself be decoded correctly so that the modulation and coding scheme can be determined. Similarly, in order for the signal field to be decoded, the packet must be correctly acquired (i.e. synchronised) at the receiver. Hence, the signal field should be at least as robust as the most robust MCS. Moreover, the training sequence should support acquisition at SNR that is at least as low as the SNR at which the signal field can be reliably decoded. Analysis of the header error probability has been included in the recommendation for VDE-SAT in Annex 4, Section 2.6.5. It is not clear if a similar analysis has been performed for VDE-TER or ASM.

8 Publications

This report is available as input document ‘GLA-ITR-VDESTechRequirements-Report-1v0’ to the intersessional meeting of the IALA e-NAV Committee Working Group 3, Dublin, Ireland, January 2016.

A Rician Fits for Channel Fading Gains

This appendix provides a set of plots that compare the Rician distribution approximations to the empirical distributions from on-sea trials. Further information on the methods used can be found in Section 5. Channels are labelled according to their function and bandwidth, e.g. VDE100 represents the 100 kHz VDE-TER channel.

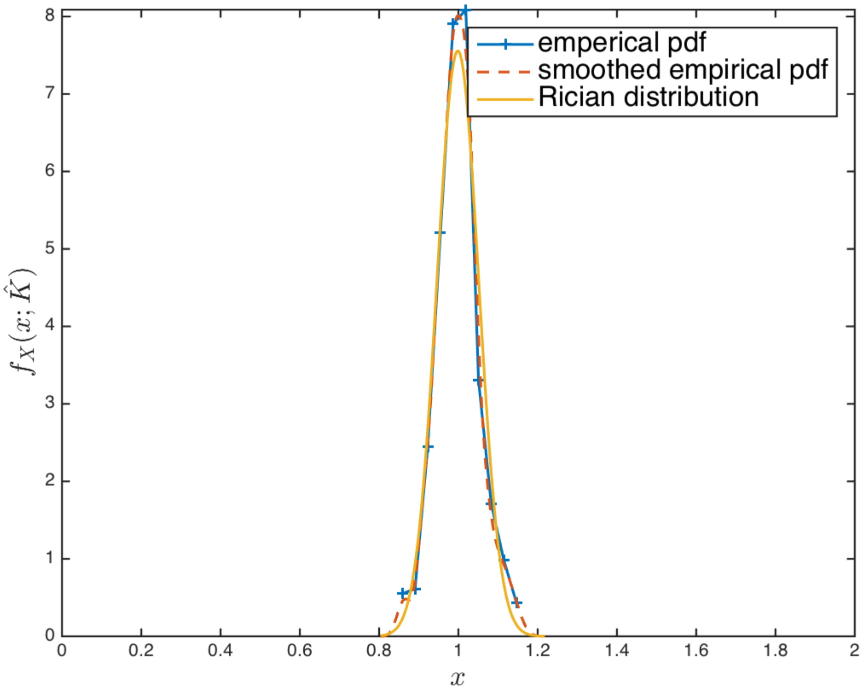

Figure 12: Rician fit for Trial 1629 (VDE100, Harwich Harbour)

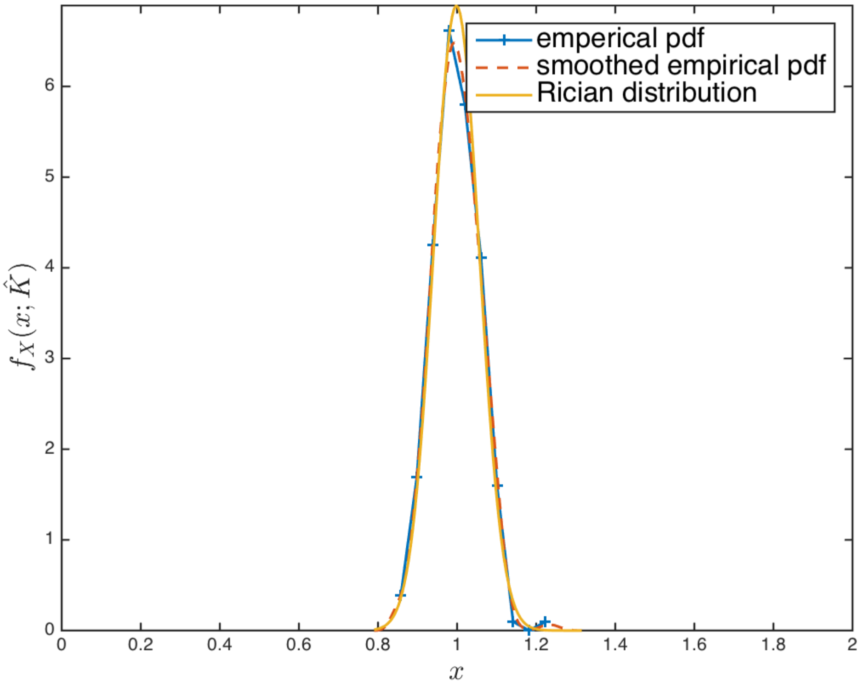

Figure 13: Rician fit for Trial 1129 (VDE100, Gunfleet Sand)

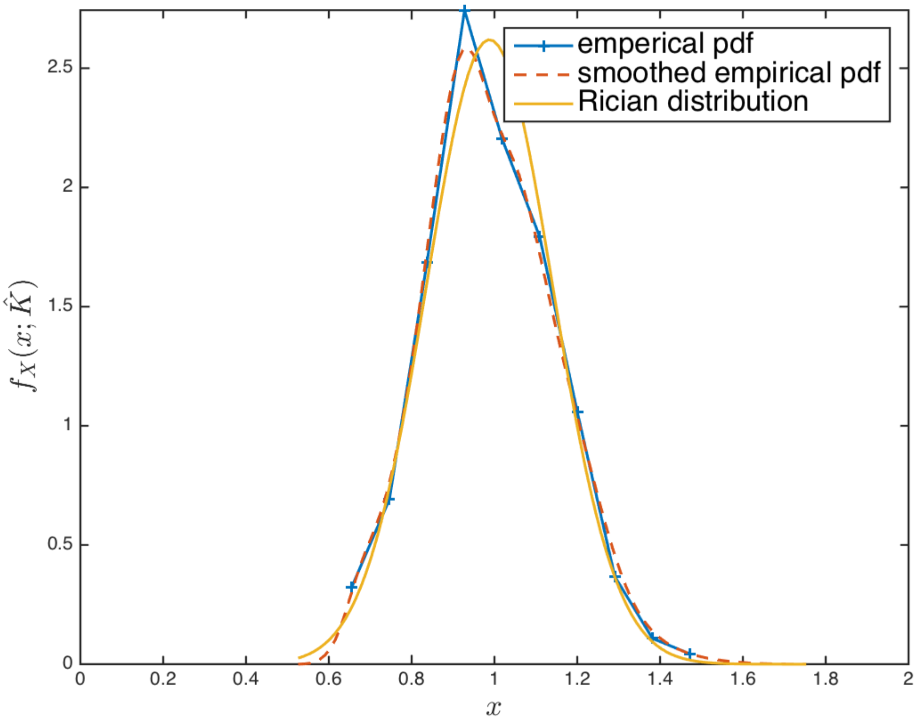

Figure 14: Rician fit for trial 1542 (VDE100, Gunfleet Sands)

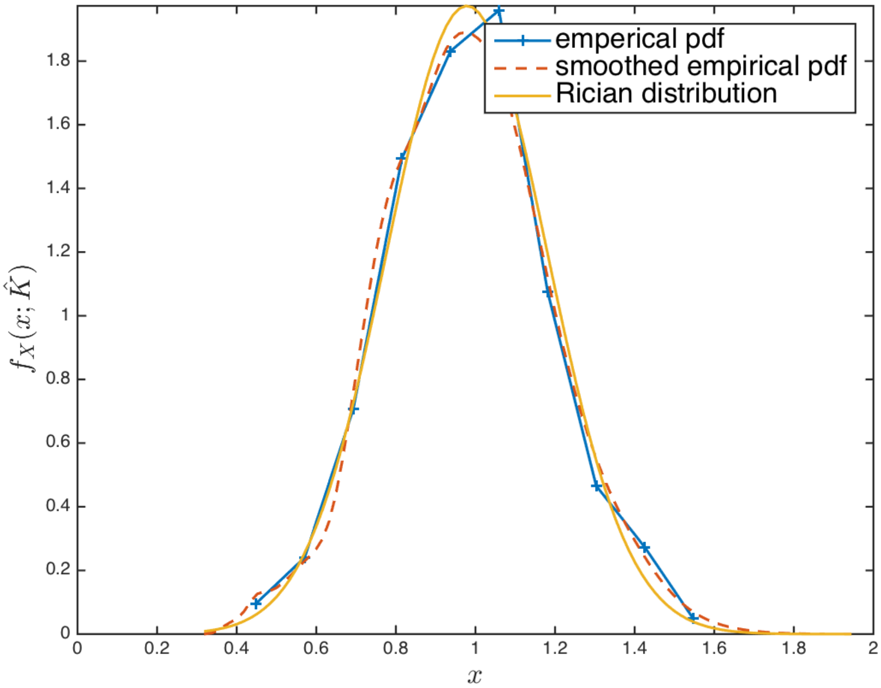

Figure 15: Rician fit for Trial 1226 (VDE100, Ipswich)

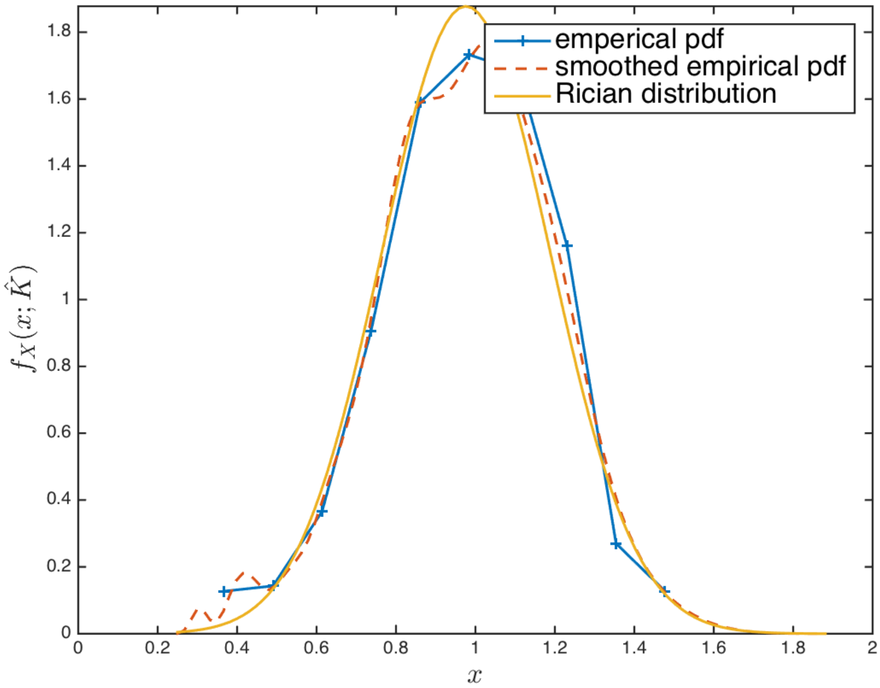

Figure 16: Rician fit for trial 1227 (VDE100, Harwich Approach)

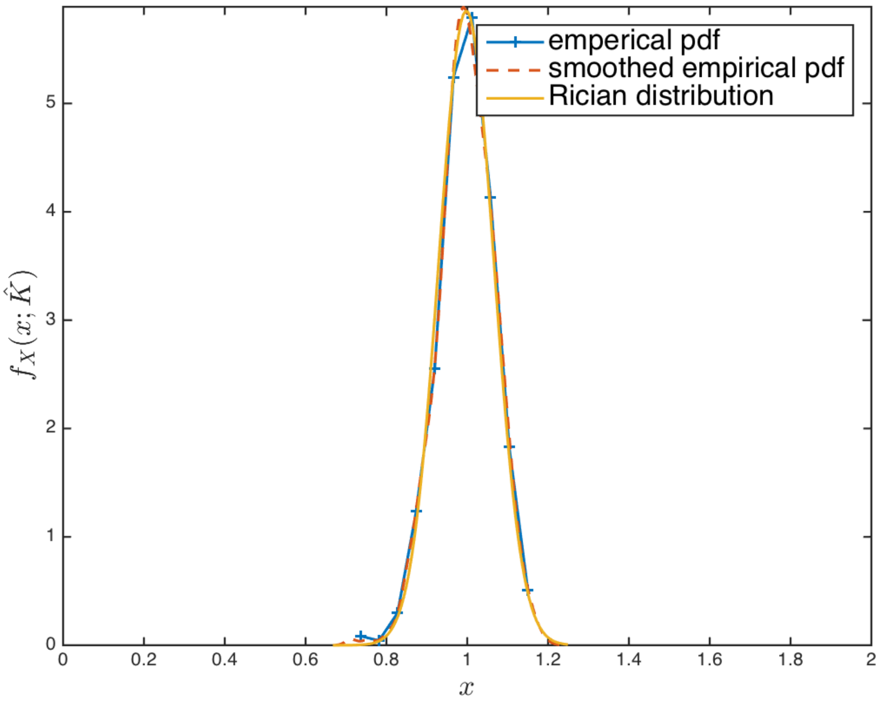

Figure 17: Rician fit for trial 1647 (VDE50, Harwich Harbour)

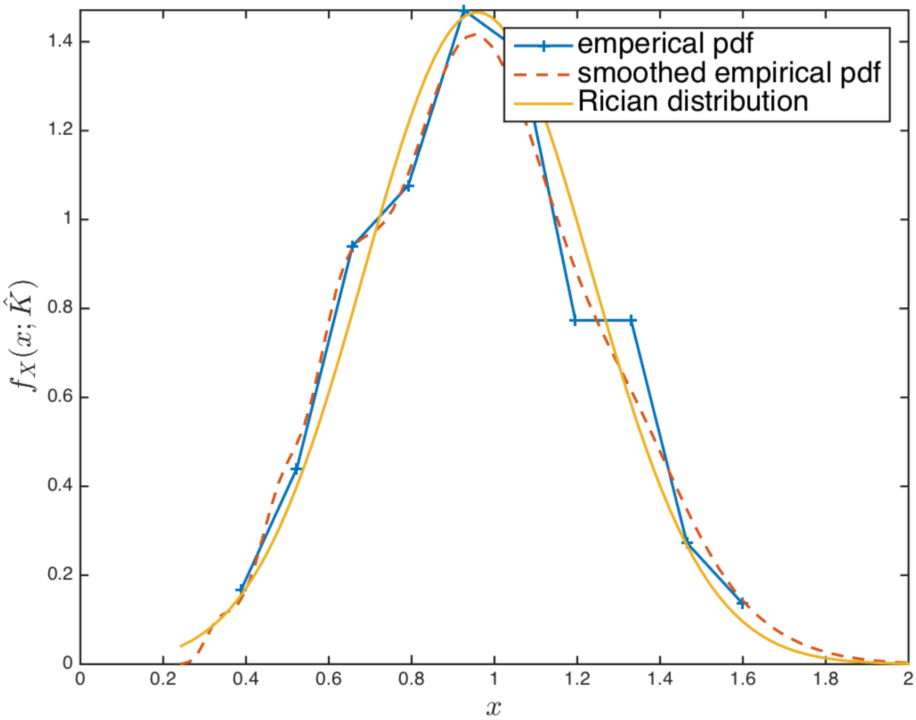

Figure 18: Rician fit for trial 1247 (VDE50, Ipswich)

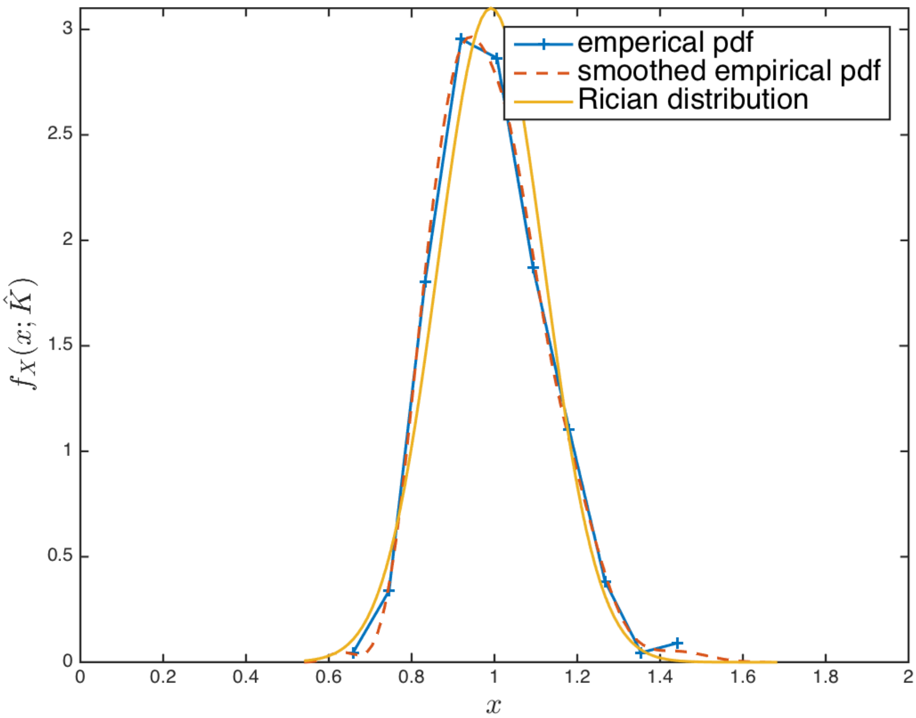

Figure 19: Rician fit for trial 1725 (ASM1, Harwich Harbour)

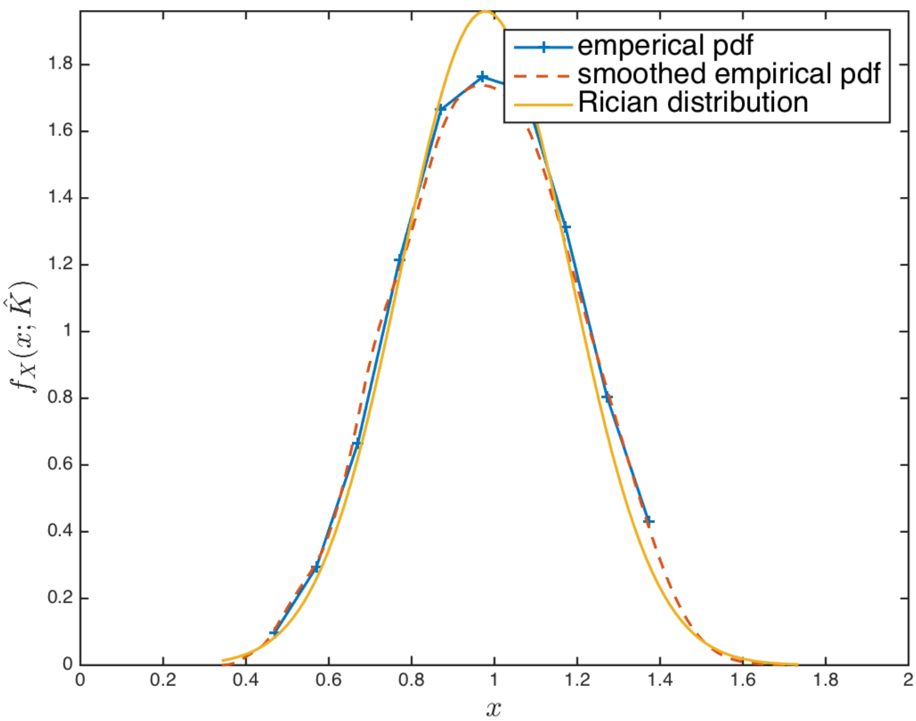

Figure 20: Rician fit for trial 1309 (ASM1, Ipswich)

B Derivation of Expected Performance

The performance of the system depends on the signal-to-noise ratio (SNR) at the receiver, among other factors. The distribution of the received signal power is characterised in Section 5. This Appendix describes the method used to evaluate expected performance. The noise floor is first characterised, and is assumed to be additive white Gaussian. The SNR is then determined and used to evaluate the performance bounds.

The noise power at the receiver depends on the channel bandwidth B (Hz), the operating temperature T (K) and the receiver noise figure NF (dB). For the purposes of calculating required SNR the implementation margin IM (dB) has also been lumped into the calculation of noise spectral density, effectively assuming a raised noise floor. At room temperature (T=300 K) the noise spectral density is -174 dBm/Hz. The noise spectral density N including noise figure and implementation loss is then calculated as follows

$$10\log_{10} N = -174 + \mathrm{NF} + \mathrm{IM}. \tag{4}$$

Recall from Section 5 that for transmission with average receive power P_{av}, then the instantaneous received power is $P_r = P_{\mathrm{av}}X^2$, where X is a random variable following a distribution $f_X(x)$ with $E[X^2] = 1$. Given a receiver antenna gain G_R, receive cable loss L_c, and pulse shaping with roll off factor α, the instantaneous SNR is [25]

$$\Gamma_s = \frac{E_s}{N} = \frac{P_r G_R(1+\alpha)}{L_c NB} = \frac{P_{\mathrm{av}}X^2 G_R(1+\alpha)}{L_c NB} = \frac{G P_{\mathrm{av}} X^2}{N}, \tag{5}$$

where $G = \frac{G_R(1+\alpha)}{BL_c}$.

The average packet error rate (PER) is therefore

$$\mathrm{PER} = \int_0^\infty P_e\left(\frac{G P_{\mathrm{av}} x^2}{N}\right) f_X(x)dx, \tag{6}$$

where $P_e(\Gamma_s)$ is the instantaneous PER.

For uncoded transmission of packets having length L symbols, the instantaneous PER is

$$P_e(\Gamma_s) = 1 - \left(1 - P_s(\Gamma_s)\right)^L, \tag{7}$$

where $P_s(\Gamma_s)$ is the symbol error probability resulting when transmitting over an AWGN channel with SNR Γ_s. The symbol error probability, which also depends on the modulation type, can be computed using the approximations given in [25].

For ideal error correcting codes, the channel can support an instantaneous communication rate $I(\Gamma_s)$ bits per channel use (bpcu), where $I(\Gamma_s)$ is the input-output mutual information of an AWGN channel with SNR Γ_s [25]. For the optimal Gaussian input distribution, $I(\Gamma_s) = \log_2(1+\Gamma_s)$. Figure 21 illustrates the mutual information for Gaussian, uniform 4-QAM (QPSK), uniform 8-PSK and 16-QAM input distributions.

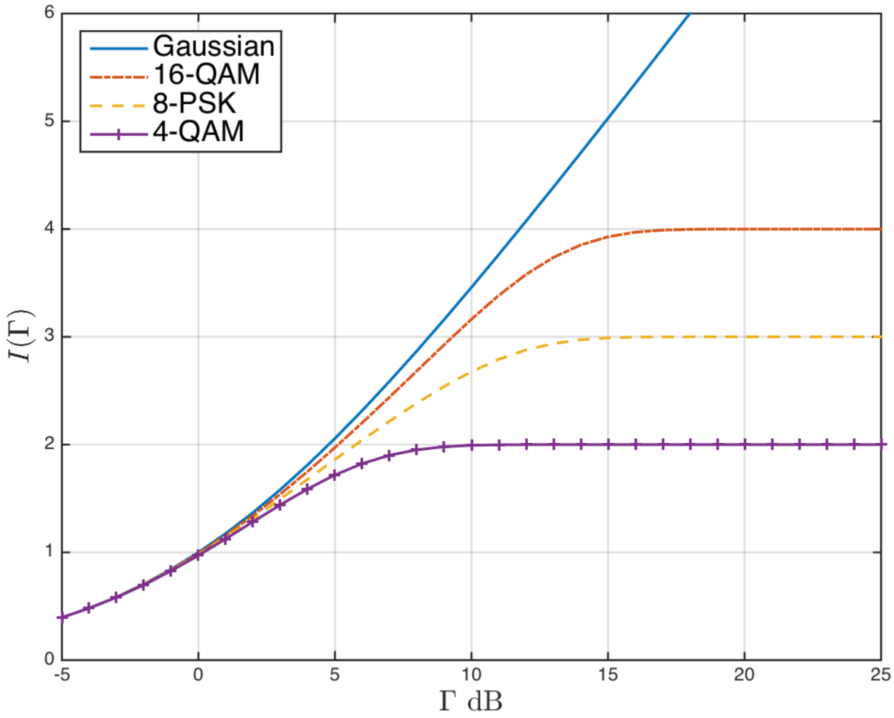

Figure 21: Mutual Information for Gaussian, 16-QAM, 8-PSK and 4-QAM (QPSK) Input Distributions

For a given transmission rate R (bpcu), an outage event is realized when $I(\Gamma_s) < R$. In other words, the instantaneous packet error probability is

$$P_e(\Gamma_s) = \begin{cases} 1, & I(\Gamma_s) < R \\ 0, & \text{otherwise.} \end{cases} \quad (8)$$

It follows from (6) that the average packet error rate is

$$\text{PER} = \int_0^{\sqrt{\frac{I^{-1}(R)N}{P_{\text{av}}G}}} f_X(x)\,dx = F_X\left(\sqrt{\frac{I^{-1}(R)N}{P_{\text{av}}G}}\right) \quad (9)$$

where $F_X(x)$ is the cumulative distribution function (cdf) of X.

Another performance measure is the SNR margin, which characterises how much the average SNR, and thus the average received power, can be reduced while maintaining an average PER ϵ. Let P'_{av} denote a hypothetical average received power such that the average PER is ϵ, i.e.,

$$\text{PER} = \int_0^{\infty} P_e\left(\frac{GP'_{\text{av}}X^2}{N}\right) f_X(x)dx = \epsilon. \quad (10)$$

Then the SNR margin is the ratio between the received average power P_{av} and the hypothetic P'_{av}, or in dB scale,

$$\Delta_{\mathrm{dB}} = 10\log_{10}\frac{P_{\mathrm{av}}}{P'_{\mathrm{av}}} = P_{\mathrm{av}_{\mathrm{dBm}}} - P'_{\mathrm{av}_{\mathrm{dBm}}}. \quad (11)$$

For coded transmission schemes where PER reduces to $F_X\left(\sqrt{\frac{I^{-1}(R)N}{GP'_{\mathrm{av}}}}\right)$, the hypothetic P'_{av} satisfies

$$P'_{\mathrm{av}} = \frac{I^{-1}(R)N}{G\left(F_X^{-1}(\epsilon)\right)^2} \quad (12)$$

Meanwhile for uncoded schemes where $P_e(\Gamma_s)$ is computed using (7), P'_{av} needs to be evaluated numerically.

References

[1] N. Ward, J. Safar, A. Grant, and D. Haley, 'GLA/ITR VHF Data Exchange System Waveform Study Proposal Summary', IALA e-Navigation Committee WG 3/4 Intersessional Meeting, St Germain, France, Input Document 11, Sep. 2014.

[2] N. Ward, 'VDES Waveform Study Proposal'. Input Document ENAV15-10.15, IALA ENAV15, St Germain, France, Oct-2014.

[3] J. Safar, D. Haley, L. Davis, A. Grant, and N. Ward, 'VDES Waveform Scoping Study', IALA ENAV Committee WG 3, ENAV 16, St Germain, France, Input Document ENAV16-11.25.2, Apr. 2015.

[4] IALA, 'User Requirement Document', IALA e-Navigation Committee WG 3 Intersessional Meeting, St-Germain-en-Laye, France, May 2015.

[5] IALA, 'User Requirements Spread Sheet', IALA e-Navigation Committee WG 3 Intersessional Meeting, St-Germain-en-Laye, France, May 2015.

[6] ITU, 'Technical Characteristics for a VHF Data Exchange System in the VHF Maritime Mobile Band', Geneva, Switzerland, Recommendation ITU-R M.2092-0, Oct. 2015.

[7] ITU, 'VHF Data Exchange System Channel Sounding Campaign', Draft New Report ITU-R M.[CHANNEL SOUNDING], Nov. 2014.

[8] N. Alagha, 'VHF Data Exchange System (VDES) for Maritime Communications, ESA Activities Status Update', presented at the CEPT Workshop on VDES, Copenhagen, Jun-2015.

[9] ITU, 'Technical Characteristics for an Automatic Identification System Using Time Division Multiple Access in the VHF Maritime Mobile Frequency Band', Recommendation ITU-R M.1371-5, Feb. 2014.

[10] 'Draft Guidelines on User Requirements for VDES', IALA ENAV 17 WG 3, Brest, France, Liaison Note, Oct. 2015.

[11] Cobham SATCOM, 'VDES Impact on GMDSS VHF Communications', ENAV 17-11.28, Oct. 2015.

[12] P. Andersen, 'Utilization of the Marine VHF Band in e-Navigation', IALA e-Navigation Committee WG 3/4 Intersessional Meeting, Brest, France, Input Document 11, Aug. 2013.

[13] ITU, 'Method for Point-to-Area Predictions for Terrestrial Services in the Frequency Range 30 MHz to 3 000 MHz', ITU-R P.1546-4, Oct. 2009.

[14] Roche Ltd., 'Canadian Coast Guard: Options and Impacts for VDE and AIS Systems', IALA e-Navigation Committee WG 2 Intersessional Meeting, St-Germain-en-Laye, France, Input Document 4, Sep. 2014.

[15] ITU, 'Technical Characteristics of VHF Radiotelephone Equipment Operating in the Maritime Mobile Service in Channels Spaced by 25 kHz', Recommendation ITU-R M.489-2, Oct. 1995.

[16] ETSI, 'Radiotelephone Transmitters and Receivers for the Maritime Mobile Service Operating in VHF Bands; Technical Characteristics and Methods of Measurement', ETSI EN 301 925 V1.4.1 (2013-05), 2013.

[17] ITU, 'Digital Selective-Calling System for Use in the Maritime Mobile Service', Recommendation ITU-R M.493-13, Oct. 2009.

[18] ETSI, 'Technical Characteristics and Methods of Measurement for Shipborne Watchkeeping Receivers for Reception of Digital Selective Calling (DSC) in the Maritime MF, MF/HF and VHF Bands', ETSI EN 301 033 V1.4.1 (2013-09), 2013.

[19] J. G. Proakis and M. Salehi, *Digital communications*. Boston: McGraw-Hill, 2008.

[20] M. Abramowitz and I. A. Stegun, Eds., *Handbook of Mathematical Functions: with Formulas, Graphs, and Mathematical Tables*, 0009-Revised edition. Dover Publications, 1965.

[21] *Statistical Inference*, 2nd edition. Australia ; Pacific Grove, CA: Duxbury Press, 2001.

[22] F. Huang, Y. Bai, and W. Du, 'Maritime Radio Propagation with the Effects of Ship Motions', *Journal of Communications*, vol. 10, no. 5, 2015.

[23] J. J. Egli, 'Radio Propagation above 40 MC over Irregular Terrain', *Proceedings of the IRE*, vol. 45, no. 10, pp. 1383–1391, Oct. 1957.

[24] JRC and IHI, 'ASM Protocol Proposal for PDNR ITU-R M.[VDES}', presented at the IALA e-Navigation Committee WG 3 Intersessional Meeting, St-Germain-en-Laye, France, Feb-2015.

[25] A. Goldsmith, *Wireless Communications*. Cambridge University Press, 2005.