Deliverable 2.1

Report on status on development of VDES

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Document Status

Authors

Name	Organisation
Peter Anderesen	Thrane & Thrane A/S
Stefan Pielmeier	Thrane & Thrane A/S
Krzysztof Bronk	NIT
Jean Jeacques Valette	CLS

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Review

Name	Organisation
Erik Christensen	Cobham Satcom
Andy Winbow	CIRM

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Contents

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1 Executive summary

This document provides a status report on progress, on developing the VDES specification at IALA, and with a test platform including the definition of the test to be undertaken as part of development of the requirements for VDES.

To date comprehensive simulation has been undertaken to both support the work done at IALA in developing the ITU recommendation ITU-R M.2092-0 for VDES and as the basis for the on-air test, which is within the scope of work under WP 2.1 under EfficienSea2. Up to now the simulation has shown that the three modulation forms π/4QPSK, 8 PSK, and 16 QAM are the best options to work from and these will be the basis for the coming test and presumably the ongoing work.

At IALA members of WP2.1 are actively participated in drafting ITU-R M.2092, and using the work done in WP2.1 as an element of their input to the work. The ongoing work at this task group EfficienSea2 WP 2.1, is aiming to maintain or even improving the final quality of this recommendation. The coming on-air test will be an important element of this work.

The recommendation ITU-R M.2092 will be the high level specification of VDES. Following this document, development of a related IEC test standard will be initiated. WP 2.1 is and will be actively participating in the work with these two documents, and by that the definition of the technical backbone for the VDES as a product available to the market.

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2 Scope

The scope of this document is to describe the activities within EfficienSea2 task 2.1 up to M18. Bearing the original plan for this task group in mind, the document includes description of the simulation done on on-air parameters and the work done at IALA for developing the ITU VDES recommendation ITU-R M.2092

The WP 2.1 task group has decided to perform an additional on-air sea trail in the project. This sea trial, intended to start at the end of Q4 2016, is a subtask to increase the quality of the final delivery in M33. Additionally this sea trial will be used as a validation of the work done at IALA in formulation of the ITU recommendation ITU-R M.2092. On this basis the work up to the sea trial and the work at IALA will be the basic topics in this document.

Abbreviations

VDES	VHF Data Exchange System
VDE – TER	VHF Data Exchange - Terrestrial
ITU	International Telecommunication Union
IEC	International Electronical Commission
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities,
AWGN	Adaptive White Gaussian Noise
MSC	Modulation and Coding Scheme
BER	Bit Error Rate
BLER	Block Error Rate
FPGA	Field Programmable Gate Array
SWR	Standing Wave Ratio
ADC	Analogue to Digital Converter
DAC	Digital to Analogue Converter

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RAM	Random Access Memory
NMEA	National Marine Electronics Association
GPS	Global Position System
USB	Universal Serial Bus
CAM	Central Alarm Management
PA	Power Amplifier
SMPS	Switched Mode Power Supply
WRC	World Radio Conference

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3 VDES in brief

VHF Data Exchange System, usually referred to as ''VDES'' is a new standard of maritime wireless data transmission in the VHF band and the development of its technical specification is one of the tasks of the EfficienSea 2 project. The purpose of the system is not only to increase achievable transmission rates but also to improve the availability of data transmission services at sea. As a result, it is expected that the VDES will improve communications between ships and ports, increase maritime safety, protect the environment and also provide means for a novel concept of so-called e-navigation. To some extent, the system is an extension of the existing AIS standard (Automatic Identification System) which was mainly created to offer an efficient and smooth exchange of navigation data between ships and between ships and coastal entities. Anyway the AIS is a broadcast system where ships in fixed intervals broadcast navigation information about own ship, in a fire and forget manner, where the VDES is a communication system which can be used for both broadcast, point to point and point to multipoint communication.

VDES is based on both terrestrial communication and communication over a satellite link. The work in WP 2.1 is mainly focused on the terrestrial communication, but also the satellite based communication is an important element of VDES and considered in the work of WP2.1. Anyway the space segment is not expected to be available until 2021 at the earliest, which is three years after the EfficienSea2 project has ended. This is basically due to problems in having the frequency allocation approved by the ITU world radio conference. A more through description of this is available in Annex 1.

Figure 1 below show the expected implementation of the VDES services. During the period 2019-2020, the satellite component of VDES will be limited to uplink with the reception of the ASM1 and ASM2 frequencies. After 2021, a satellite service is developed with full operational capability of the VDES including the Satellite downlink service.

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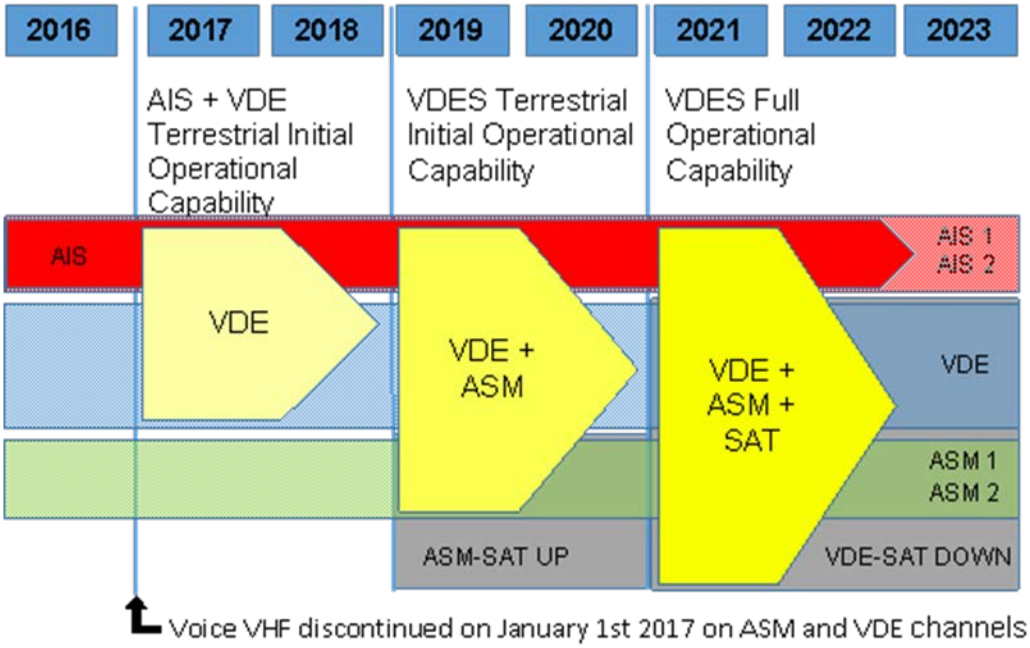

Figure 1: Implementation of the VDES services

4 Work in the IALA e-navigation working group

4.1 Aim of the working group

In relation to the IALA e-NAV working group 3 (WG3) the aim of this working group is to support in developing the preliminary ITU-R M.2092-0 towards a successful ITU-R M.2092-2 for the whole VDES system, including Satellite component with worldwide coverage at comparably low cost.

The goal for ITU-R M.2092-2 is to provide the maritime community with a standard means for transferring digital navigation and security relevant data, between ships and to/from shore. This aims to improve security at sea through digital services provided from shore to the ship through the maritime cloud. The VDES is the low budget system of choice for mariners wishing to engage with high quality aligned digital e-Navigation services.

4.2 Status of the work

The team members from NIT (National Institute of Telecommunication), and Thrane & Thrane A/S (Cobham SATCOM) have been present in nearly all of the working group meetings since start of the EfficienSea 2 project and participated very actively in writing whole chapters of the recommendation, including providing the currently chosen

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synchronization method, forward error correction and modulations for the terrestrial part and have contributed to organizing the work on the working document towards ITU-R M.2092-2. One of the EfficienSea2 participants is co-chairing the work on ITU-R M.2092-1 to ensure progress towards the planned goals.

In the IALA WG3 work related to the space segment of VDES, the WP2.1 partner CLS (Collecte Localisation Satellites) has been active in the discussions, and the task of finding solution to overcome the recent decision from ITU to discontinue the work on the space segment, until further clarification in relation to possible disturbance og has been reached. This work has resulted in the document ITU 5B/ TEMP/ 4-E (Annex 1).

The plan is to have 2092-1 adopted by ITU WP 5B in 2018. For information the first version of the Recommendation ITU-R M.2092 on VDES is now available at https://www.itu.int/rec/R-REC-M.2092

Following this the plan is to have 2092-2 (with SAT component) sent to ITU WP 5B in 2020.

4.3 E2 participation and related activities

Future activities include participation in field tests of the VDE-TER baseband to evaluate the chosen synchronization preamble, packet header protection and forward error correction together with the chosen modulation types.

This feedback will provide new insights into the feasibility of the system, which might subsequently require changes to ITU-R M.2092 in the period of EfficienSea 2 involvement.

In the future, the working group also has to define the interfacing with the maritime cloud, which provides routing, transport, service location, authentication and security mechanism for transporting the maritime services between ships and to/from shore. Cooperation with the relevant EfficienSea 2 working groups will be coordinated.

EfficienSea 2 participation in WG3 is crucial to ensure a critical mass of knowledge and organization is available to make the development of a successful standard possible.

5 Space segment

5.1 VDE-SAT use cases

Task 2.1represented by CLS is active in an IALA WG3 sub-working group, which is dedicated to the identification and specification of VDE-Sat use cases. Several use

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cases have been identified being of high interest in the context of VDE-SAT, most important are SAR communications, and Safety related information.

Two examples are developed and reported in “VHF DATA EXCHANGE SYSTEM (VDES) OVERVIEW”, IALA guideline (under construction).

Communication options:
When available, the VDES satellite component (VDE-SAT) is intended to be an effective means to extend the VDES to areas outside of terrestrial coverage. The VDES-SAT will deliver information as broadcast, multicast and unicast, addressing many ships using only minimal radio spectrum resources. The VDE-SAT will provide a communication channel that is complementary to GMDSS and the terrestrial components of the VDES system (i.e. coordinated with terrestrial VDES, application specific messages (ASM) and AIS functionalities and their supporting systems).

SAFETY RELATED INFORMATION - SCENARIO - GNSS AUGMENTATION:
Distribution of GNSS augmentation corrections via VDES will allow GNSS users to get timing, integrity data and improved position accuracy through the VDES service. Utilizing this option VDES will increase the benefits of GNSS required in SOLAS Chapter V, Regulation 19.
The table below represents the present vision of task 2.1 concerning services in the maritime service portfolio which can benefit from communication over VDES.

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Nature of info	Services	Use case 1	Use case 2	Use case 3	Use case 4	Coverage Arctic	Coverage Global	Refreshment On event	Refreshment Periodic #/day
MSI	Heavy weather conditions	X	X			X	X	X	
	Dissemination of ice charts	X				X			3/day
	Ice bulletins	X				X			3/day
	Navigation hazards (bulletin)	X				X	X	X	
	Navigation hazards (charts)	X				X	X		12/day
	Area notice		X		X	X	X	X	
	Route information	X	X		(X)	X	X	X	
	Route suggestion	(X)	X		X	X	X	X	
	Resquest from ship		X		X			X	
	SBAS_corrections (*)	X				X			6'
Report from ship	Weather report from ships			X		X	X		4/day
	Navigation hazards report			X		X	X		
	Voyage data recorder (VDR)			X		X	X		X
	Imminent collision MSI			X		X	X		
	Cargo indication				X	X	X	X	
	Position report			X		X	X		
	Piracy 1 victim			X		X	X	X	
	Piracy 2 witness			X		X	X	X	
SAR	SAR Operations				X	X	X	X	

	Use case 1	Downlink broadcast
	Use case 2	Downlink unicast
	Use case 3	Uplink
	Use case 4	Interactive link
	Mission VDE-SAT uplink	
	Mission VDE-SAT downlink	

Figure 2 Services which may benefit from the use of VDES. it must be noted that the figures for the refreshment rate are to be consolidated.

5.2 WP 2.1 sea trial in relation to the space segment

One concern in relation to the space segment is potential conflicts in the compatibility with the terrestrial segment.

Do ESA have VDE-Sat satellite in orbit during the on-air sea trials performed by WP2.1 the performance of the terrestrial link will be analysed for any consequences related to the satellite signals. This input will be valuable in defining the on-air parameters to mitigate potential interference.

6 Simulation

This chapter is a short introduction to the document entitled ‘’Report on the software simulator for the analysis of the VDES system terrestrial segment’’ which describes

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briefly the physical layer of the VDES and introduces the software simulator of this layer. Generally, the report is comprised of three main segments. In the first one, the physical layer of the VDES terrestrial (VDE-TER) component is presented. (In the document, the authors did not deal with the satellite part of the system). For the purpose of this new maritime data exchange standard, the following transmission channels have been assigned:

- Channels 2027 and 2028 for the ASM system (Application Specific Messages),
- Channels 24, 84, 25, 85 with 100 kHz band for the VDE-TER segment.

In the system, three modulation and coding schemes (MCS) have been defined (using $\pi/4$ QPSK, 8PSK and 16QAM modulations). There are also three possible channel bandwidths: 25, 50 and 100 kHz, so the resulting **raw** throughput is in the range from 38,4 kb/s (MCS-1, 25 kHz) to 307,2 kb/s (MCS-3, 100 kHz). The first chapter of the report described all the most crucial segments of the VDES transmitter (including the turbo encoder, scrambler, modulator and RRC filter) and the receiver (power detector, time/phase/amplitude synchronizers, channel equalizer, demodulator, descrambler and turbo decoder). In this chapter it was also explained what the VDES frame is composed of and how the MCS is determined in the receiver. Additionally, in this chapter the authors presented three types of radio channels that could be useful for the VDE-TER analysis or simulations. Two of those are the standard AWGN and Rayleigh channels, whereas the third one is called maritime radio channel and it includes two scenarios:

- the case where the ship is out at sea, and the multipath propagation is virtually nonexistent; the transmission channel in this case is simply an AWGN channel,
- the case where the ship is in the harbor or its vicinity. In this scenario, the multipath effect is significant, and consequently it is recommended that it should be modelled using a two-tap AWGN channel in which the second path attenuation varies depending on the ship's location and the number of objects in the harbor.

In the second chapter of the document, the software simulator of the VDE-TER physical layer was introduced. The authors discussed its general description, assumptions and parameters, as well as the simulator's algorithm. After that, the user interface was presented in a very detailed way, which provided a "user guide" and also highlighted the simulator's capabilities.

In the third chapter, the simulation results obtained using the software tool were presented. The results demonstrated the performance of the VDE-TER physical layer in various scenarios.

The following simulations were performed:

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- **Characteristics of BER and BLER as a function of E_b/N_0 for MCSs.** Simulations were performed in the AWGN channel for the bandwidth values of 25, 50 and 100 kHz. In the simulations the coding gains for every MCS were obtained; as it turned out the highest coding gain was observed for 100 kHz bandwidth, because in this case the data blocks are the longest, which improves the turbodecoding quality. On the other hand, this particular bandwidth is much more susceptible to synchronization errors than the narrower channels (25 and 50 kHz).
- **The influence of synchronization error on transmission quality.** In this case, three parameters: synchronization time error, signal info error and BLER were calculated as a function of E_s/N_0. The simulation showed that for the higher MCS schemes (MCS-3, MCS-5) the influence of synchronization error and errors of 'signal info' field gets less and less significant.
- **The influence of channel information delay.** In the simulations, the bit rate vs. E_b/N_0 was calculated in the AWGN channel for three bandwidth values: 25 kHz, 50 kHz and 100 kHz. Two cases of channel information delay have been considered: no delay and 3 frames delay. The conclusion from this part of analysis is as follows: as the E_b/N_0 increases, so does the bit rate, which is mainly due to the adaptive modulation and coding algorithms. The better the channel quality, the higher the MCS – and consequently: the higher the bit rate. Additionally, it was observed that the channel state info delay negatively affected the bit rate for E_b/N_0 from 5 dB to 9 dB. For other values of E_b/N_0, the resulting bit rate values were almost identical and did not seen to be affected by the discussed delay. That shows that in the future stages of VDES development, a new MCS scheme could be introduced to increase achievable bit rates.
- **VDES signal spectrum.** In this part of simulations, the spectra of the VDES signal were calculated. The simulations were performed for the two-tap AWGN channel, for different values of bandwidth and different values of the second tap attenuation. The influence of the channel equalizer on the resulting spectrum was also demonstrated. The main conclusion: for 25 and 50 kHz, the fading's are flat or almost flat, whereas in the 100 kHz bandwidth, the fading's are frequency selective. Consequently, the channel equalizer is mostly required for 100 kHz channels.
- **Constellations for various MCSs.** In this part of simulations, the modulations constellations, associated with different MCS schemes, were presented. It was done for the AWGN channel, then for two-tap AWGN channel without equalizer and finally for two-tap AWGN channel with equalizer. Conclusion: if the equalization is not used, the fading and intersymbol interference (ISI) strongly influence the signal and make the correct transmission almost impossible. When

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the equalizer was actually used, the influence of ISI is substantially reduced (however, at the same time the equalizer might amplify the noise!).

7 Building the test platform

7.1 Aim with the test platform

The VDES specification document ITU-R M.2092 is defining three different modulation forms to be used for VDES, these are π/4 QPSK, 8 PSK, and 16 QAM, each of these to be available in three different bandwidths; 25, 50 and 100 kHz.

The aim with this test is to collect large volumes of raw data from receiver's onboard two vessels as described in more detail in chapter 6. This data is to be analysed to validate the performance of the on-air parameters in question under real sea conditions. The results of these analyses and the subsequent simulation will be communicated to the IALA drafting group, developing the ITU recommendation ITU-R M.2092 thus providing empiric evidence for the best choice of modulation forms relative to bandwidth and distance for terrestrial VDES communication.

7.2 Design principles

The VDES test platform used for validation of the on-air parameters is a Software Defined Radio (SDR), designed for the marine environment, taking the environmental requirements specified in IEC 60945-4 into consideration.

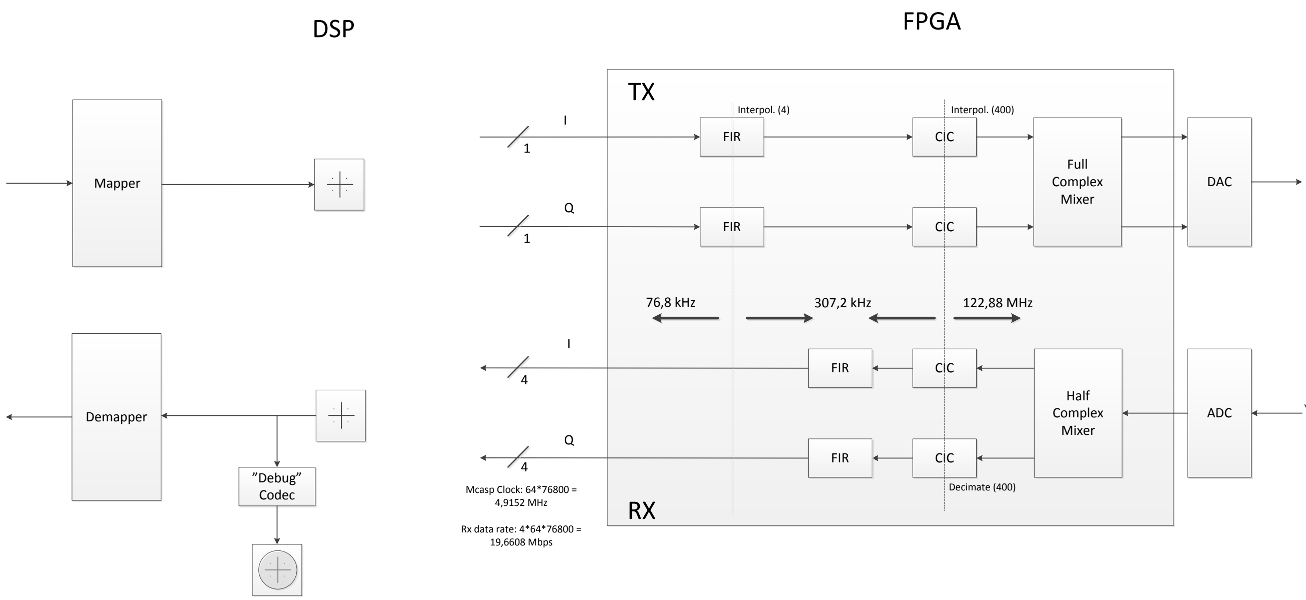

Figure 3 principle block diagram of the SDR receiver used for testing on-air parameters of VDES

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The high performance SDR design used allows high flexibility in the on-air parameters but also requires specialized high level programming and in- depth knowledge of the parameters influencing this type of test.

Below are pictures of the Hardware and mechanics used for the test platform. It must be underlined that these pictures cannot be taken to be indicative of how the final VDES equipment will look, especially the mechanical solution shown, as it is a practical solution for the purpose of this test only.

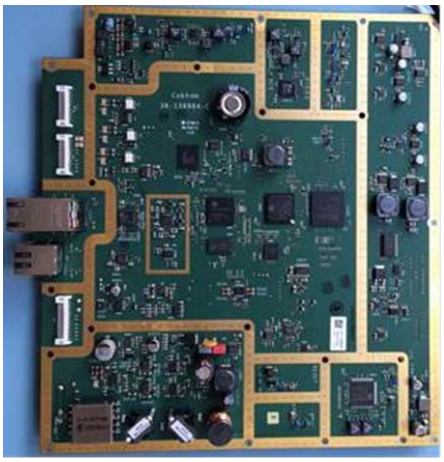

Figure 4: The SDR used for on-air testing of VDES

The basic main items used in the test platform are:

- Local power supplies generating supplies to the integrated circuitry present on the board
- RF input with Surge Arrester (90VDC +/- 20% and in accordance with ITU-T Rec. K. 12 and DIN 57845/VDE0845
- Anti-aliasing and power line noise filter with pass band of 150 kHz to 30 MHz
- Variable Gain Amplifier and input overload protection.
- 16 bit Analog to Digital Converter sampled at 122.88 MHz generated by 0.3 ppm local oscillator on 17.8176 MHz
- FPGA doing direct sampling, multiple receiver chains, filtering, SWR protection and direct up-conversion transmitter chain.
- Flash ADC used as input to protection circuitry yielding response time in microseconds towards bad SWR
- Dual TX DAC modulating directly on the transmitter frequency

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- Broad band high linearity amplifier outputting RF signal at approximately +9 dBm.
- DSP for signal processing, modulation schemes, power loop, and modem
- ARM processor with DDR3 RAM and eMMC Flash for LAN connectivity, control and boot of other peripherals. Furthermore, NMEA, real time clock and CAM

Figure 5: The SDR fitted into a ruggedized cabinet with power filtering

7.3 Preparations

For the first sea-trial the test set-up is to include additional equipment to get accurate timing, allowing exact logging of the test sequences in relation to time and position of the receiver, and to facilitate remote access to the system.

For timing and positioning a dedicated GPS unit is a part of the set-up, and for system logging a Laptop PC with an external 3 Tera byte memory unit is used. For remote monitoring and to enable altering of the settings of the test set-up include an USB 4G connection.. Principle diagrams of the receiver and transmitters are shown below.

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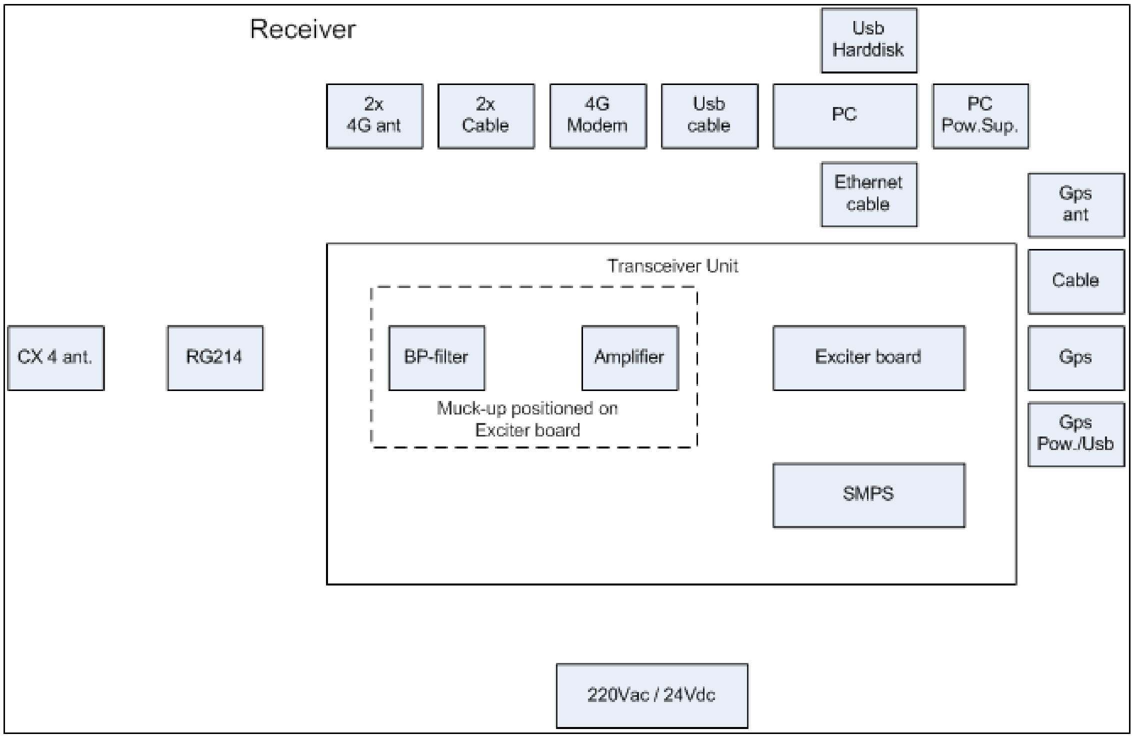

Figure 6: configuration of the ship based receiver installation

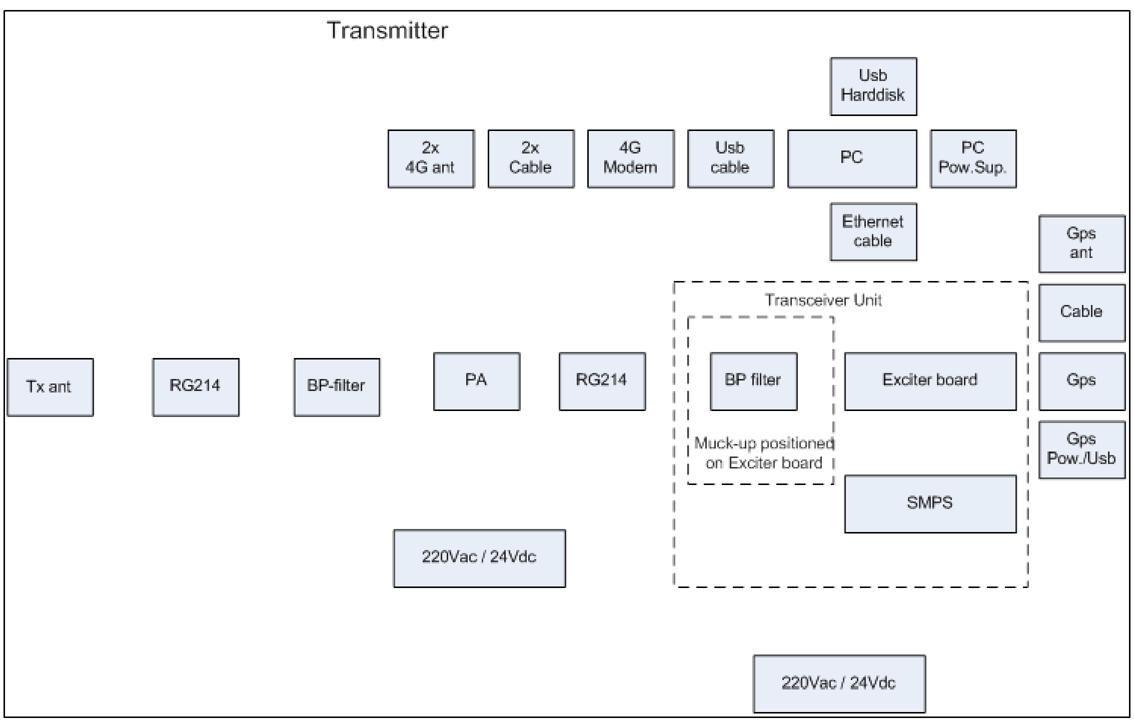

Figure 7: Configuration of the shore based transmitter installation

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7.4 Status

At the time of writing the hardware is being finally tested at Tharne & Thrane A/S (Cobham SATCOM) and aligned with the simulation tool at NIT where the results are to be used. Fact finding visits at M/F Copenhagen at Faryard in Denmark, and at the Scandlines terminal facilities in Gedser, have been done. Based on the findings at the fact finding visits, the final solutions for the test set-ups are defined and preparations for the actual installations can commence.

8 1st Sea trial

The Sea trial will be performed with one VDES transmitter located in Gedser Havn, and two receivers, one installed onboard the Scandlines Ferry M/F Berlin, and the other on her sister ship M/F Copenhagen, all facilities kindly made available by Scandlines. The installation onboard the vessels will be done bearing a normal VHF installation in mind, this to make the test as realistic as possible, and give the best possible results. To be able to analyse the propagation effects related to antenna height, the antennas fitted on the two vessels will be placed at different heights if possible.

The sailing distance is approx. 30 nautical miles (see map below), which suits the test purpose very well. Additionally, when the vessels are at the greatest distance from the transmitter, they are navigating partly inland, which will add further to the value of the test as the noise level is higher and propagation more difficult under these conditions.

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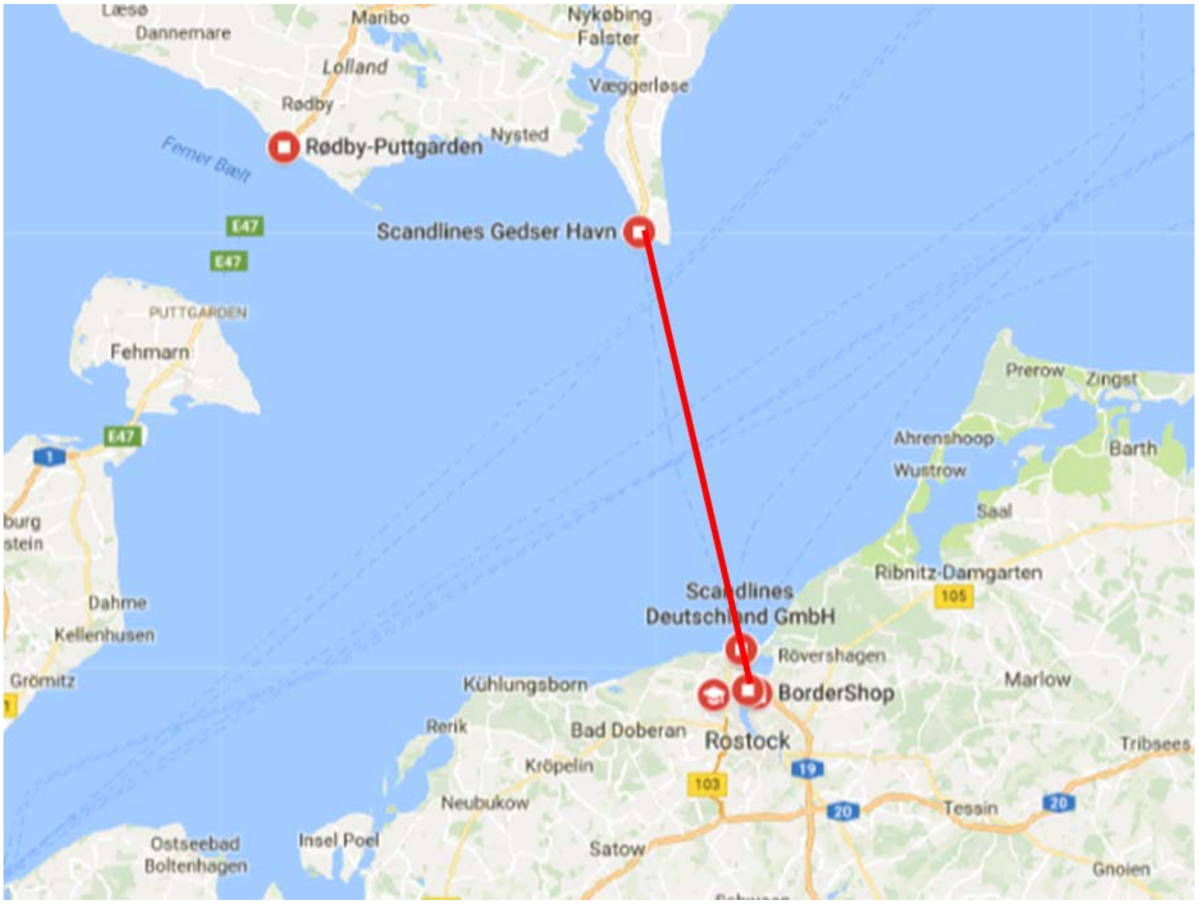

Figure 8: Map showing the route on which to two ferries, used for data collection, are sailing. The transmitter is fitted on Gedser Havn.

Figure 9: M/F Berlin fitted with one VDES receiver for data collection.

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9 Interim conclusion (PAN)

At IALA the work on development of ITU-R M.2092-1 is ongoing and, based on the findings in the coming sea trial, the choice of modulations forms will be confirmed or the knowledge gained used for defining more suitable solutions.

In the efforts to get the VDES space segment accepted by ITU, argumentation is being collected and made available in ITU Document 5B/TEMP/4-E, to prepare for a decision at ITU WRC-19

With the target of WP 2.1 in mind, the conclusion is that the EfficienSea2 WP 2.1 is substantially participating in the work of making VDES a reality. Much work is still ahead of us, but both the work at IALA and the tests done, maintain momentum in developing the specifications for VDES, and by that paving the way for VDES as a product in the marine market.

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Appendix 1:

ITU Working document towards a preliminary draft new report ITU-R M.[VDES-SAT]. Technical characteristics of the satellite component for the VHF data exchange system in the VHF maritime mobile band

EFFICIENSEA 2.0 GETTING CONNECTED

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Radiocommunication Study Groups

INTERNATIONAL TELECOMMUNICATION UNION

Source: Documents 5B/30, 5B/32

Subject: WRC-19 agenda item 1.9.2

Document 5B/TEMP/4-E
16 May 2016
English only

1 Working Party 5B
(Working Group 5B-3)

WORKING DOCUMENT TOWARDS A PRELIMINARY
DRAFT NEW REPORT ITU-R M.[VDES-SAT]

Technical characteristics of the satellite component for the VHF data exchange system in the VHF maritime mobile band

1 Introduction

At the WRC-15 ITU-R Resolution 360 was revised and updated to invite the WRC-19 to consider, based on the results of ITU-R studies, modifications of the Radio Regulations, including new spectrum allocations to the maritime mobile-satellite service (MMSS) (Earth-to-space and space-to-Earth), preferably within the frequency bands 156.0125-157.4375 MHz and 160.6125-162.0375 MHz of Appendix 18, to enable a new VDES satellite component, while ensuring that this component will not degrade the current terrestrial VDES components, ASM and AIS operations and not impose any additional constraints on existing services in these and adjacent frequency bands as stated in recognizing d) and e) of ITU-R Resolution 360.

Furthermore, in preparation for WRC-19, ITU-R was invited to conduct, as a matter of urgency, and in time for WRC-19, sharing and compatibility studies between VDES satellite components and incumbent services in the same and adjacent frequency bands specified in recognizing d) and e) of ITU-R Resolution 360 to determine potential regulatory actions, including spectrum allocations to the MMSS (Earth-to-space and space-to-Earth) for VDES applications. This report is the response from ITU-R to that invitation, and it provides a summary of why a VDES satellite component is needed, spectrum requirements, technical description and the appropriate sharing and compatibility studies.

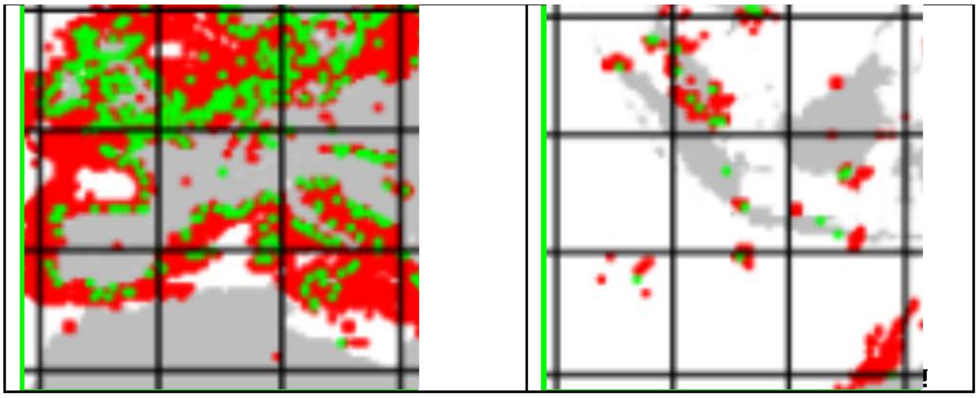
2 VDE-SAT, the essential supplement to coastal VDES

2.1 Practical aspects of deploying coastal coverage

Analysis of ship density at global scale shows that coastal areas play a key role in ship traffic and safety management and the VDES terrestrial (VDE-TER) will always remain a key component a successful implementation of VDES for a competent authority. However, the current state of AIS-TER deployment shows that while some areas like Europe, the US and Japan are largely covered, others like the West of Africa or the South West of Asia have much sparser coverage Figure 2-1 illustrates this well.

FIGURE 2-1

AIS costal station locations (green points) and AIS data coverage (red points)



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Many countries with long coastlines are currently not able to ensure adequate terrestrial infrastructure to cover their coastlines. There are numerous challenges, but one of the main difficulties is to find appropriate hosting sites, especially with a reliable power supply. Figure 2-2 represents a 10-minute distribution of terrestrial AIS data over three consecutive days in the Gulf of Guinea illustrating critical gaps in routine operations.

FIGURE 2-2

Representation of the 10 minute distribution of terrestrial AIS data over 3 consecutive days in the Gulf of Guinea.

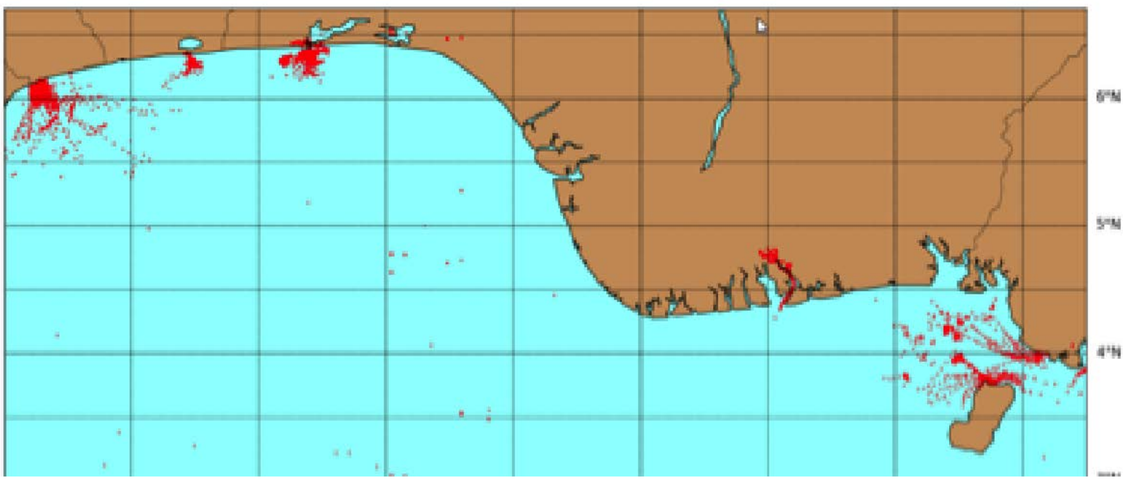

Figure 2-3 exemplifies the high variability observed on the temporal distribution of AIS messages collected from coastal stations. Such high variability indicates severe disruption to ship tracking and, given that AIS is a component of VDES we can assume these same sites will be used, thus

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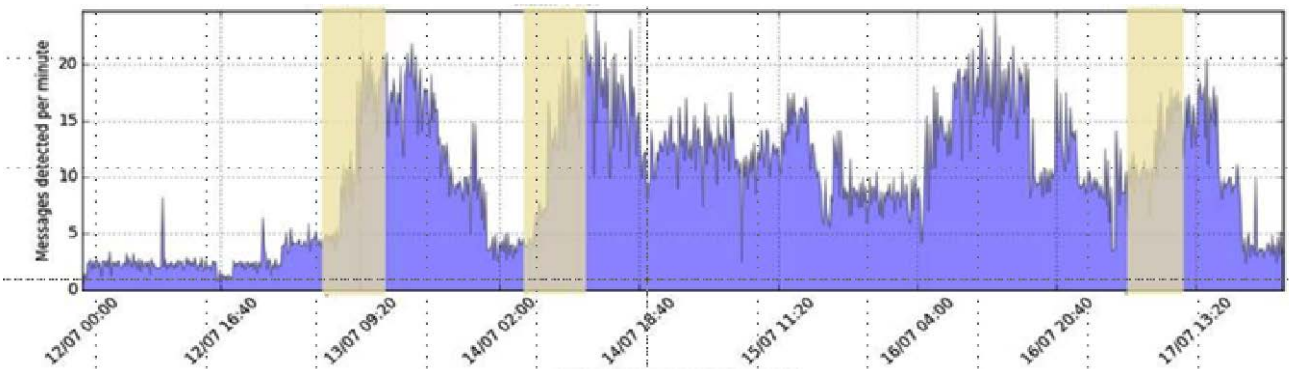
VDES will suffer the same issues. These problems of infrastructure distribution, reliability and maintenance in remote and difficult to access areas, or operators with insufficient budget for technical support, are difficult to solve and affects many maritime zones.

FIGURE 2-3

High variability observed on the distribution of AIS messages collected from coastal stations in the Gulf of Guinea. The grey line corresponds to sunrise when power generators possibly are activated on some sites.



VDE-SAT will provide an opportunity to fill the gaps in the coverage of coastal areas. VDE-SAT can also provide redundancy in operations in a situation where parts of the terrestrial infrastructure experience outages. VDE-SAT technical characteristics provide a flexible mode of operation, allowing VDE-SAT services to dynamically adapt to changes in the terrestrial VDE coverage.

2.2 To expand the VDES from the coastal area to global coverage

The implementation of the SAT-AIS has already demonstrated how the capabilities of the terrestrial AIS can be extended to global coverage, this is illustrated in Figure 2-4. Like SAT-AIS, VDE-SAT, will enable the extension of terrestrial VDE capabilities to long-range communications on a global scale. With polar orbiting satellites the Arctic and Antarctic will also be covered. However, unlike SAT-AIS, the satellite operations have been carefully considered during the definition of the technical characteristics for VDE-SAT therefore it will certainly be even more effective than SAT-AIS.

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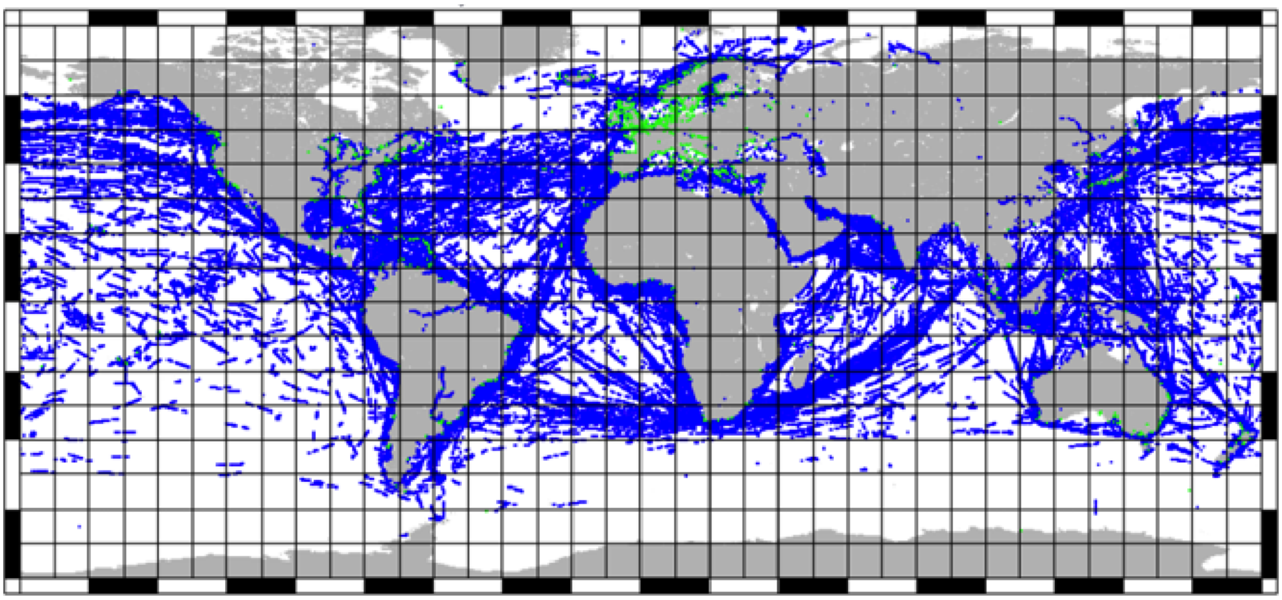
FIGURE 2-4

Comparison of one day of terrestrial AIS data (green dots) to one day of satellite AIS data (blue dots) - April 2015.



2.3 Use case descriptions

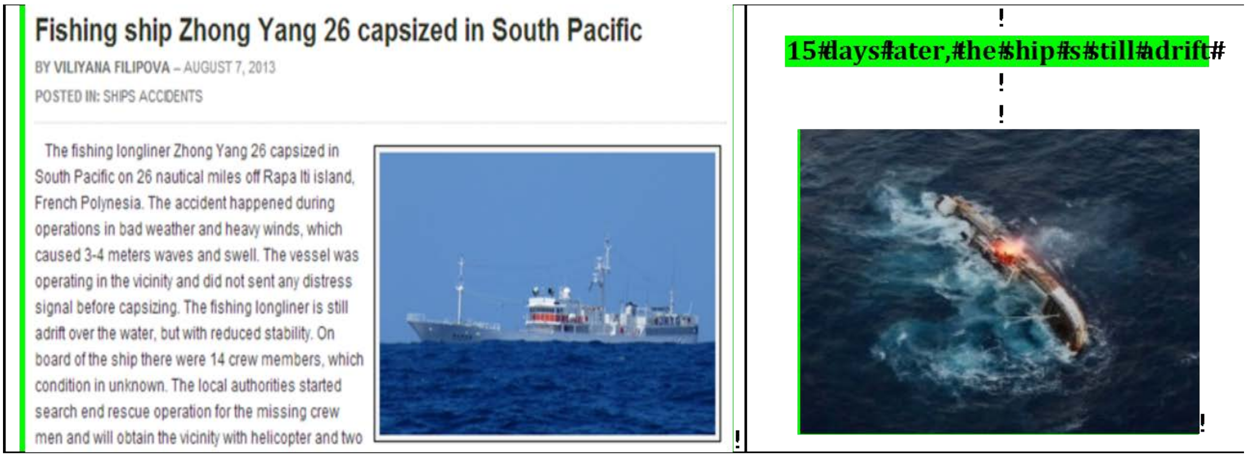
2.3.1 Distribution of maritime safety information

The MSI (Maritime Safety Information) consists of navigational and meteorological warnings, meteorological forecasts, and other urgent safety-related messages broadcasted to ships. VDE-SAT, as the only standard (non-proprietary) global communications link for the maritime community would provide for the global distribution of MSIs extending existing terrestrial coverage and providing coverage where a terrestrial infrastructure isn't practical such as the Arctic Sea. Maritime Safety Information may concern the following topics:

- Warnings of severe live or forecasted weather conditions to make the trip as safe and comfortable (passengers trip) as possible,
- Warnings of navigation hazards like dangers at sea (floating objects like containers, offshore structures, drifting buoys or ships...) (Figure 2-5),
- Route information, protected marine environment areas, restricted navigation zones, under keel clearance (Figure2-6)
- Piracy or armed robbery at sea information including scene identification, warnings, procedures for example with the schedule plans for convoys with security resources (to be discussed)...

FIGURE 2-5

Example of danger at sea caused when a ship capsizes in the Pacific Ocean.



Fishing ship Zhong Yang 26 capsized in South Pacific

BY VILIYANA FILIPOVA – AUGUST 7, 2013

POSTED IN: SHIPS ACCIDENTS

The fishing longliner Zhong Yang 26 capsized in South Pacific on 26 nautical miles off Rapa Iti island, French Polynesia. The accident happened during operations in bad weather and heavy winds, which caused 3-4 meters waves and swell. The vessel was operating in the vicinity and did not sent any distress signal before capsizing. The fishing longliner is still adrift over the water, but with reduced stability. On board of the ship there were 14 crew members, which condition in unknown. The local authorities started search end rescue operation for the missing crew men and will obtain the vicinity with helicopter and two

FIGURE 2-6

Ex. AMSA/Torres Strait where under keel clearance information is essential for safe navigation.

2.3.2 Automated or on event ship reporting

In addition to supporting shore side services, VDE-SAT will also support ship services. Ship reporting may be mandatory, collaborative or of specific interest. For example, IMO has published guidelines for setting up a single window system in maritime transport with the aim to reduce the administrative burden and facilitate coordination between stakeholders. In particular, it includes reporting requirements for ships visiting foreign ports, the 96 hours pre-entry (IMO Fal forms). Before entering into the terrestrial VDES coverage, a ship can push its report via the VDE-SAT to the relevant authority Similar procedures can also be used for mandatory reporting of fish catching.

Another ship reporting case relevant for VDE-SAT is the Voluntary Observing Ship (VOS) program in which ships regularly report weather. The record and data transmission is completely automatic without any manual operation. This data is critical for accurate weather forecasting and modelling.

2.3.3 VDE-SAT opportunity for small vessels fleet or developing areas

The VDE-SAT is designed for satellite communications and so will support a simplified low cost transceiver. This low cost highly robust option will provide significant value for a large number of fishermen in developing areas. They will be able to receive weather warnings and alerts, allowing them to seek a safe harbour. In addition, the fishermen will be able to send a message to call for technical assistance to address incidents like an engine failure or a problem on the helm control.

The VDE-SAT may also be the solution for developing countries to manage their EEZ where a terrestrial infrastructure is cost prohibitive or where the necessary power infrastructure just doesn't exist.

2.3.4 Ice chart distribution

Information on sea ice conditions is important to help ensure safe passage at sea. Knowledge of areas with sea ice along a ship's planned route allows ships to find the most efficient route. Together with prognoses for expected ice movements, ice charts allow mariners to plan ahead and significantly reduce the risk of vessels becoming ice locked.

The Norwegian Meteorological Institute produces ice charts for the European part of the Arctic. Today ice charts and prognoses for the next 24 hours are generated on a daily basis. The ice charts are available as graphic files from the website of the Norwegian Meteorological Institute for free. An example ice chart showing the European part of the Arctic is provided in Figure 2-7.

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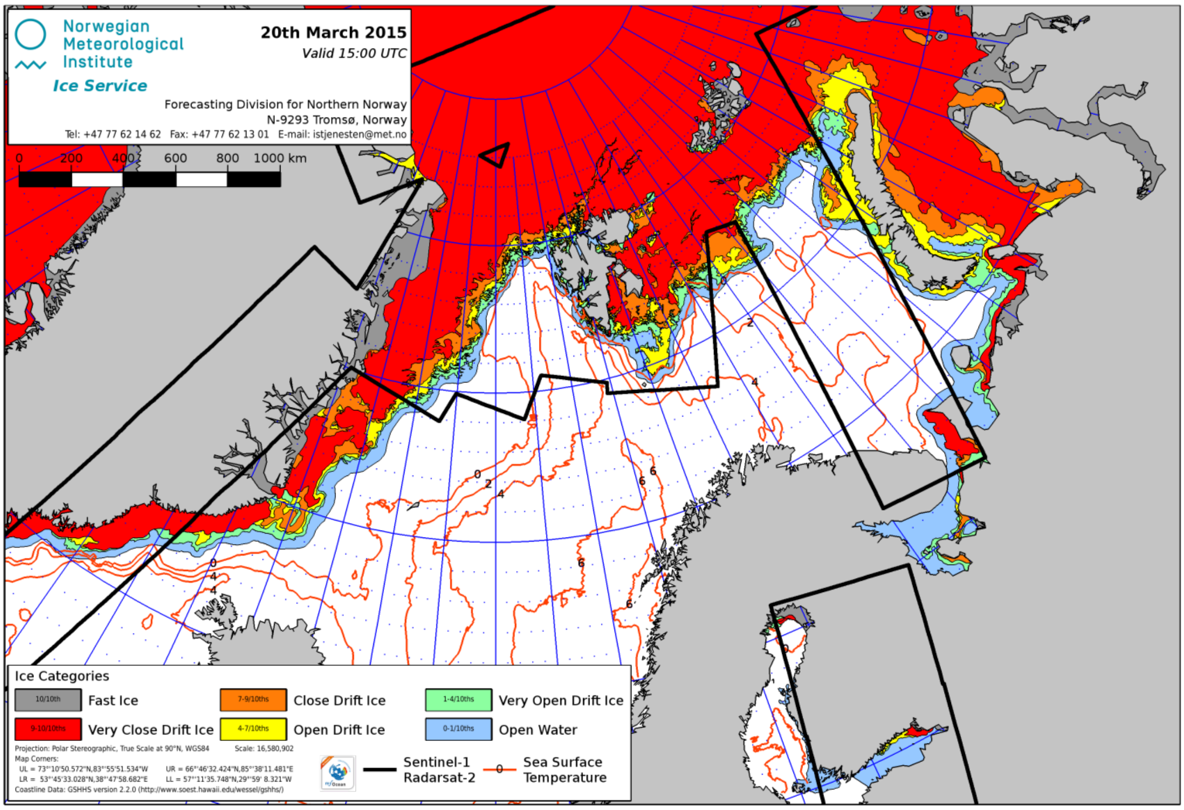
FIGURE 2-7

Example ice chart graphics showing the European part of the Arctic, available online from the Norwegian Meteorological Institute.



The ice information should also become available as a grid of geographical positions, both the current ice situation and prognoses. It could then be formatted in a way suitable for distribution to electronic chart plotters. The amount of data to transfer depends on the size of the area and the geographical resolution of the ice information.

A future ice chart service should be expected to produce updated ice charts and prognoses every 6 hours. The distribution systems currently in use are unnecessarily manual. With VDE-SAT the distribution systems should become more automated and user friendly. Ships should get access to the updated ice charts and prognoses as soon as possible, as well as upon request when needed by the navigator on-board.

3 Identification of spectrum requirements and rationale for the use of the frequency bands of RR Appendix 18

3.1 Spectrum requirement for the VDE - SAT

The VDE-SAT communications functions (ship-to-satellite and satellite-to-ship) are intended to be fully integrated with the VDE-TER communications functions (AIS, ASM, ship-to-ship, ship-to-shore and shore-to-ship) in the shipborne VDES equipment, which preferably would utilize one combined transmitting/receiving VDES antenna system. For this reason, it is desirable to utilize

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frequencies that are within the range of RR Appendix 18 (156.025 MHz to 162.025 MHz), as shown in Figure 3-1. The bandwidth allocated to each function should be as much as possible, considering the large number of ships globally that carry AIS and may decide to upgrade to VDES.

3.2 Potential use of the frequency band 160.975-161.475 MHz versus channels 2024/2084/2025/2085/2026/2086 for the satellite downlink

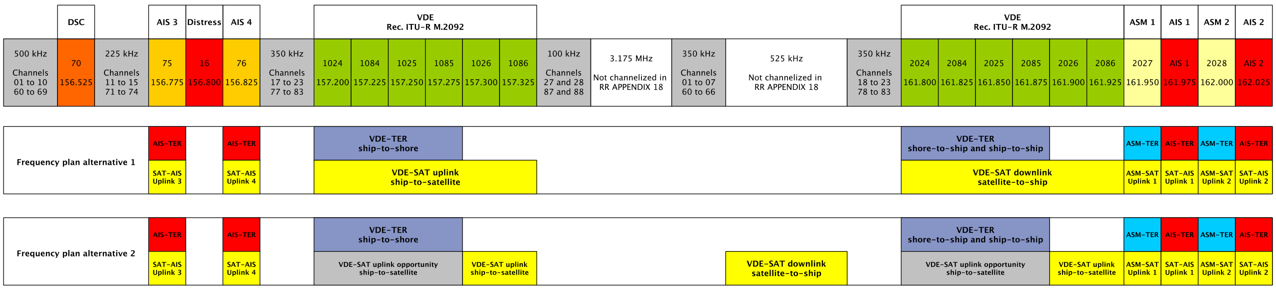
Note the organization and frequency use of RR Appendix 18, channelized in two sections of 25 kHz channels, a lower section with center frequencies at 156.025 MHz to 157.425 MHz and an upper section with center frequencies at 160.625 MHz to 162.026 MHz, spaced 4.6 MHz apart. The channels are numbered in two groups, 60 numbers apart, 01 to 28 and 60 to 88. Some of the channels are duplex channels with paired frequencies that are 4.6 MHz apart, for example, channel 60 (156.025 MHz and 160.625 MHz) is followed by channel 01 (156.050 MHz and 160.650 MHz), then by channel 61 (156.075 MHz and 160.675 MHz), then by channel 02 (156.100 MHz and 160.700 MHz), etc., and this sequence continues to channel 07 (156.350 MHz and 160.950 MHz). But then the channels 67 to 77 are implemented as simplex channels, where only the lower side (156.375 MHz to 156.875 MHz) is used. The unused upper side of these 25 kHz channels with center frequencies at 160.975 MHz to 161.475 MHz comprises a 525 kHz bandwidth that may be considered as an alternative for the VDES satellite downlink, since it poses no conflict to incumbent maritime services and could be constrained with an appropriate PFD mask to protect incumbent terrestrial services. Utilization of this band could provide a very robust satellite-to-ship service.

3.3 Frequency plan alternatives

The channels 24, 84, 25, 85, 26 and 86 are allocated for VDE after WRC-15, with the lower leg frequencies used for ship-to-shore and the upper leg frequencies used for shore-to-ship and ship-to-ship. The channels 2027 (ASM 1) and 2028 (ASM 2) are allocated for ASM. Currently, 2 alternative frequency utilization plans for VDES are under consideration. They describe how resources are allocated and shared between VDE-TER, VDE-SAT and ASM. These 2 alternative frequency utilization plans are illustrated in Figure 3-1, and described further below.

FIGURE 3-1

RR APPENDIX 18 and VDES frequency utilization plans



3.3.1 Frequency plan alternative 1

Frequency plan alternative 1 allow for utilization of the channels 24, 84, 25, 85, 26 and 86 in a shared manner between VDE-TER and VDE-SAT.

– The four channels 1024, 1084, 1025 and 1085 are shared between ship-to-shore and ship-to-satellite (VDE-SAT uplink) services

– The two channels 1026 and 1086 are exclusively reserved for ship-to-satellite (VDE-SAT uplink) services

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– The four channels 2024, 2084, 2025 and 2085 are shared among shore-to-ship, ship-to-ship and satellite-to-ship (VDE-SAT downlink) services

– The two channels 2026 and 2086 are exclusively reserved for satellite-to-ship (VDE-SAT downlink) services.

– Two channels 2027(ASM 1) and 2028 (ASM 2) are shared between ship-to-shore, ship-to-ship, shore-to-ship and ship-to-satellite services

3.3.2 Frequency plan alternative 2

Frequency plan alternative 2 allow for utilization of channels 24, 84, 25 and 85 primarily for VDE-TER, while channels 26 and 86 exclusively reserved for VDE-SAT uplink. VDE-SAT uplink is also possible in channels 24, 84, 25 and 85, but the VDE-SAT uplink in these channels do not impose constraints on VDE-TER. Frequencies are exclusively reserved for VDE-SAT downlink within the frequency range 160.9625 MHz to 161.4875 MHz, which is not channelized in RR Appendix 18.

– The four channels 1024, 1084, 1025 and 1085 are reserved for ship-to-shore services, but ship-to-satellite (VDE-SAT uplink) services are possible without imposing constraints on ship-to-shore services

– The four channels 2024, 2084, 2025 and 2085 are reserved for shore-to-ship and ship-to-ship services, but ship-to-satellite (VDE-SAT uplink) services are possible without imposing constraints on shore-to-ship and ship-to-ship services

– The four channels 1026, 1086, 2026 and 2086 are exclusively reserved for ship-to-satellite (VDE-SAT uplink) services.

– Frequencies are exclusively reserved for satellite-to-ship (VDE-SAT downlink) services within the frequency range 160.9625 MHz to 161.4875 MHz, which is not channelized in RR Appendix 18

– Two channels 2027(ASM 1) and 2028 (ASM 2) are shared between ship-to-shore, ship-to-ship, shore-to-ship and ship-to-satellite services

4 Technical description of the VDE-SAT

4.1 Technical characteristics of the VDE-SAT Downlink in the VHF Maritime Mobile band

[Editorial note: new/updated Annex TBD]

4.2 Technical characteristics of the VDE-SAT Uplink in the VHF Maritime Mobile band

[Editorial note: new/update Annex to TBD]

4.3 Resource sharing method for VDE-TER and VDE-SAT services

[Editorial note: new/update Annex TBD]

5 Interoperability and resource sharing with the terrestrial VDES and between VDES satellite systems

5.1 Resource sharing method for VDE-TER and VDE-SAT services

The VDES resource assignment between the VDE-TER and the VDE-SAT services is outlined in Section 4.3 Resource sharing method for VDE-TER and VDE-SAT services. In particular the

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signalling and control mechanisms envisaged to coordinate the use of each time slot either for terrestrial or satellite communication.

Shore stations utilize the terrestrial bulletin board (TBB) and the announcement signalling channels (ASC) to coordinate the resource assignment within the control area. Shore stations may provide information regarding VDE-SAT communications and availability as part of their information service. VDE-SAT information may be acquired by shore stations, either directly from the satellite bulletin board (SBB) and the ASC or through coordination with the satellite service providers.

There are dedicated slots and frequency bands for TBB and ASC that are reserved to communicate the required information to each vessel in the control area of a shore station.

Each satellite system will use satellite bulletin board (SSB) and announcement signalling channels (ASC), as defined Section 4.1, to communicate the VDE-SAT resource assignments, for both downlink and uplink, to vessels in the coverage area. There are dedicated slots and frequency bands for the SBB and ASC that are reserved to communicate the required information to each vessel in the field of view of a satellite.

Since the satellite coverage may include several shore station control areas, the VDE-SAT resource assignment should respect all requirements of shore control areas that are within the field of view at any given time. Within each satellite orbit the information regarding the resource assignment should be updated according to the shore station control areas in the satellite field of view.

How and to which extent resources are shared between VDE-TER and VDE-SAT are closely linked to the frequency utilization plan selected for VDES. Section 4.3 currently discuss three alternative frequency plans and their implications on resource sharing between VDE-TER and VDE-SAT. Methods for resource sharing are also discussed in Section 4.3, thus further detail can be found there.

5.2 Resource sharing between multiple VDES satellite systems

The sharing of VDE-SAT resources between two or more satellite systems is envisaged in section 4 by means of signalling that can be implemented in the SBB and ASC. The bulletin board, transmitted frequently on the VDE-SAT Downlink, provides the necessary information on how resources should be utilized for any given satellite. Sharing of resources between satellites are coordinated between satellite service operators.

The physical channel used for the bulletin board should allow for detection of overlapping signals received from multiple satellites. The use of direct sequence spreading as defined in Section 4 allows for detection of up to 8 overlapping signal. The waveform definition for VDE-SAT transmission as defined in Section 4, allows sharing of different time slots for different VDE-SAT downlink services.

The transmission timing of all VDES components (i.e. AIS, ASM, VDE-SAT and VDE terrestrial), is defined based on a common frame structure that is synchronized in time on the earth's surface to the UTC. This will allow multiple satellite systems to coordinate the transmission of data services in a time-sharing manner within common coverage areas.

6 Interference to incumbent services and those in adjacent frequency bands

[Editorial note: at a future meeting the studies for in bands interference and out of bands interference should be clearly separated]

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6.1 In-band interference

6.1.1 Fixed services in-band

6.1.2 Land and aeronautical mobile services in-band

[Editorial note: A PFD mask was agreed upon during the previous study period. The studies leading up to that PFD mask should be included here either directly or incorporated by reference]

The VDE-SAT uplink has common characteristics with VDE terrestrial ship-to-shore. Therefore it will not create any additional interference to land and aeronautical mobile services.

The VDE-SAT downlink has been imposed a pfd mask, as specified in Section 4, which was coordinated and agreed between all relevant ITU Study Groups. This pfd mask ensures that VDE-SAT downlink will not cause harmful interference to land and aeronautical mobile services.

6.2 Out-of-band interference

6.2.1 Maritime Distress and voice services

[Editorial note: see Report ITU-R M.2371]

The impact of introducing VDE-SAT services into channels 24, 84, 25, 85, 26 and 86 of RR Appendix 18 was addressed in Report ITU-R M.2371, along with introduction of terrestrial VDES in channel 24, 84, 25 and 85 of RR Appendix 18.

The VDE-SAT uplink has common characteristics with VDE terrestrial ship-to-shore. Therefore, VDE-SAT uplink will not create any additional interference to maritime distress and voice services.

The VDE-SAT downlink is located in the upper leg channels of RR Appendix 18, while maritime distress services and ship-to-ship and ship-to-shore voice is located in the lower leg channels. The 4.6MHz frequency separation between VDE-SAT downlink and these services ensure that they can be protected from harmful interference.

6.2.2 Satellite AIS

The impact of introducing VDE-SAT services into channels 24, 84, 25, 85, 26 and 86 of RR Appendix 18 was addressed in Report ITU-R M.2371, along with introduction of terrestrial VDES in channel 24, 84, 25 and 85 of RR Appendix 18.

The VDE-SAT uplink has common characteristics with VDE terrestrial ship-to-shore. Therefore, VDE-SAT uplink will not create any additional interference to satellite AIS.

The impact of the VDE-SAT transmission on the AIS1, AIS2, ASM1, ASM2 and LR-AIS reception by satellite has been highlighted in Report ITU-R M2371. Due to a large frequency separation between VDE-SAT transmission frequencies and LR-AIS frequencies, there is no impact on the satellite detection of LR-AIS is expected. The impact of VDE-SAT transmission on the reception of AIS1, AIS2 and ASM1 and ASM2 depends on the system scenarios.

In a system scenario where the VDE-SAT transmission and SAT-AIS reception are hosted on different satellites the space separation between the satellite orbits and their coverage will reduce the impact. In this case, when the two satellites are close together, the use of bulletin boards and the announcement channels as specified in Section 4., provides a practical solution to coordinate and control the duty cycle of the VDE-SAT transmission. Using this mechanism, system operators can schedule the VDE-SAT transmission on a dynamic manner (with a repetitive control as frequent as every minute) to avoid the interference of the VDE-SAT on the detection of SAT-AIS. The high

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repetition rate for AIS transmissions from ships also increase the detection of ships by SAT-AIS even if some AIS messages are lost to interference from VDE-SAT transmissions. The time that a VDE-SAT satellite is within interference range of a SAT-AIS satellite will not be continuous, and in most circumstances limited to only a few minutes.

The co-location of SAT-AIS receiver and VDE-SAT transmission may require a more sophisticated solution on board of the satellite. One such solution can be a full-duplex radio design that would allow for the cancellation of interference caused by the transmitted signal. This may impact the complexity of the on-board transceivers. However, also in this case, the high repetition rate for AIS transmissions from ships also increase the detection of ships by SAT-AIS even if some AIS messages are lost to interference from VDE-SAT transmissions.

6.2.3 Radiolocation service in the 154-156 MHz band

6.2.3.1 Introduction

Radio regulations (RR) No. **5.225A** specifies that in certain countries of Region 1 the frequency band 154-156 MHz is allocated to the radiolocation service on the primary basis. Application of the radiolocation service in those frequency bands is limited to the space surveillance radars. Study results reflected in Report ITU-R M.2172-1 show that the mentioned radars could operate in a shared manner with the maritime mobile service (MMS) ground systems operating in the adjacent frequency band 156-174 MHz.

A sharing study has been performed to ascertain if the potential VDE-SAT downlink service will generate harmful interference into the radiolocation service.

6.2.3.2 Transmitter and receiver characteristics of the radiolocation service used for the sharing study

Table 6-1 presents characteristics of the space surveillance radars operating in the frequency band 154-156 MHz. The characteristics were taken from Report ITU-R M.2172-1 and were used in the compatibility studies.

2 TABLE 6-1

3 Radiolocation service systems characteristics

4	5 **Radar A (narrow-band radar)**	6 **Radar B (wideband radar)**
Frequency band (MHz)	154-156	
Output pulse power (min/max) (dBW)	27/46	40/46
Mean output power (min/max) (dBW)	22/41	35/41
Polarization	Linear	
Pulse duration (μs)	13 000	3 200
Duty cycle	0.322	
Modulation type	pulse	
Altitude above the ground level (m)	19	
Antenna type	Phased array	
Maximum antenna gain (dB) – transmitter – receiver	 25 30	
Maximum antenna gain on the horizon	9	

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4	5 Radar A (narrow-band radar)	6 Radar B (wideband radar)
(dB)		
Antenna pattern	See § 1.1 in Appendix 1 of Report ITU-R M.2172-1	
Main beam pattern, degree – horizontal plane (Rx/Tx) – vertical plane (Rx/Tx)	2.6/5.2 2.6/2.6	
Receiver noise temperature (K)	800	
Operational receiver passband (kHz) (−3 dB level)	0.132	625
Receiver thermal noise (dBW)	−178.4	−141.6

In Recommendation ITU-R M.1802-1 the protection criteria for the radiolocation service is given as I/N=-6 for both radar types. When converting the receiver thermal noise level stated for Radar A and Radar B in Table 6-1 to receiver thermal noise density, they both end up with a receiver thermal noise density level of -199.6 dBW/Hz. To ensure the protection of the radiolocation service, any interference must be at least 6 dB below that noise level. That corresponds to an I_0 of -205.6 dBW/Hz.

According to the to the technical characteristics of the radiolocation service as presented in Table 6-1, the maximum receiver gain is 30 dB. It is assumed this is the gain at 156 MHz. The effective aperture area of the receiver antenna is then $A_{eff} = (G*c^2)/(f^2*4\pi) = 24.7$ dBm^2. Thus, to ensure protection of the radiolocation service, the interference power flux density in the 154-156 MHz band must be less than -230.3 dBW/(Hz*m^2)

6.2.3.3 VDE-SAT downlink proposed power spectral and PFD mask

In Section 4.1 a power spectral and PFD mask is proposed for the VDE-SAT downlink in band signal. This mask is presented in Table 6-2.

7 TABLE 6-2

8 Proposed power spectral and PFD mask

$$\boldsymbol{\theta° = earth - satellite\ elevation\ angle}$$

$$PFD(\theta°)_{\ (\mathrm{dBW/(m^2*4\ kHz)})} = \begin{cases} -149 + 0.16 * \theta° & 0° \le \theta < 45°; \\ -142 + 0.53 * (\theta° - 45°) & 45° \le \theta < 60°; \\ -134 + 0.1 * (\theta° - 60°) & 60° \le \theta \le 90°. \end{cases}$$

$$PFD(\theta°)_{\ (\mathrm{dBW/(m^2*Hz)})} = \begin{cases} -185 + 0.16 * \theta° & 0° \le \theta < 45°; \\ -178 + 0.53 * (\theta° - 45°) & 45° \le \theta < 60°; \\ -170 + 0.1 * (\theta° - 60°) & 60° \le \theta \le 90°. \end{cases}$$

6.2.3.4 VDE-SAT downlink out of band noise

Without filtering of the spectral side lobes, the noise generated by a VDE-SAT transmitter in the 154-156 MHz frequency band be will more than 25 dB bellow that of the in band signal. Appropriate filtering can ensure an additional 40 dB of reduction of the out of band noise. Table 6-3 presents the resulting interference PFD mask for the 154-156 MHz frequency band.

9 TABLE 6-3

10 **Proposed interference PFD mask for the 154-156 MHz frequency band**

$$\boldsymbol{\theta° = earth - satellite\ elevation\ angle}$$

$$PFD(\theta°)_{\ (\mathrm{dBW/(m^2*Hz)})} = \begin{cases} -250 + 0.16 * \theta° & 0° \leq \theta < 45°; \\ -243 + 0.53 * (\theta° - 45°) & 45° \leq \theta < 60°; \\ -235 + 0.1 * (\theta° - 60°) & 60° \leq \theta \leq 90°. \end{cases}$$

The significant frequency separation between the radiolocation service in the 154-156 MHz frequency band and the upper leg of the RR Appendix 18 frequencies starting at 160.625 MHz ensures that this interference PFD mask will be the worst case interference level in the 154-156 MHz frequency band.

6.2.3.5 Conclusions

According to Section 7.4.6, the radiolocation service in the 154-156 MHz frequency band operates in an elevation span from 2-70 degrees. The interference PFD mask presented in Table 6-3 provide a maximum interference PFD at 70 degrees of -239.0 dBW/(Hz*m^2). This is 3.7 dB below the protection criteria level calculated in Section 6.3.2.

The VDE-SAT downlink uses circular polarisation, while the radiolocation service uses linear polarisation. This results in a 3 dB reduction in interference from the VDE-SAT downlink to the radiolocation service due to polarisation loss. The additional 3 dB of margin ensure an I/N of less than -12.7 dB.

Based on these calculations it is concluded that the VDE-SAT downlink will not cause harmful interference to the radiolocation service in the 154-156 MHz frequency band as it is characterized in Report ITU-R M.2172-1 and Recommendation ITU-R M1802-1.

6.2.4 Broadcasting service in the 162-164 MHz band

[Editorial note: See RR No 5.229]

6.2.5 Space operation service (space-to-Earth) in the 162-164 MHz band

[Editorial note: See No 5.230]

6.2.6 Land and aeronautical mobile services in adjacent frequency bands

[Editorial note: A PFD mask was agreed upon during the previous study period. The studies leading up to that PFD mask should be included here either directly or incorporated by reference]

[Editorial note: Relevant frequency band as specified in ITU-R Resolution 360 is 154-164 MHz]

The VDE-SAT uplink has common characteristics with VDE terrestrial ship-to-shore. Therefore it will not create any additional interference to land and aeronautical mobile services.

The VDE-SAT downlink has been imposed a pfd mask, as specified in Section 4, which was coordinated and agreed between all relevant ITU Study Groups. This pfd mask ensures that VDE-SAT downlink will not cause harmful interference to land and aeronautical mobile services.

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6.2.7 Radio astronomy out of band pfd mask

7 Satellite receiver resilience to harmful interference from incumbent services and those in adjacent frequency band

7.1 Link budget analysis for the VDE-SAT uplink

7.1.1 VDES ship terminal transmission characteristics

7.1.2 Propagation model

7.1.3 Noise level at VDE-SAT satellite receiver

7.1.4 Link budget analysis and link margin discussions

7.1.5 Conclusions

7.2 Compatibility of a new VHF data exchange system (VDES) satellite component with radars operating in the frequency band 154-156 MHz

7.2.1 Introduction

Radio regulations (RR) No. **5.225A** specifies that in certain countries of Region 1 the frequency band 154-156 MHz is allocated to the radiolocation service on the primary basis. Application of the radiolocation service in those frequency bands is limited to the space surveillance radars. Study results reflected in Report ITU-R M.2172-1 show that the mentioned radars could operate in a shared manner with the maritime mobile service (MMS) ground systems operating in the adjacent frequency band 156-174 MHz. At the same time to provide protection for the MMS stations in the frequency bands 156.5125-156.5375 MHz, 156.7625-156.8375 MHz, 161.9625-161.9875 MHz and 162.0125-162.0375 MHz additional constrains specifying that EIRP of out-of-band emissions produced by the space surveillance radars should not exceed the level of –16 dBW was imposed by RR No. **5.225A**. The mentioned requirement is met by integrating additional notch filters into radar transmitting circuits for the mentioned frequency bands. The rest frequency bands related to provisions of RR Appendix 18 contain no constrains imposed on operation of the space surveillance systems and no specific measures are applied to reduce out-of-band emissions.

Recommendation ITU-R M.2092-0 specifies that the VDES up-link should be established in the frequency band 157.1875-157.3375 MHz by combining channels 1024, 1084, 1025, 1085, 1026, 1086 of RR Appendix **18** into a single channel of 150 kHz.

This Report presents results of studies in compatibility of a new VHF data exchange system (VDES) satellite component up-link in the frequency band 156.0125-157.4375 MHz with space surveillance radars operating in the frequency band 154-156 MHz.

7.2.2 Characteristics of space surveillance radars operating in the 154-156 MHz

Table 7-1 presents characteristics of the space surveillance radars operating in the frequency band 154-156 MHz. The characteristics were taken from Recommendation ITU-R M.1802-1 and were used in the compatibility studies.

11 TABLE 7-1

Characteristics of radars operating in the frequency band 154-156 MHz

Parameter	Value

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	Radar A	Radar B
Radar type	Primary ranging radar	
Radar function	Space objects recognition and trackinge	
Frequency band (MHz)	154–156	
Relative frequency instability	10^{-11}	
Output pulse power (min/max) (dBW)	27/46	40/46
Mean output power (min/max) (dBW)	22/41	35/41
Polarization	Linear	
Pulse length (μs)	13 000	3 200
Duty cycle	0.322	
Modulation type	Pulse	
Altitude above the ground level (m)	19	
Antenna type	Phased array	
Maximum antenna gain (dB): – transmitter – receiver	 25 30	
Max antenna gain into horizon (dB)	9	12
Main beam pattern (degrees) – horizontal plane (Rx/Tx) – vertical plane (Rx/Tx)	 2.6/5.2 2.6/2.6	
Scan angle ranges (degrees): – horizontal plane – vertical plane	 0–360 2–70	
Receiver noise temperature (K)	800	
Operation receiver passband (kHz)	0.132	625
Required frequency band (kHz)	0.132	625
Emission class	P0N	MXN
I/*N* protection ratio (dB)	−6	
Level of unwanted emissions	Complies with provisions of RR Appendix 3[1]	

7.2.3 Characteristics of VDES satellite link (ship-to-satellite)

VDES system ship-to-satellite link is described in Recommendation ITU-R M.2092-0 which assumes a low-Earth orbit (LEO) satellite system with altitude of 600 km[2]. It is also assumed that such satellite system could use antennas of two types, i.e. Yagi antenna and Isoflux isotropic antenna. Technical characteristics of VDES system up-link taken from Recommendation ITU-R M.2092-0 are described below.

Table 7-2 depicts minimum transmitting ship station EIRP as a function of elevation angle. Patterns for Yagi-antenna and Isoflux antenna are shown in Tables 7-3 and 7-4 accordingly.

TABLE 7-2

Minimum ship station EIRP vs. elevation angle

1 Values of unwanted emissions in the VDES receiver frequency band are described in section 6 herein.
2 Due to unavailability of relevant data for the VDES satellite receiver characteristics the low-Earth orbit system described in Recommendation ITU-R M.2092-0 is used herein. But it is to note that Report ITU-R M.2084 deals with different characteristics of AIS satellite receivers.

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12 Ship elevation angle	13 Ship antenna gain	14 Minimum ship EIRP with 6 W transmitter*
degree	dBi	dBW
0	3	10.8
10	3	10.8
20	2.5	10.3
30	1	8.8
40	0	7.8
50	–1.5	6.3
60	–3	4.8
70	–4	3.8
80	–10	–2.2
90	–20	–12.2

* Note: Multilevel and filtered modulation is used, and 3 dB back-off from saturation is assumed. Transmit average power shall be at least 1.0 watts and not exceed 25 watts as declared by the manufacturer. The ship stations may be equipped with antennas having patterns different from that shown in Table 2 (see Recommendation ITU-R M.2092-0 § 3.7.1).

TABLE 7-3

Satellite Yagi-antenna gain vs. nadir offset angle

Satellite elevation angle	Nadir offset angle	Satellite antenna gain
degrees	degrees	dBi
0	66.1	8
10	64.2	8
20	59.2	8
30	52.3	7.8
40	44.4	6.9
50	36	5.5
60	27.2	3.6
70	18.2	0.7
80	9.1	–2.2
90	0	–5.5

TABLE 7-4

Satellite Isoflex-antenna gain vs. nadir offset angle

Satellite elevation angle	Nadir offset angle	Satellite antenna gain
degrees	degrees	dBi
0	66.1	2
10	64.2	1.5
20	59.2	1
30	52.3	–0.5
40	44.4	–2
50	36	–4
60	27.2	–5
70	18.2	–7
80	9.1	–8
90	0	–8.5

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The VDES maximizes frequency efficiency by using adaptive coding and modulation based on the actual link quality. Initial system access is done using a combination of spread spectrum, low bitrate and powerful FEC. The VDE-SAT defined in M.2092-0, uses the waveforms defined in Table 7-5 for uplink. The thresholds C/N_0 and C/(N+I) on a Gaussian channel have been estimated.

TABLE 7-5

Estimated thresholds for the VDE-SAT uplink waveforms

Physical Layer Frame Format #	1	2	3	4	5
Channel bandwidth (kHz)	50	50	50	50	50
Occupied bandwidth (kHz)	42	42	42	42	42
CDMA chip rate (kcps)	19.2	38.4	NA	NA	NA
Symbol rate (ksps)	2.4	2.4	33.6	33.6	33.6
Packet size (ms)	133.3	133.3	26.7	26.7	800
Modulation	QPSK	CPM/QPSK	QPSK	16APSK	16APSK
FEC rate	1/3	1/3	3/4	3/4	3/4
Information rate (kbps)	1.6	1.6	50.4	100.8	100.8
Estimated threshold Es/N0 for a Gaussian channel (dB) (BER=1E-5)	0.1	0.1	4.4	11.4	11.4
Symbol error rate at threshold (%)	30	30	10	2	2
Estimated required C/N0 (dBHz)	33.9	33.9	51.4	61.4	61.4
Estimated required C/(N+I) (dB)	-12.3	-12.3	5.2	15.2	15.2

[Editorial note: Table needs to be verified, especially the values for C/N and C/(N+I)]

Satellite noise levels at the receiver front end are presented in Table 7-6. The system noise temperature is taken to be 25.7 dBK assuming no external interference. The required C/(N+I) listed in Table 7-6 is for the most robust waveform. Adaptive coding and modulation allow the usage waveforms with higher throughput when the necessary link quality is available.

TABLE 7-6

Characteristics of VDES system satellite receiver

Antenna noise temperature	200.0	K
Feed losses	1.0	dB
LNA noise figure	2.0	dB
LNA noise temperature	159.7	K
Feed loss noise temperature at LNA	56.1	K
Antenna noise temperature at LNA	158.9	K
System noise temperature at LNA	374.7	K
System noise temperature at LNA	25.7	dBK
Intrinsic noise power density	-202.9	dBW/Hz
Intrinsic noise power in 42 kHz bandwidth	-156.6	dBW
Required carrier-to-noise-plus-interference ratio (C/(N+I))	-12.3	dB
Interference-to-noise protection ratio (I/N) with Isoflux antenna	11.9 (10.0)	dB

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Interference-to-noise protection ratio (I/N) with Yagi antenna	20.8 (20.0)	dB

7.2.4 Scenario of interference from unwanted emissions by radars operating in the frequency band 154-156 MHz on VDES satellite receiver

Subject to Recommendation ITU-R M.2029-0 the VDES up-link should be established in the frequency band 157.1875–157.3375 MHz by combining channels 1024, 1084, 1025, 1085, 1026, 1086 of RR Appendix 18 into a single channel of 150 kHz.

FIGURE 7-1

Scenario of radar unwanted emission interference effect on VDES satellite receiver

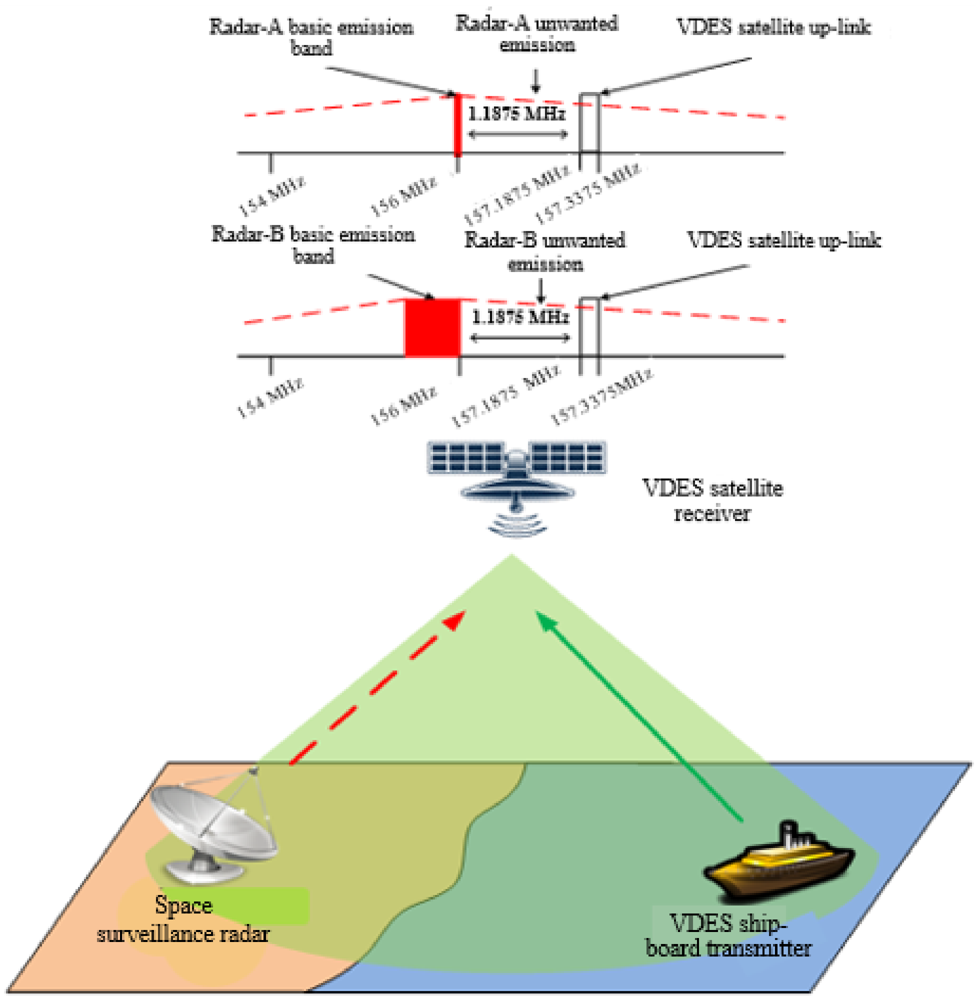

Figure 7-1 depicts scenario of effect caused by interference from space surveillance radar emissions on the VDES satellite receivers. A wanted signal from the ship transmitter is shown as a solid green arrow whereas interference from the space surveillance radar is reflected as a dashed red arrow.

7.2.5 Estimation of interference level from unwanted emissions by radars operating in the frequency band 154-156 MHz on VDES satellite receiver

Methodology described in Report ITU-R M.2172-1 was used for estimating the levels of unwanted emissions from Radar A in the band of the VDES satellite receiver. Assuming frequency separation of 1.2 MHz it was found that the unwanted emission power at the radar antenna front end in 25 kHz

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bandwidth would be minus 30.7 dBW and that in 150 kHz bandwidth would be minus 22.9 dBW. Given the 25 dB transmit gain of the radar, this is equal to a peak EIRP in 42 kHz of -3.4 dBW

The obtained result meet the RR Appendix **3** provisions for spurious emissions as specifying that for radars of the given type the level power delivered to the antenna feed shall not exceed minus 21.3 dBW in 77 Hz reference band.

A satellite with a VDES on-board receiver is in a circular orbit of 600 km in altitude. Interference-to-noise (I/N) and carrier-to-interference (C/I) ratios are estimated using satellite elevation angle steps of 10 degrees for the angles of satellite visibility by the ship station from 0 to 90 degrees corresponding to appropriate angles of satellite visibility by the radar. Since space surveillance radar scans in vertical plane within angle sector of 2-70 degrees the estimation assumes that a receiving antenna onboard a satellite be aligned with the space surveillance radar main lobe. Table 7-7 and Table 7-8 show the resulting the I/N using the satellite isoflux antenna and the 8 dBi Yagi antenna as defined in M.2092-0. These calculations are worst case in that they assume that the radar and satellite antenna boresigths are aligned, a rare occurrence. It can be seen that the worst-case interference level is 11.9 dB above the noise level for the isoflux case. The worst case I/N for the Yagi is 20.8 dB for a radar elevation angle to the satellite of 40 degrees.

TABLE 7-7

Radar emissions into a 600 km LEO satellite using isoflux antenna.

Radar elevation angle	Radar peak EIRP in 50 kHz at 157 MHz	Polarisation loss	Path length	Path loss	Satellite antenna gain	Interference level at LNA, including feed loss	I/N0	I/N
deg	dBW	dB	km	dB	dBi	dBW	dBHz	dB
0,0	-3.4	3.0	2830.0	145.4	2.0	-150,9	52,0	5,8
10.0	-3.4	3.0	1932.0	142.1	1.5	-148,0	54,8	8,6
20.0	-3.4	3.0	1392.0	139.3	1.0	-145,7	57,2	10,9
30.0	-3.4	3.0	1075.0	137.0	-0.5	-145,0	57,9	11,7
40.0	-3.4	3.0	882.0	135.3	-2.0	-144,7	58,1	11,9
50.0	-3.4	3.0	761.0	134.0	-4.0	-145,5	57,4	11,2
60.0	-3.4	3.0	683.0	133.1	-5.0	-145,5	57,4	11,1
70.0	-3.4	3.0	635.0	132.4	-7.0	-146,9	56,0	9,8
80.0	-3.4	3.0	608.0	132.1	-8.0	-147,5	55,4	9,1
90.0	-3.4	3.0	600.0	131.9	-8.5	-147,9	55,0	8,7

TABLE 7-8

Radar emissions into a 600 km LEO satellite using 8 dBi Yagi antenna.

Radar elevation angle	Radar peak EIRP in 50 kHz at 157 MHz	Polarisation loss	Path length	Path loss	Satellite antenna gain	Interference level at LNA, including feed loss	I/N0	I/N
deg	dBW	dB	km	dB	dBi	dBW	dBHz	dB
0.0	-3.4	3.0	2830.0	145.4	8.0	-144,9	58,0	11,8
10.0	-3.4	3.0	1932.0	142.1	8.0	-141,5	61,3	15,1
20.0	-3.4	3.0	1392.0	139.3	8.0	-138,7	64,2	17,9
30.0	-3.4	3.0	1075.0	137.0	7.8	-136,7	66,2	20,0

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40.0	-3.4	3.0	882.0	135.3	6.9	-135,8	67,0	20,8
50.0	-3.4	3.0	761.0	134.0	5.5	-136,0	66,9	20,7
60.0	-3.4	3.0	683.0	133.1	3.6	-136,9	66,0	19,7
70.0	-3.4	3.0	635.0	132.4	0.7	-139,2	63,7	17,5
80.0	-3.4	3.0	608.0	132.1	-2.2	-141,7	61,2	14,9
90.0	-3.4	3.0	600.0	131.9	-5.5	-144,9	58,0	11,7

7.2.6 Estimation of link budget for VDES up-link with a satellite receiver in a 600 km altitude orbit

Tables 7-9 and 7-10 present worst case link budgets for VDES up-link with a satellite receiver in a 600 km altitude orbit using Isoflux and Yagi antennas accordingly assuming 6 W ship station transmitter and the interference level from unwanted emissions by radars operating in the frequency band 154-156 MHz as calculated in Table 7-7 and Table 7-8.

Table 7-9 and Table 7-10 show that formats 1 and 2 will ensure link availability with substantial margins under the worst case radar interference condition for ship elevation angles up to 80 degrees, Format 3 will be available for ship elevation angles up to 60 degrees and Formats 4 and 5 will require additional discrimination or mitigation techniques. Table 7-11 summaries a few potential discrimination factors and mitigation techniques.

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TABLE 7-9

Worst-case link budget for VDE-SAT uplink with 6 W ship transmitter, Isoflux satellite receiving antenna and interference from unwanted emissions by radars.

Ship elevation angle	Ship antenna gain	Ship EIRP	Polarization loss	Path length	Path loss	Satellite antenna gain	Carrier level at LNA, including feed loss	C/N0	C/N	I/N	C/(I+N)
deg	dBi	dBW	dB	km	dB	dBi	dBW	dBHz	dB	dB	dB
0,0	3,0	10,8	3,0	2830,0	145,4	2,0	-136,6	66,2	20,0	11,9	7,8
10,0	3,0	10,8	3,0	1932,0	142,1	1,5	-133,8	69,0	22,8	11,9	10,6
20,0	2,5	10,3	3,0	1392,0	139,3	1,0	-132,0	70,9	24,7	11,9	12,5
30,0	1,0	8,8	3,0	1075,0	137,0	-0,5	-132,7	70,1	23,9	11,9	11,7
40,0	0,0	7,8	3,0	882,0	135,3	-2,0	-133,5	69,4	23,1	11,9	11,0
50,0	-1,5	6,3	3,0	761,0	134,0	-4,0	-135,7	67,1	20,9	11,9	8,7
60,0	-3,0	4,8	3,0	683,0	133,1	-5,0	-137,3	65,6	19,3	11,9	7,2
70,0	-4,0	3,8	3,0	635,0	132,4	-7,0	-139,7	63,2	17,0	11,9	4,8
80,0	-10,0	-2,2	3,0	608,0	132,1	-8,0	-146,3	56,6	10,4	11,9	-1,8
90,0	-20,0	-12,2	3,0	600,0	131,9	-8,5	-156,7	46,2	0,0	11,9	-12,2

TABLE 7-10

Worst-case link budget for VDE-SAT uplink with 6 w ship transmitter, Yagi satellite receiving antenna and interference from unwanted emissions by radars.

Ship elevation angle	Ship antenna gain	Ship EIRP	Polarization loss	Path length	Path loss	Satellite antenna gain	Carrier level at LNA, including feed loss	C/N0	C/N	I/N	C/(I+N)
deg	dBi	dBW	dB	km	dB	dBi	dBW	dBHz	dB	dB	dB
0,0	3,0	10,8	3,0	2830,0	145,4	8,0	-130,6	72,2	26,0	20,8	5,2
10,0	3,0	10,8	3,0	1932,0	142,1	8,0	-127,3	75,5	29,3	20,8	8,5
20,0	2,5	10,3	3,0	1392,0	139,3	8,0	-125,0	77,7	31,7	20,8	10,8
30,0	1,0	8,8	3,0	1075,0	137,0	7,8	-124,4	78,4	32,2	20,8	11,4
40,0	0,0	7,8	3,0	882,0	135,3	6,9	-124,6	78,3	31,2	20,8	11,2
50,0	-1,5	6,3	3,0	761,0	134,0	5,5	-126,2	76,6	30,4	20,8	9,6
60,0	-3,0	4,8	3,0	683,0	133,1	3,6	-128,7	74,2	27,9	20,8	7,1

70,0	-4,0	3,8	3,0	635,0	132,4	0,7	-132,0	70,9	24,7	20,8	3,8
80,0	-10,0	-2,2	3,0	608,0	132,1	-2,2	-140,5	62,4	16,2	20,8	-4,7
90,0	-20,0	-12,2	3,0	600,0	131,9	-5,5	-153,7	49,2	3,0	20,8	-17,9

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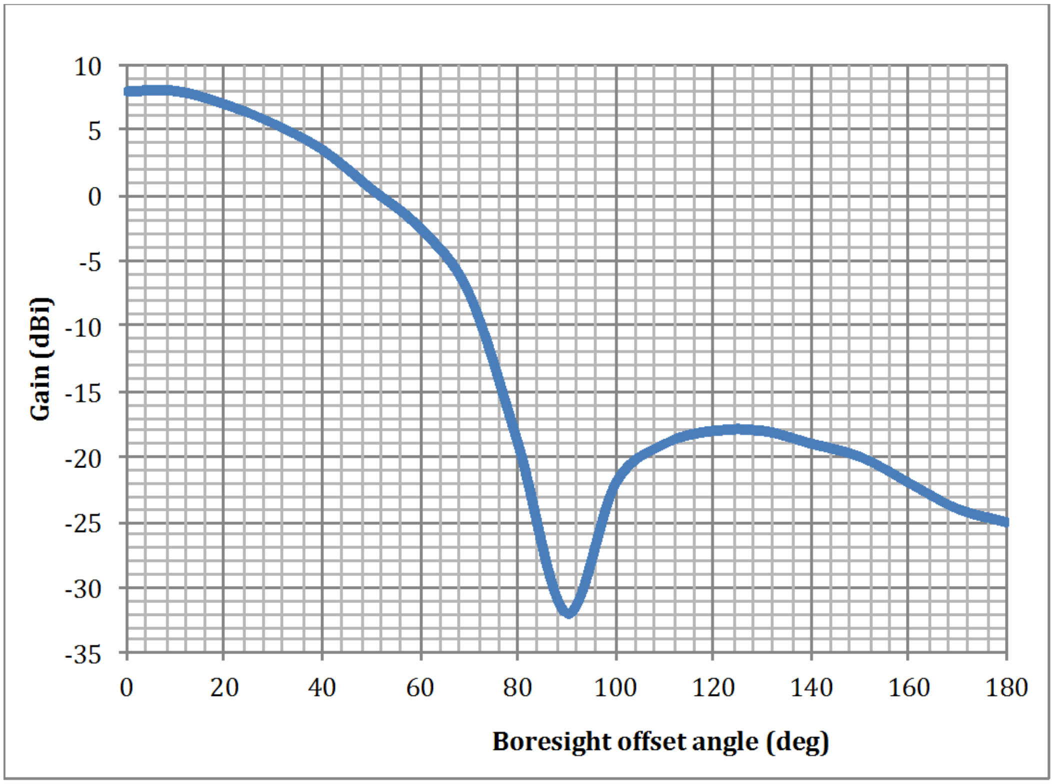
TABLE 7-11

Summary of a few potential discrimination factors and mitigation techniques for VDE-SAT uplink against interference from unwanted emissions by radars.

Factor	Description	Effect
Range	Radars more than 2800 km from sub-satellite point are below horizon	No interference
Radar operating mode	When the radar is operating in a scan mode, it will only affect the satellite for the short time it points directly at it.	There are approximately 69 horizontal beam positions and 27 vertical beam positions, or a total of 1863 beam positions. Assuming a beam offset of 2 beamwidths provides sufficient discrimination, the probability that transmission in one of the seven possible beams is 0,4 %. This level of interference blocking can be handled by FEC and/or ARQ
Radar scan loss	Planar phased array radars have a scan loss when not pointing orthogonal to the flat surface.	The scan loss depends on the number of planar arrays used. A horizontal scan of 60 degrees will cause a 3 dB loss, a vertical scan of 35 degrees will cause a scan loss of 0.9 dB. This reduce the interference level down from the worst case situation.
Yagi antenna isolation	The Yagi antenna provides discrimination when pointed away from the radar	Figure 7-2 shows typical Yagi isolation of 10 dB, 60 degrees off boresight and 20 dB 75 degrees off boresight

FIGURE 7-2

Typical Yagi gain pattern as a function of boresight offset angle.



7.2.8 Potential for burnout and blocking of the VDE-SAT receiver caused by unwanted emissions from the radar

Table 7-12 and Table 7-13 show the radar levels at the antenna for both the isoflux and Yagi antennas, with peak output EIRP from the radar of 71 dBW at 156 MHz. It can be seen that the maximum level is less than -61 dBW. This is more than 30 dB below expected burnout levels. Thus, the VDE-SAT receiver will not be exposed to an interference level from the radar that potentially can be capable of destroying the satellite receiver.

The presence radar signal between 154 and 156 MHz will add a blocking performance requirement for the VDE-SAT receiver. This requirement is not expected to be a concern.

TABLE 7-12

Maximum signal level of unwanted emissions from radar with Isoflux antenna onboard the satellite.

Elevation angle	Radar EIRP	Polarisation loss	Range	Pathloss	Satellite antenna gain	Received signal level
Degrees	dBW	dB	km	dB	dBi	dBW
0	71,0	3,0	2830,0	-145,3	2,0	-76,3
10	71,0	3,0	1932,0	-142,0	1,5	-73,5
20	71,0	3,0	1392,0	-139,2	1,0	-71,2
30	71,0	3,0	1075,0	-136,9	-0,5	-70,4
40	71,0	3,0	882,0	-135,2	-2,0	-70,2
50	71,0	3,0	761,0	-133,9	-4,0	-70,9
60	71,0	3,0	683,0	-133,0	-5,0	-71,0
70	71,0	3,0	635,0	-132,4	-7,0	-72,4

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80	71,0	3,0	608,0	-132,0	-8,0	-73,0
90	71,0	3,0	600,0	-131,9	-8,5	-73,4

TABLE 7-13

Maximum signal level of unwanted emissions from radar with Yagi antenna onboard the satellite.

Elevation angle	Radar EIRP	Polarization loss	Range	Pathloss	Satellite antenna gain	Received signal level
deg	dBW	dB	km	dB	dBi	dBW
0,0	71,0	3,0	2830,0	-145,3	8,0	-70,3
10,0	71,0	3,0	1932,0	-142,0	8,0	-67,0
20,0	71,0	3,0	1392,0	-139,2	8,0	-64,2
30,0	71,0	3,0	1075,0	-136,9	7,8	-62,1
40,0	71,0	3,0	882,0	-135,2	6,9	-61,3
50,0	71,0	3,0	761,0	-133,9	5,5	-61,4
60,0	71,0	3,0	683,0	-133,0	3,6	-62,4
70,0	71,0	3,0	635,0	-132,4	0,7	-64,7
80,0	71,0	3,0	608,0	-132,0	-2,2	-67,2
90,0	71,0	3,0	600,0	-131,9	-5,5	-70,4

7.2.9 Conclusions

Based on the calculations and estimations presented above it is clear that most robust waveforms defined for the VDE-SAT uplink is resilient to harmful interference from radars operating in the frequency band 154-156 MHz for all elevation angles up to 60-80 degrees, depending on waveform used, without any additional interference discrimination or mitigation techniques. Allowing for potential discrimination factors and mitigation techniques discussed above, also the less robust waveforms are expected to perform as stipulated in Section 4. The adaptive modulation and coding scheme defined for VDE-SAT can be utilized to ensure the link is closed.

These calculations and estimations also show that the VDE-SAT receiver will not be exposed to an interference level from the radar that potentially can be capable of destroying the satellite receiver.

8 Testing, demonstrations and measurements

9 Future demonstrations and measurements

[Editorial note: This section is intended only as information on planned and on-going demonstration and measurement projects, and should be removed from the final report. As results from these projects are available they should be summarised and moved to Section 8.

[Editorial note: Additional demonstration and measurement projects/activities should be included as they become public.]

9.1 NORSAT-2 (ESA VDE-SAT downlink verification planned H1 2017)

The objective of the ESA VDE-SAT Downlink Verification is to demonstrate the feasibility of the VHF data exchange via satellite in a real operating environment. The feasibility of VDE-SAT will be demonstrated by a test campaign as well as a VDE-SAT service demonstration.

The main purpose of the test campaign is to assess the performance of the waveforms considered, enabling standardisation of a suitable set of waveforms and corresponding parameters. Based on these results, recommendations regarding the downlink physical layer will be given.

Two test receivers, one on-board a Norwegian Coast Guard vessel and a reference receiver at FFI premises at Kjeller (Norway) will be used during the test campaign. The Coast Guard vessel will receive VDE-SAT transmissions at sea. The terminal at the FFI premises will be used as reference, for transmitter (Tx) and ship terminal receiver (Rx) verification, and debugging if necessary.

The specification and performance figures are derived from the Recommendation ITU-R M.2092-0. The activity shall demonstrate the functionality and performance of VDE-SAT Downlink waveforms and data link protocols that are currently being consolidated by international working groups in IALA and ITU for data exchange via satellite in VHF maritime bands.

9.2 Efficiensea 2 coordination

EfficienSea2 is a European Community project for a safer and more efficient waterborne operation through new technologies and smarter traffic management. This project, which is planned for a 3-year period from mid-2015 to mid-2018, is in the scope of the Horizon 2020, the biggest EU Research and Innovation programme. Lead by the DMA, 33 entities are contributors. One of activities is dedicated to novel maritime communications and among them the VDES. Taking into account the radio technical standards and specifications under construction at IALA and the resolution adopted in November 2015 by ITU during the WRC15, the first initiative to develop VDES hardware prototypes in a lab environment will be lead. In addition, live sea trials are planned for testing exchanges of ship-to-ship and ship-to-shore data with real-life e-navigation scenarios. EfficienSea 2 also intends to coordinate the terrestrial VDES activities with satellite VDES activities that are fortunately also envisaged during the same period of time. They are lead by ESA under the ARTES program dedicated to research on the telecommunications systems. One of these activities is focussed on the VDE-SAT user needs and requirements to derive the system design. Another is aimed at the realisation of a test satellite with a flight demonstration within the EfficienSea 2 timeframe (Figure 6). A liaison between ESA, the main actors of the VDE-SAT activities and the EfficienSea 2 terrestrial VDES actors will permit to include the satellite VDES downlink component into the testbed.

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Appendix 2:

Report on the software simulator for the analysis of VDES system terrestrial segment.

"This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 636329".

Report on the software simulator for the analysis of the VDES system terrestrial segment

Project no.	636329
Project acronym:	EfficienSea2
	EFFICIENSEA2 – efficient, safe and sustainable traffic at sea
Funding scheme:	Innovation Action (IA)
Start date of project:	1 May 2015
End date of project:	30 April 2018
Duration:	36 months
Due date of deliverable:	N/A
Actual submission date:	N/A
Organisation in charge of deliverable:	N/A

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Authors

Name	Organisation
Krzysztof Bronk	NIT
Adam Lipka	NIT
Marcin Mazurowski	NIT

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Review

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"This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 636329".

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Introduction

In recent years, a significant growth of interest in data transmission systems using maritime radio equipment has become a global trend. Such systems are utilized for many reasons: in order to improve communications between ships and ports, to increase maritime safety, to protect the natural environment and also to provide means for a novel concept of so-called e-navigation. One of the projects that deals with e-navigation is the EfficienSea2 project, one of whose targets is a development of: (a) a hybrid communication system for the purpose of maritime applications and (b) a new standard of wireless data transmission called VDES.

The VDES system is being developed not only to increase achievable transmission rates but also to improve the availability of data transmission services at sea. To a certain extent, the system is an extension of the existing AIS standard (Automatic Identification System) which was mainly created to offer an efficient and smooth exchange of navigation data between ships and between ships and coastal entities.

In general, three segments of the VDES system have been defined: terrestrial segment, satellite segment for the uplink and satellite segment for the downlink. The following report is dedicated to the physical layer of the terrestrial part, which is often referred to as the VDE-TER.

For the purpose of this new maritime data exchange standard, the following transmission channels have been assigned:

- Channels 2027 and 2028 for the ASM system (Application Specific Messages),
- Channels 24, 84, 25, 85 with 100 kHz band for the VDE-TER segment.

In the VDES system, three modulation and coding schemes (MCS) have been defined. The assumed MCSs and three possible transmission bandwidths (25 kHz, 50 kHz and 100 kHz) fully define the capabilities of the VDE-TER; those parameters have been gathered in table 1.1.

Tab. 1.1. Achievable throughput in in the VDE-TER segment

Modulation and Coding Scheme (MCS)	*Throughput (kb/s) per bandwidth (RAW[3]/NET[4])*		
	25 kHz	*50 kHz*	*100 kHz*
MCS-1 (π/4 QPSK, CR[5]=½)	38,4/15	76,8/32	153,6/66
MCS-3 (8PSK, CR=¾)	57,6/35	115,2/74	230,4/150
MCS-5 (16QAM, CR=¾)	76,8/47	153,6/100	307,3/200

[3]RAW– raw bit rate.
[4]NET – net bit rate.
[5]CR – coding rate.

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1. VDE-TER segment's physical layer

In the following chapter, the physical layer of the VDES system's terrestrial component has been described. The authors introduced the process of the data bit stream transmission and reception and discussed the relevant radio transmission channels.

1.1. Transmitter

The block diagram of the VDE-TER transmitter is depicted in fig. 1.1.

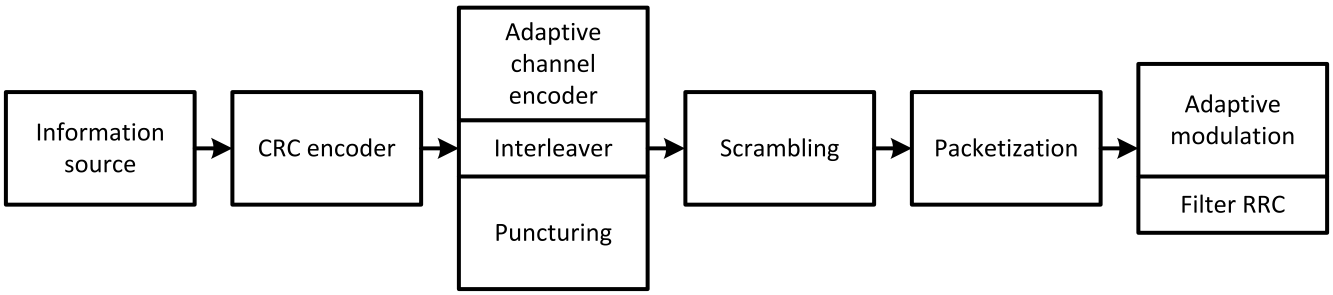

Fig. 1.1. Block diagram of the transmitter implemented in the VDE-TER software simulator

The first step of the signal transmission is the input data generation. The information prepared in this way is then fed into the input of the CRC32 cyclic encoder, where the 32-bit checksum is appended. In the next stage, the channel coding is performed using a turbocoder. After that, the processed data are fed into the scrambler's input and randomized. The resulting data stream is than subjected to packetization, modulation and filtering and finally is transmitted over the radio channel.

The description of the transmitter's components and the way they have been implemented is discussed in the following part of this subchapter.

1.1.1. Frame format

For each of the bands, a structure of the frame has been defined (fig. 1.2). The frame duration is the same for every bandwidth and equals to 26,667 ms. On the other hand, the number of symbols transmitted in a single frame varies depending on the bandwidth: in case of 25 kHz there are 512 symbols per frame, in case of 50 kHz – 1024 symbols and in case of 100 kHz – 2048 symbols.

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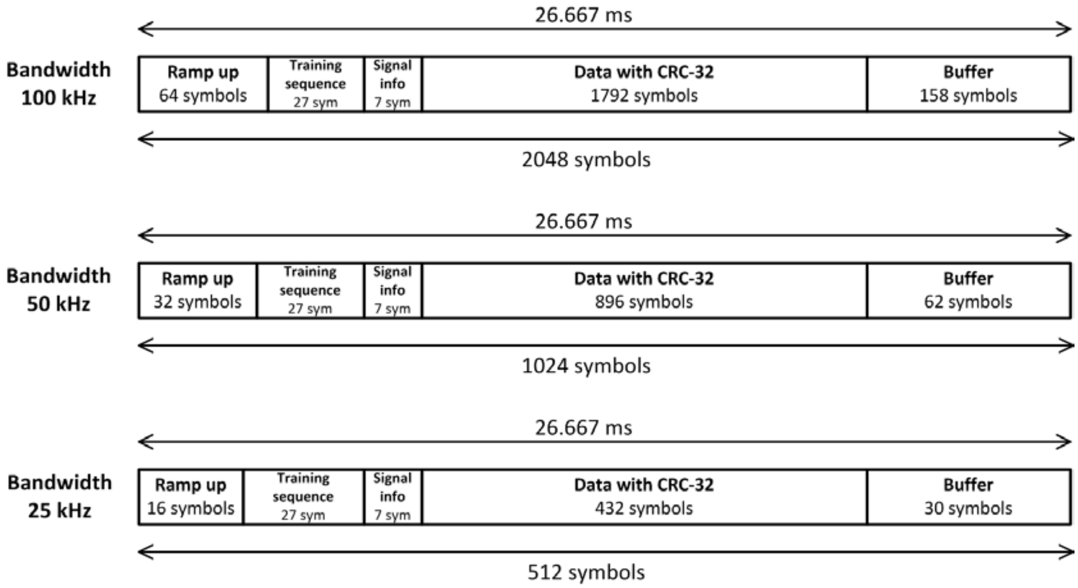

Fig. 1.2. A single frame structure for the VDE-TER

The frame is comprised of five blocks:

- The initial segment responsible for the power detector's activation,
- Training sequence comprised of two orthogonal Barker codes. The Barker code provides very good autocorrelation properties, which makes detection of the subsequent frames simple and reliable.
- The information about the MCS scheme. The basic information about MCS is comprised of four bits which are encoded using the Hamming (7,4) code. The resulting stream is 7 bit long.
- Data block which is composed of the user data encoded using a detection (cyclic) code and a correction code.
- A buffer which acts as a time reserve to eliminate the influence of delays which occur due to the varying distance between the transmit and receive station.

1.1.2. Turbocoding

Turbocoding is a method to detect and correct errors and is one of the most significant ways to ensure the reliability of digital transmission.

The turbocoding (the 3GPP2 turbocode) in the VDES system is performed using an interleaver, two identical systematic encoders of the convolutional code and a puncturing block. The general structure of the turbocoder is shown in fig. 1.3. Each of the coders shown in the figure generates 3 output bits per one input bit. On the output of the first coder, the X, Y_0 and Y_1 bits are generated, which account for the vector u, whereas the output of the second coder is a permutation of that vector.

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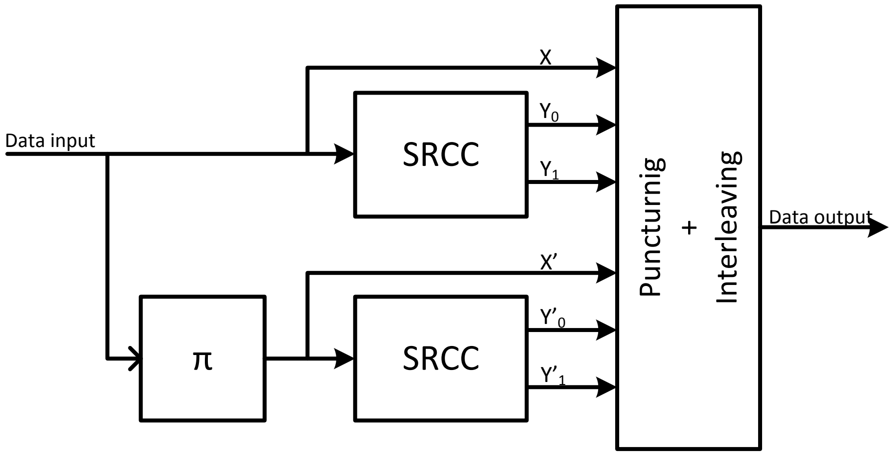

Fig. 1.3. Turbocoder block diagram

The input data are fed into two SRCC coders with a code rate of 1/6. After that, they are fed into the block responsible for puncturing and interleaving, in order to produce the required code rates (1/2 and ¾). The block diagram of a single SRCC coder is shown in fig. 1.4

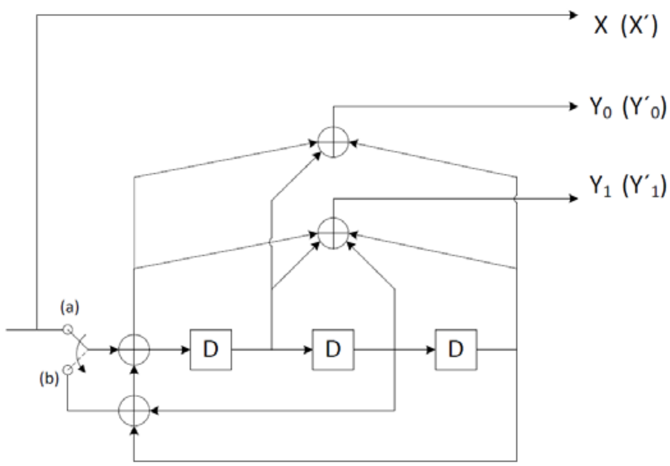

Fig. 1.4. SRCC coder block diagram

In the first k clock signals, the switch is in the (a)-position to gather the data from the coder's input. Then, for the next six clock signals, the switch is in the (b)-position, to finish the calculations.

1.1.3. Scrambling

The scrambling process in the VDE-TER is performed by the additive scrambler, the same as in the DVB (*Digital Video Broadcasting*) technology. It converts the input stream using a binary pseudorandom sequence. As a result the data stream is randomized to preserve a maximally uniform envelope of the modulated signal and to ensure the signal spectrum is uniform in the whole transmission bandwidth. The scrambling block works using the following generator polynomial: $1+x^{-14}+x^{-15}$.

Fig. 1.5 shows the block diagram of the implemented scrambler.

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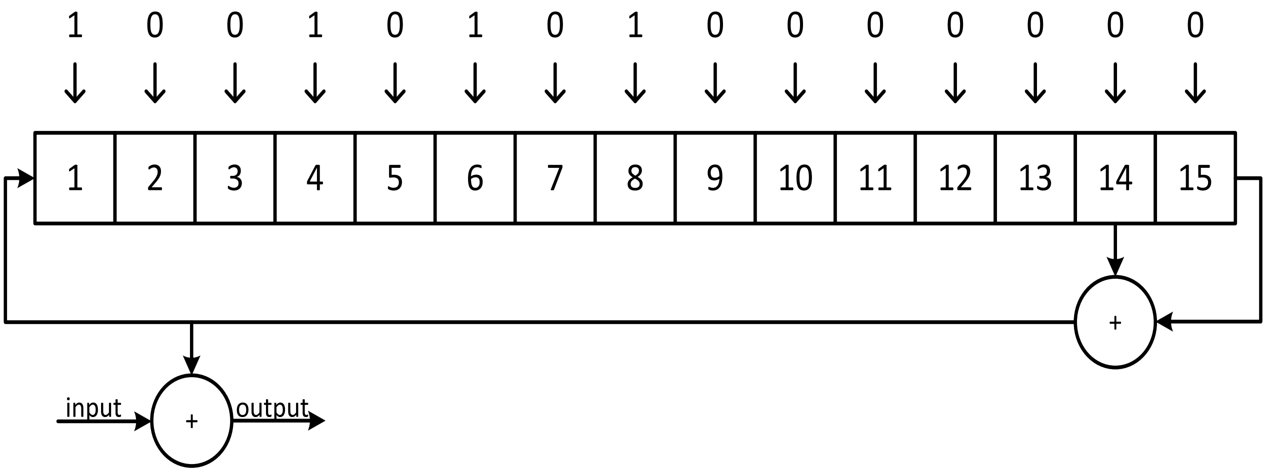

Fig. 1.5. Additive scrambler used in the DVB technology

The scrambling is performed only on the block of data.

1.1.4. Modulation and filtering

In the VDE-TER system, three modulation schemes have been defined: π/4 QPSK, 8PSK and 16QAM, all of which are performed using the same algorithm, depicted in fig. 1.6.

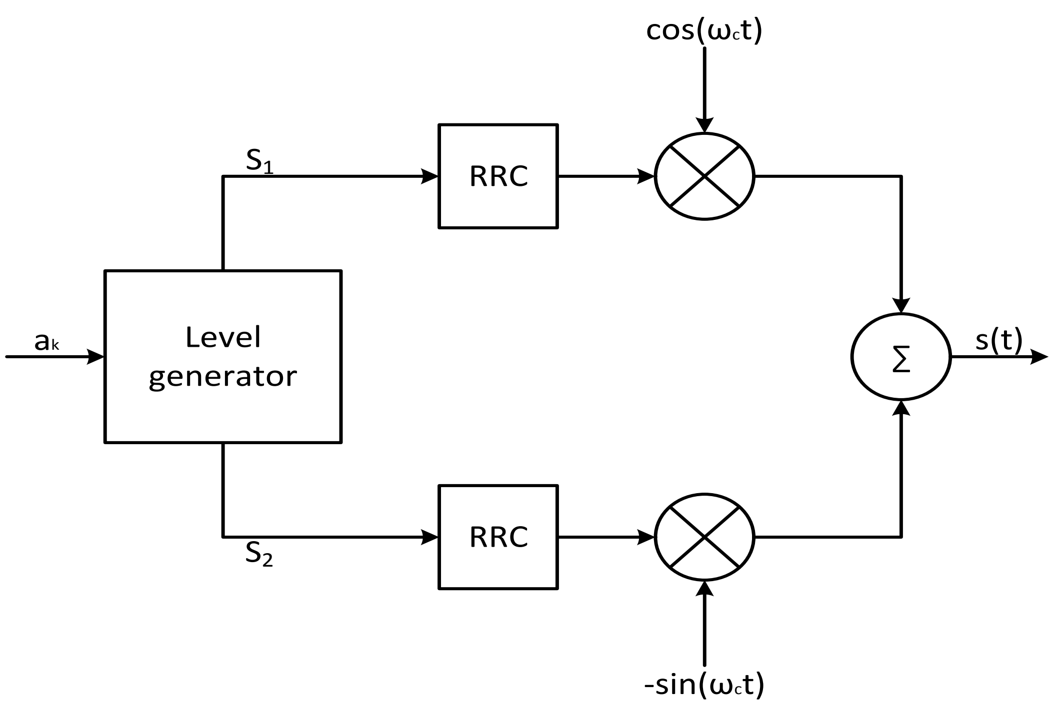

Fig. 1.6. General concept of the modulator utilized in the VDE-TER system

It is assumed that data block of the preamble and buffer are always modulated using the π/4 QPSK modulation in order to ensure a reliable time synchronization (in case of the user data, each of the three possible modulation schemes can be used).

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To the modulator's input, a symbol stream of the user data, preamble or buffer (a_k) is fed. Each symbol can be assigned a n-element bit sequence depending on the modulation scheme (there is a following relation between the modulation order M and the coefficient n: $M=2^n$). On the basis of those sequences, the level generator established the symbol's position on the constellation and assigns the sign and level of the amplitude for the symbols processed in synphase and quadrature channels (denoted as S_1 and S_2, respectively, in fig. 1.6). In the next stage, the shaping and sampling of the impulses takes place. Every modulation symbol can be represented as 4, 8 or 16 samples, depending on the transmission bandwidth (the values mentioned above were defined for 100 kHz, 50 kHz and 25 kHz). The shaped symbols are fed into the input of the RRC filter (*Root Raised Cosine).* It is done in order to limit the modulated signal bandwidth and to minimize the intersymbol interferences ISI. To achieve that goal, a FIR filter (Finite Impulse Response Filter) of the order N=128 has been designed. It introduces a delay equal to N/2=64 samples. After the filtering process is concluded, the signals are modulated by two carrier components: $\cos\omega_c t$ oraz $-\sin\omega_c t$. The resulting, modulated signal s(t) is composed of the sum of these two components.

In the following figures (1.7-1.9), the constellation of every modulation used in the VDE-TER system are presented. The symbols have been coded using the Grey code, so consequently, two successive code words differ in only one bit.

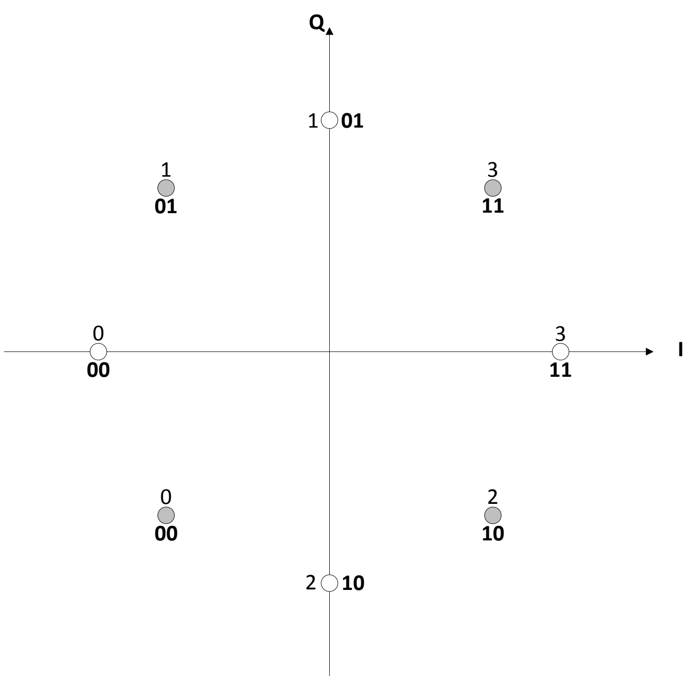

Fig. 1.7. π/4 QPSK constellation

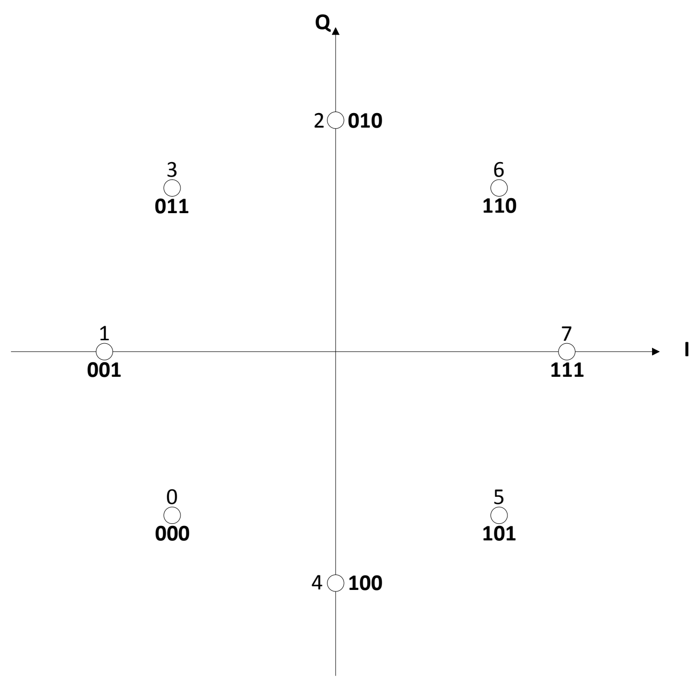

Fig. 1.8. 8PSK constellation

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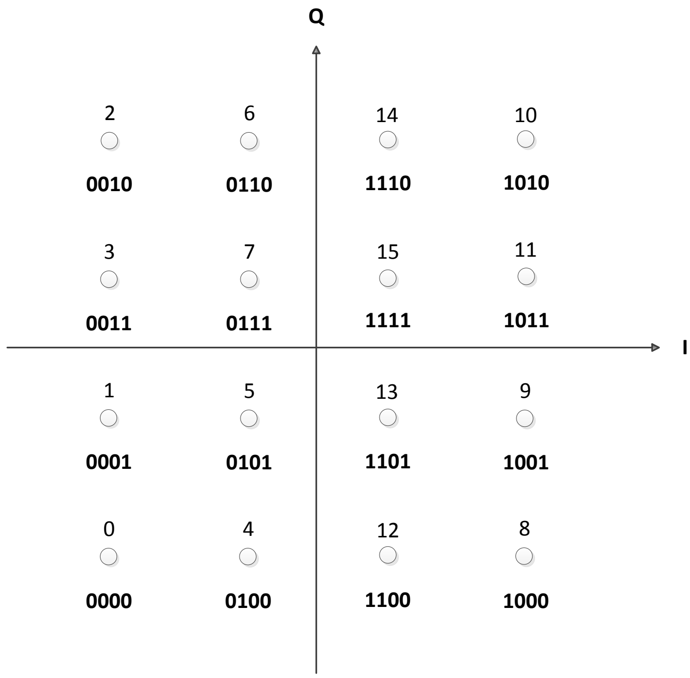

Fig. 1.9. 16QAM constellation

1.2. Receiver

The block diagram of the VED-TER receiver is depicted in fig. 1.10.

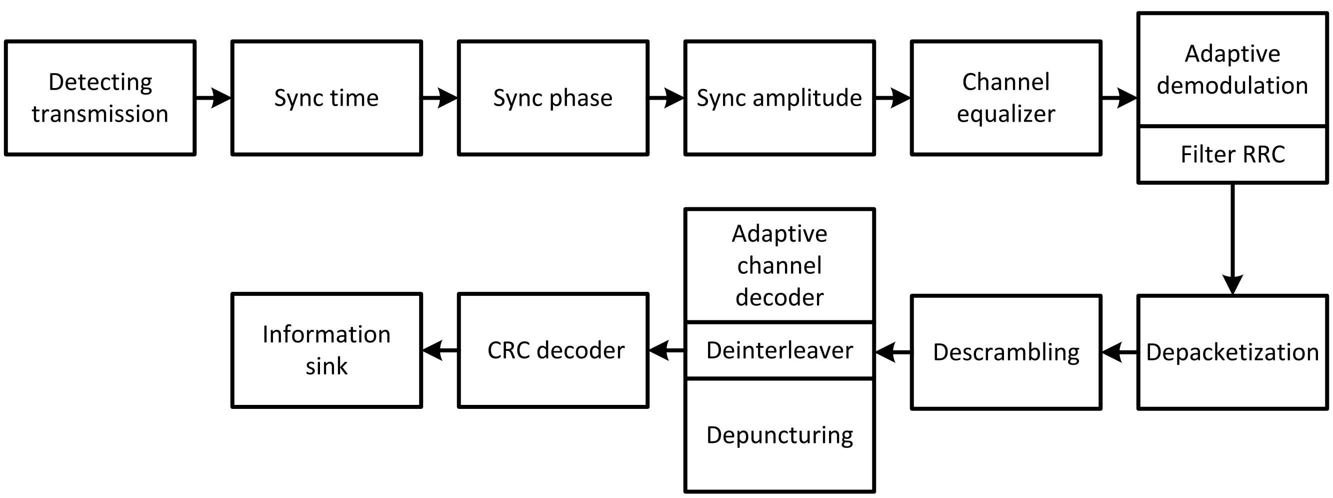

Fig. 1.10. VDE-TER receiver block diagram

The first step of the reception procedure is the detection of transmission. It is performed using a power detector. The subsequent stages are: time synchronization, phase synchronization and amplitude synchronization. After that, the coefficients of the channel equalizer's filter are calculated in the receiver, which is followed by filtering and demodulation of the received signal. Then, the bits are fed to the depacketizer block which selects only the bits that belong to the data block. Those blocks are descrambled and then – turbodecoded. The data after turbodecoding are validated (using the CRC32 cyclic code) and finally the input information is determined.

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1.2.1. Power detector

In the first stage of the receiving process it is necessary to confirm, that radio transmission actually takes place. The transmission detection comes down to checking whether the average signal power in the transmission channel is above the designated threshold, or not. The block diagram of the power detector can be depicted as in fig. 1.11.

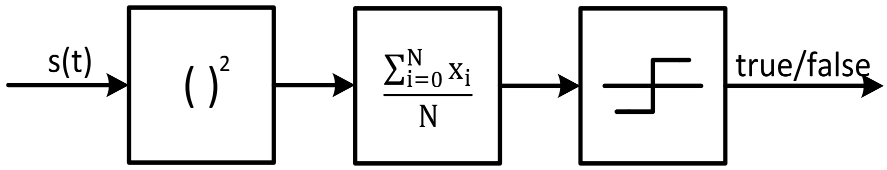

Fig. 1.11. Power detector block diagram

First, the system writes N samples from the radio channel into the receiver's memory. Packets s(t) prepared in this way are then fed into the power detector's input where they are squared and averaged. The result of this operation is an input of a decision-making system which verifies if the channel signal power is greater than the assumed threshold. If this is the case, the receiver initiates time synchronization process, if not – transmission detection has to start over.

1.2.2. Time synchronization

When the receiver detects a transmission, it becomes necessary to determine the position of the transmitted frame. The block diagram of the module that performs such a procedure is presented in fig. 1.12.

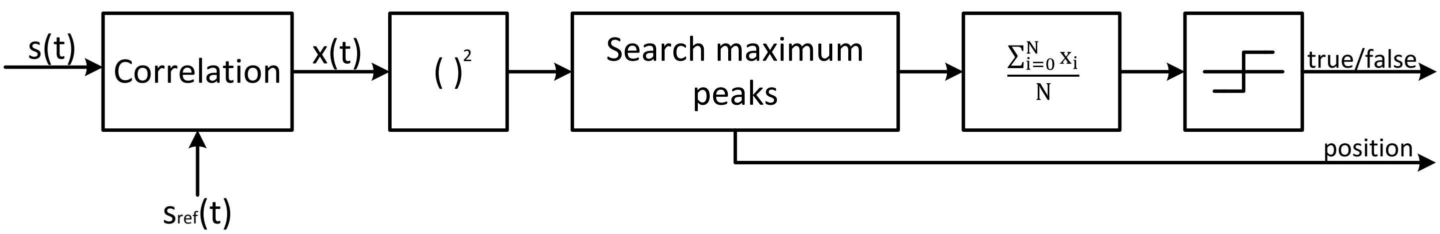

Fig. 1.12. Time synchronization block diagram

As soon as there are enough samples in the receiver's memory, the time synchronization algorithm starts. First, the received signal is correlated with a known reference signal (it is possible thanks to the training code placed in the frame structure. This training code is composed of two Barker codes which have very good autocorrelation properties). The resulting values are squared. In the next stage, the algorithm searches for N neighbouring peaks whose average value is maximum (the value of N depends on the number of samples per single symbol and can be defined as: N=(number of samples per symbol)/2 + 1). The position of the located peaks is stored in the memory and this calculated value is processed by decision-making block which compares it with the designated threshold. If the value is greater than that threshold, the receiver assumes the frame is being transmitted and starts obtaining the data from the transmission channel. Otherwise, the receiver resumes the transmission

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detection procedure.

In the simulator, a precise mechanism of position determination has been implemented. This mechanism generally works according to the same algorithm as the time synchronization block, the only difference is that the correlator receives as an input a reference signal with different phases (0^0 to 180^0 with a fixed step). Information such as: the position of the frame, correlation peak's height and the decision whether that peak is greater than the threshold are written into the tables. In the next step, those tables are searched in order to locate the maximum value peak to which its final position has been assigned.

1.2.3. Phase synchronization

After the frame's position has been determined and the sufficient amount of data has been gathered, in the next step, the phase of the signal needs to be calculated. To do so, a device that works according to the following block diagram (fig. 1.13) has been implemented.

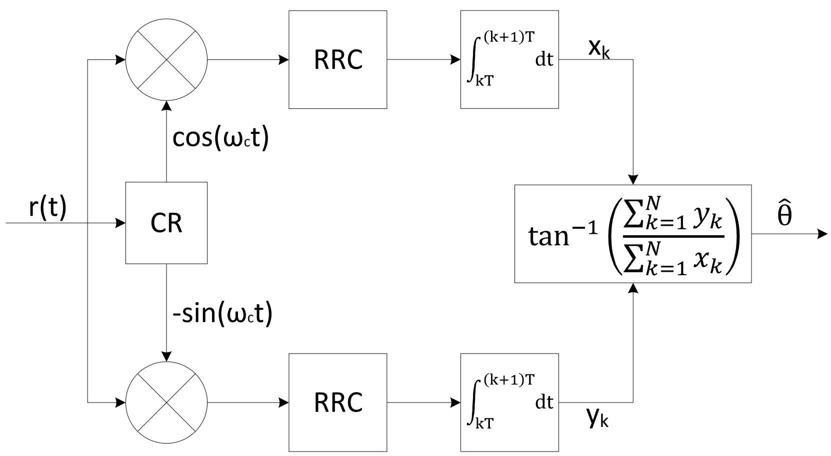

Fig. 1.13. Phase synchronization module – block diagram

The received signal r(t) at the phase synchronization module's input is multiplied by the signal $\cos\omega_c t$ (upper branch) and the signal $-\sin\omega_c t$ (lower branch). The frequencies of these signals are equal to the carrier frequency. The resulting impulses are then fed into the RRC filter's input whose task is to limit the signal bandwidth and minimize the influence of the intersymbol interference (ISI). After that, the impulses are subjected to the integration process. As a result, two tables are created into which the position of the received symbols on the Re axis (x_k) and Im axis (y_k) is written. In the next step, each of the tables is averaged, which allows to calculate the position of the resulting symbol and to determine its phase (which is equal to: arctg (symbol's position on the Im axis/symbol's position on the Re axis)).

1.2.4. Amplitude synchronization

The module responsible for the amplitude's determination works according to the similar algorithm as the one described in the previous subchapter (1.2.3). The only difference is the last component in which the actual parameter is calculated. In case of the amplitude synchronization, the calculation to be made is a squared root of the sum of squared values from tables x_k and y_k.

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The amplitude synchronization module is depicted in fig. 1.14.

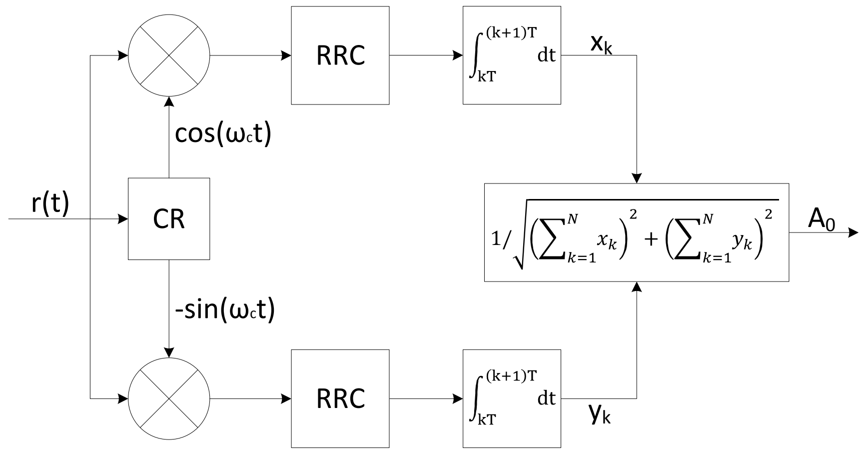

Fig. 1.14. Amplitude synchronization module – block diagram

1.2.5. MER coefficient calculation

In the VDE-TER segment, the system adapts itself to the conditions in the radio channel. It is assumed that on the basis of the MER coefficient (*Modulation Error Ratio*) the system adopts the most suitable modulation and coding scheme (after the transmitter gets a feedback information from the receiver). The value of this coefficient depends on the volume and type of noise that interferes with the signal. Generally, the MER should be interpreted as a distance from the total signal fading.

The MER coefficient can be calculated using the equation 1.1.

$$MER(dB) = 10\log_{10}\left(\frac{P_{signal}}{P_{error}}\right) \tag{1.1}$$

where:

- P_{signal} – RMS power (*Root Mean Square*) of the ‘perfect’ signal,
- P_{error} – RMS power of the erroneous signal.

The implemented simulator allows to enter the MER coefficients value at which the system should change its current MCS.

1.2.6. MCS determination

It is of crucial importance to correctly determine which modulation and coding scheme was used by the transmitter. On the basis of this information, the receiver selects the relevant demodulator. The encoded (by the Hamming code) MCS information is located in the frame field “Signal info” and it is modulated using the π/4 QPSK modulation. Consequently, to obtain the information about MCS it is necessary to demodulate the received signal and decode the relevant field in the frame.

By utilizing various MCS schemes and the module to determine MER, the system can work adaptively: it adapts to the condition in radio channel and maximizes the throughput and transmission quality.

1.2.7. Channel equalizer

In order to minimize the way the fadings might affect the transmitted signal, a channel equalizer was

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introduced, i.e. a module which determines the filter coefficients on the basis of synchronization signal and the known reference signal.

The equalizer that was implemented in the VDE-TER simulator is based on the zero-forcing algorithm. It is a linear equalizer which minimizes the influence of intersymbol interferences and is ideal in case of a noise-free transmission channel. However, when the channel is noisy, the zero-forcing equalizer will amplify the noise greatly at frequencies f where the channel response H(j2πf) has a small magnitude (i.e. near zeroes of the channel) in the attempt to invert the channel completely.

This module is necessary to minimize the influence of fadings that exist in the maritime radio channel – especially when the ship is in close proximity to the shore where signal reflection and heavy attenuation can be an issue.

1.2.8. Demodulation and filtering

The last stage of the signal processing in the receiver is its filtering and demodulation. Three demodulators have been implemented in the VDE-TER software simulator: π/4 QPSK, 8PSK and 16QAM, all of which work according to the same algorithm presented in fig. 1.15. The decision making-making block, however, is different for all of these demodulators. Additionally, since soft turbodecoding is utilized, each of the analyzed demodulators is equipped with a soft-output decision-making block.

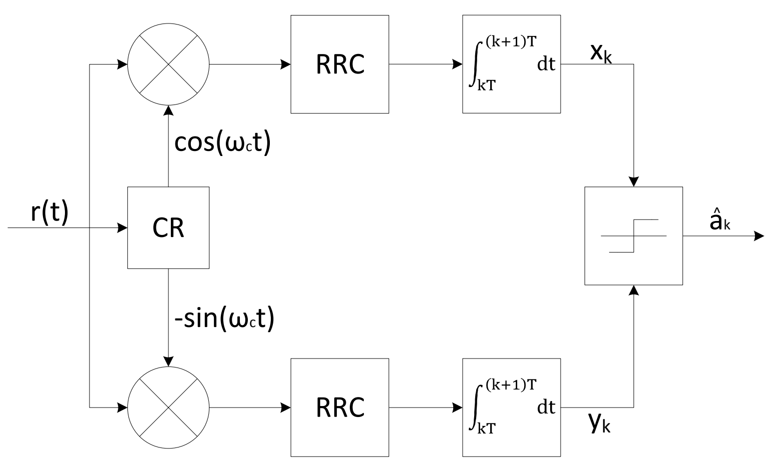

Fig. 1.15. Ogólny schemat blokowy demodulatora wykorzystwanego w systemie VDE-TER

The received signal is multiplied by the signal $cos\omega_c t$ (upper branch) and the signal $-sin\omega_c t$ (lower branch). The frequency of these signals is equal to the carrier frequency. This process ensures that the signal is shifted from high frequency band towards the baseband. The impulses are then fed into the RRC filter's input. The filter's task is to limit the signal bandwidth and minimize the influence of the intersymbol interference (ISI). Additionally, the filter shapes the impulses which – in the next stage – are subjected to integration. As a result two tables x_k and y_k are created (they represent k-th symbol on the Re and Im axis, respectively).The last block of the demodulator is a decision-making module which assigns position to a specific symbol. As it was mentioned previously, each of the demodulators is equipped with a soft-output decision-making block.

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In case of the π/4 QPSK and 8PSK demodulators, only the phase of the received signal is detected (the temporary amplitude of the received signal does not carry any information about the transmitted data). Soft decision is made on the basis of the phase shift between the received signal and subsequent known MPSK symbols. The detector will select the symbol for which the shift phase is the smallest and the value of this shift determines the confidence of the decision.

Each symbol is assigned (by a decision-making block) a value proportional to its deviation from the constellation point. The smaller the deviation, the greater the assigned value. It has also been assumed that whenever the phase of the received symbol is equal to the phase of a constellation point, the assigned value is 1, and whenever the received symbol is located between two constellation points, the assumed value is 0. A few examples of how the above algorithm works are shown in fig 1.16. That picture was drawn for the π/4 QPSK demodulator; for 8PSK the algorithm is the same but obviously the are more points on the constellation.

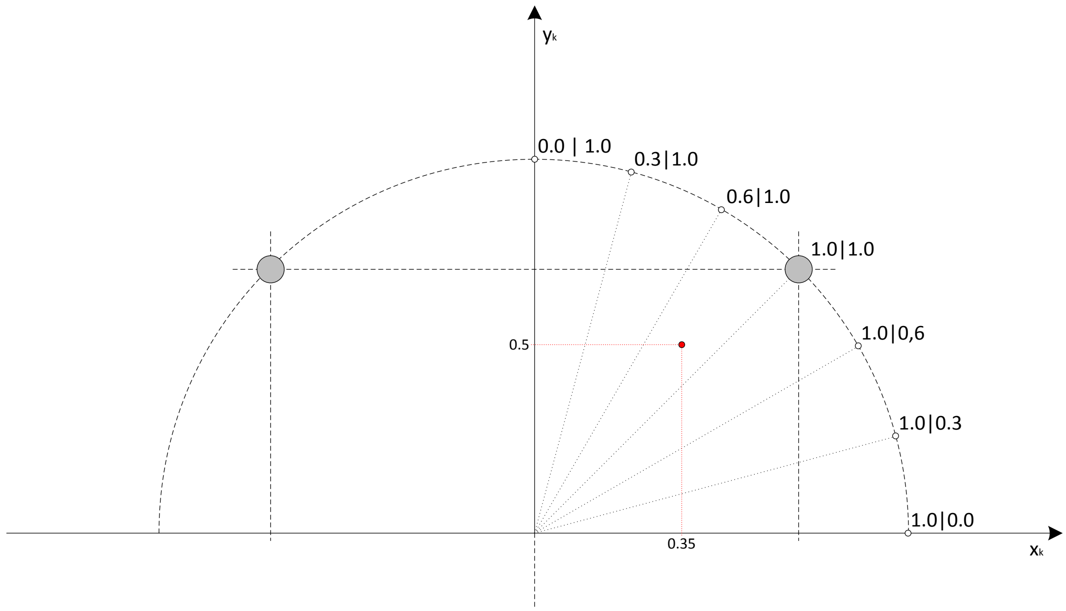

Fig. 1.16. Signal detection for the /4 QPSK modulation

Fig. 1.16 indicates a sample point whose coordinates are: x_k = 0,35 and y_k=0,5; for this point an example of how the detector works is shown. First, the decision-making block calculates the angle of the received symbol, using the following formula:

$$\theta = \tan^{-1}\left(\frac{0,5}{0,35}\right) = 55^{\circ} \qquad (1.2)$$

On the basis of this value, the decision is made:

$$b_1 = 2 - \frac{55^{\circ}}{45^{\circ}} = 0,77 \qquad (1.3)$$

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$$b_2 = 1{,}0$$

where:

- b_1 – first bit
- b_2 – second bit

Depending the constellation's section to which the point belongs, the assigned value could be positive or negative.

In case of the 16QAM detection, not only the phase but also the amplitude is detected. The decision is made on the basis of the Euclidean distance between the received signal point's location and subsequent constellation points for that modulation.

1.2.9. Descrambling

Descrambling is complementary to the scrambling process. Since the VDE-TER utilizes an additive scrambler (the same as in the DVB technology), the design and algorithm of the scrambler and descrambler are identical (see section 1.1.3).

1.2.10. Turbodecoding

The decoding process is performed using a soft-decision Viterbi algorithm SOVA (*Soft Output Viterbi Algorithm*), in which the metrics are calculated using soft decisions produced by two decoders which "support" one another in subsequent turbodecoding iterations (fig. 1.17).

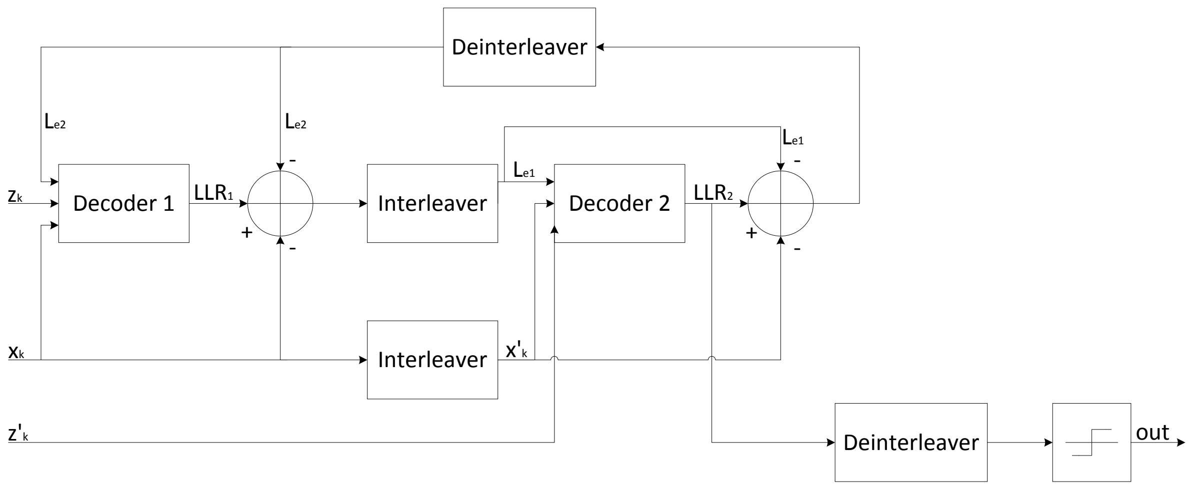

Fig. 1.17. SOVA turbodecoder

The SOVA turbodecoder is comprised of two convolutional codes decoders, interleaver and deinterleaver blocks. The decoding is an iterative process and is based on the highest probability criterion. The main rule of this kind of decoding is that the optimum path through which the detector reaches the current state is comprised of the path with the smallest metric through which the decoder reaches one of the previous states and the path to the current state.

SOVA is not the only convolutional codes decoding algorithm, but it is the most popular mainly due to the simplicity in the hardware implementation.

1.3. Transmission channels

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In the VDE-TER simulator, three transmission channels have been implemented:

- AWGN (Additive White Gaussian Noise) channel,
- Rayleigh channel – channel with additive Gaussian white noise and Rayleigh fading,
- Two-path AWGN channel – two-path channel with additive white Gaussian noise and slow fading.

1.3.1. AWGN channel

It is a basic model of a noisy transmission channel which can be used to describe a lot of random processes. The name "AWGN" can be "deciphered" in the following way:

- A – additive, because it is possible to add noise which can be generated by the internal devices of the system,
- W – white, because it has the same power in the entire system bandwidth,
- G – Gaussian, because it has a uniform distribution in time domain with a zero mean value.

AWGN is described by the following probability distribution:

$$p(u) = \frac{1}{\sigma_u \sqrt{2\pi}} e^{-\frac{u^2}{2\sigma_u^2}} \tag{1.4}$$

To ensure the appropriate signal/noise level, it is first necessary to calculate noise variance which – for the Gaussian distribution – is σ_u^2. After some transformations, the formula for Gaussian noise variance can be presented as follows:

$$\sigma_u^2 = \frac{S \cdot L}{mod\_id \cdot \frac{E_B}{N_0}} \tag{1.5}$$

where:

- *S* – signal power (depends on the modulation scheme),
- *L* – number of samples per symbol,
- *mod_id* – number of bits per single symbol,
- E_B – energy of bit,
- N_0 – noise spectral density.

If the noise variance is known, it is possible to provide required signal to noise ratio during the simulations.

1.3.2. Rayleigh channel

Fading in radio channel is usually modelled using the Rayleigh probability distribution whose formula is as follows:

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$$p(a) = \frac{a}{\sigma_r^2} e^{\frac{a^2}{2\sigma_r^2}} \tag{1.6}$$

The Rayleigh distribution is a relatively simple, single-parameter model, which, nevertheless, is sufficient to describe statistical properties of the fading signals.

As it was previously mentioned, the Rayleigh channel has been implemented in the simulator, but in case of data transmission at sea it is not deterministic.

1.3.3. Maritime radio channel

To facilitate analysis of the new wireless data transmission system at sea, a novel maritime radio channel model in the VHF band has been defined. It was observed that in the maritime conditions two channel states can be distinguished:

- The case where the ship is out at sea, and the multipath propagation is virtually nonexistent (the calculations showed that the delay of the second propagation path on the high seas is a few nanoseconds). Consequently, the transmission channel in this case is simply an AWGN channel.
- The case where the ship is in the harbor or its vicinity. In this scenario, the multipath effect is significant, and consequently – after analysis – it is recommended that this special scenario should be modelled using a two-tap AWGN channel in which the second path attenuation varies depending on the ship's location and the number of objects in the harbor.

In both scenarios above, it is assumed that due to small speed of ships and other objects, the Doppler offset is small and almost constant. Consequently, the Rayleigh fading effect is virtually nonexistent.

Three variants of the maritime radio channel have been proposed; their parameters are listed below:

- Delay of the second path in relation to the main path is 10 µs,
- Attenuation of the second path (second tap) depends on the severity of multipath phenomenon and might be equal to: -3 dB, -6 dB or -10 dB,
- Doppler shift is almost constant and it does not exceed 5 Hz at 160 MHz.

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2. VER-TER simulator

The chapter describes the VDE-TER software simulator, including its algorithm and user interface.

2.1. General description of the simulator

The simulator was developed in the C++ language using the C++ Builder 2007 programming environment. To simplify its management, all the functions were divided into several categories and located in separate *.cpp files:

- additional_function – contains functions used by other files.
- channel – includes elements necessary to simulate the AWGN, Rayleigh and the two-path AWGN channel,
- coeffes – it contains RRC filters coefficients
- data_structures – describes properties of a particular data type and includes symbolic constants used in the application,
- demodulator – includes functions common for all three demodulator: π/4 QPSK, 8PSK and 16QAM,
- demodulator_8PSK - contains the functions responsible for the 8PSK demodulation.
- demodulator_16QAM - contains the functions responsible for the 16QAM demodulation.
- demodulator_PI4_QPSK - contains the functions responsible for the PI4_QPSK demodulation.
- filters – contains functions responsible for the signal filtering,
- hamming – performs coding/decoding of data using the Hamming (7,4) code,
- equalizer – channel equalizer, responsible for the calculation of filter coefficients on the basis of the input and reference samples,
- MER – contains the functions responsible for the calculation of the MER (modulation error),
- modulator – contains the functions common for all three modulators: π/4 QPSK, 8PSK and16QAM,
- modulator_8PSK – contains the functions responsible for the 8PSK modulation.
- modulator_16QAM – contains the functions responsible for the 16QAM modulation.
- modulator_PI4_QPSK – contains the functions responsible for the PI4_QPSK modulation.
- interleaver – includes functions responsible for the interleaving,
- receiver – contains the function responsible for the reception of the transmission signal.
- RRCFilterDesigne – contains the function responsible for the design of the RRC (Raised root cosine) filter coefficients,
- scrambling – contains the functions responsible for the data scrambling,
- slot – contains the functions responsible for data slot creation,
- spectrum – contains the function responsible for the calculation of the signal spectrum,
- synchronization – contains functions that perform signal detection, time and phase synchronization, amplitude and MCS determination,
- training_sequence – contains a table with a synchronization sequence,
- transmitter – contains the function responsible for the generation of the transmission signal.

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- turbocoding – includes functions that perform turbocoding of the input data and turbodecoding,
- VDES_simulator_about – displays information about the VDE-TER simulator,
- VDES_simulator_BER – performs bit error rate calculation as well as the presentation of signal constellations for every MCS scheme,
- VDES_simulator_CCDF – It calculates CCDF,
- VDES_simulator_general – main window of the application, it allows to conduct simulation analysis of the VDES system terrestrial component,
- VDES_simulator_modulation – presents the subsequent steps of the modulation and demodulation,
- VDES_simulator_RRCFilterDesigner – enables to generate the RRC filter coefficient table,
- VDES_simulator_spectrum – enables to display the spectrum of the modulated signal,
- VDES_simulator_transmitter_receiver – enables to generate the signal, to write/read it to/from the text file and to demodulate it,
- window_functions – contains window functions required for the channel equalizer coefficient calculation.

In the simulator, the library fftw3 was used in the simulator to implement convolution and some other procedures.

The file *data_structures.h* contains symbolic constants used in the simulator:

- const double fc = 76800.0
  – carrier frequency,
- const double fs = 4*fc
  – sampling frequency,
- const int lengthChannelTabBuffer = 10752
  – length of table that includes the samples from the channel,
- const double preciseFramePositionStep = M_PI/8.0
  – auxiliary variable the defines angular resolution for the block that determines the position,
- const int MAX_INPUT_LEN = 18000
  – length of the table with signal spectrum samples,
- const int FILTER_LEN = 128
  – the number of RRC filter coefficients,
- const int CHE_FILTER_LEN = 64
  – the number of channel equalizer coefficients.

In the simulator, there exist connections between the files, which was indicated below:

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additional_function
- fftw3
- slot

channel
coeffes
data_structures
demodulator
demodulator_16QAM
- demodulator
- filters

demodulator_8PSK
- demodulator
- filters

demodulator_PI4_QPSK
- demodulator
- filters

filters
- data_structures

hamming
korektor
- fftw3
- coeffes
- filters
- modulator_PI4_QPSK
- training_sequence
- window_functions

MER
- additional_function
- demodulator_PI4_QPSK

modulator
modulator_16QAM
- modulator
- filters

modulator_8PSK
- modulator
- filters

modulator_ PI4_QPSK
- modulator
- filters

interleaver
receiver
- additional_function
- demodulator_16QAM
- demodulator_8PSK
- demodulator_PI4_QPSK
- filters
- equalizer
- MER
- scrambling
- synchronization
- turbocoding

RRCFilterDesigne
scrambling
slot
- additional_function
- hamming
- scrambling
- training_sequence
- turbokodowanie

spectrum
- data_structures
- fftw3

synchronization
- additional_function
- demodulator_PI4_QPSK
- hamming
- modulator_PI4_QPSK
- training_sequence

training_sequence
turbocoding
- interleaver

VDES_simulator_about
VDES_simulator_BER
- additional_function
- channel
- data_structures
- demodulator_16QAM
- demodulator_8PSK
- demodulator_PI4_QPSK
- filters
- korektor
- modulator_16QAM
- modulator_8PSK
- modulator_PI4_QPSK
- scrambling
- synchronization
- transmitter
- turbocoding

VDES_simulator_CCDF
- additional_function
- data_structures
- transmitter

VDES_simulator_general
- additional_function
- channel
- data_structures

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- filters
- modulator_PI4_QPSK
- receiver
- synchronization
- training_sequence
- transmitter
- VDES_simulator_about
- VDES_simulator_BER
- VDES_simulator_CCDF
- VDES_simulator_modulation
- VDES_simulator_RRCFilterDesigner
- VDES_simulator_spectrum
- VDES_simulator_transmitter_receiver

VDES_simulator_modulation
- additional_function
- channel
- demodulator
- demodulator_16QAM
- demodulator_8PSK
- demodulator_PI4_QPSK
- filters
- modulator
- modulator_16QAM
- modulator_8PSK
- modulator_PI4_QPSK

VDES_simulator_RRCFilterDesigner
- RRCFilterDesigne

VDES_simulator_spectrum
- additional_function
- channel
- data_structures
- filters
- equalizer
- spectrum
- transmitter

VDES_simulator_transmitter_receiver
- additional_function
- channel
- data_structures
- modulator_PI4_QPSK
- receiver
- training_sequence
- transmitter

window_functions

2.2. Simulator's algorithm

The VDE-TER software simulator described in this document works according to the algorithm presented in fig. 2.1.

After the application has been started, it is possible to enter input parameters and to select required options. In the first stage, the application randomly draws the position of the transmitted frame and its phase. After that, transmitter block is initiated: the data bits are generated and the resulting stream is modulated. At the transmitter's output, the signal samples are written into a table that represents transmission channel. In the next step, the noise is added to some of the channel samples (this process is repeated and depends on the length of the table that represents the channel). The resulting packets are fed into the receiver's input, where it is first verified if the average signal power is above the required threshold. If it is, the programme goes into the next stage where the received signal is correlated with the reference sequence; on the basis of this procedure, the frame's position is determined. When the correlation peak is greater than the threshold, samples are moved from the channel to the receiver's memory. If the number of those samples is sufficient, the phase and amplitude synchronization are initiated, MER coefficient is calculated, MCS is determined and the coefficients of the equalizer filter are determined. Finally, the received signal is filtered and subjected to demodulation, which ends the receiver's procedure.

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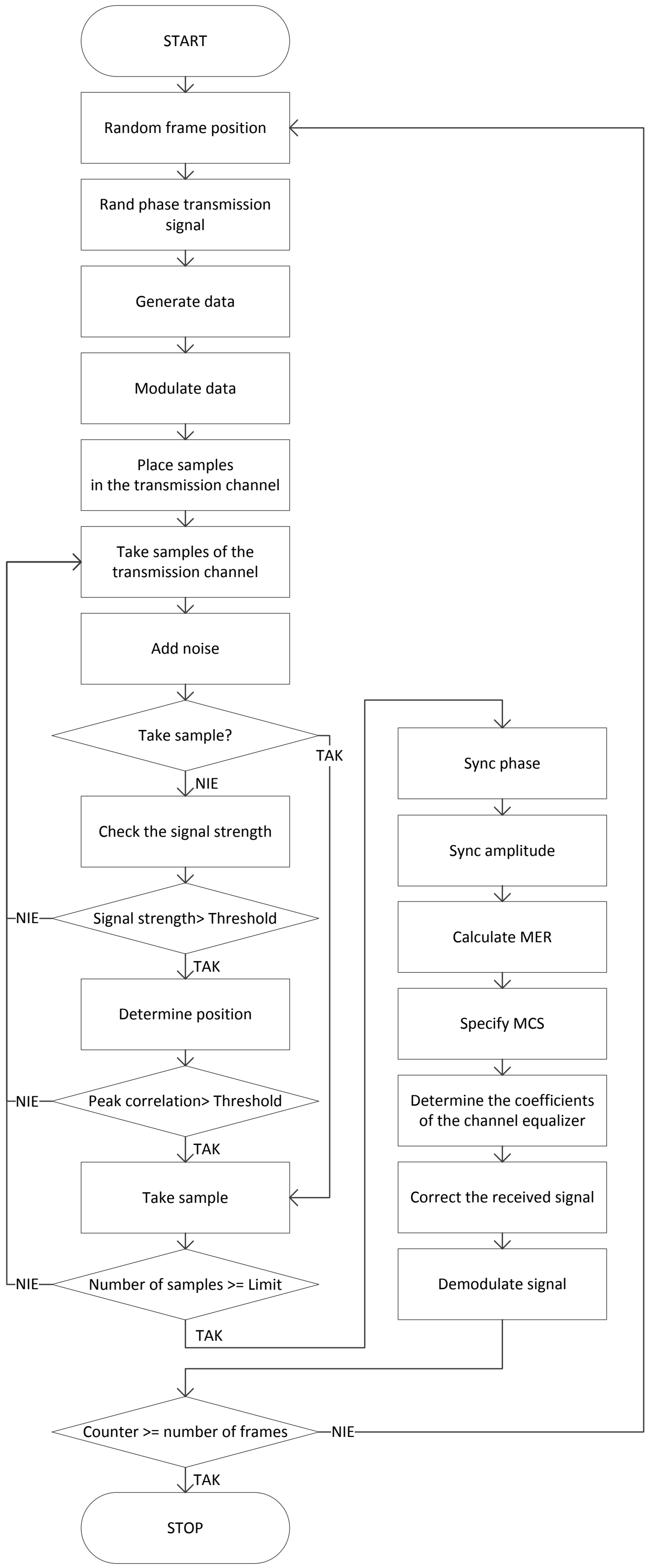

Fig. 2.1. Simulator's algorithm

2.3. User interface

In the following section the user interface of the simulator is presented. We discussed the

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parameters, the way the software should be operated and a sample execution of the programme.

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2.3.1. Window: VDES simulator

The main window of the programme is shown in fig. 2.2 (VDES simulator).

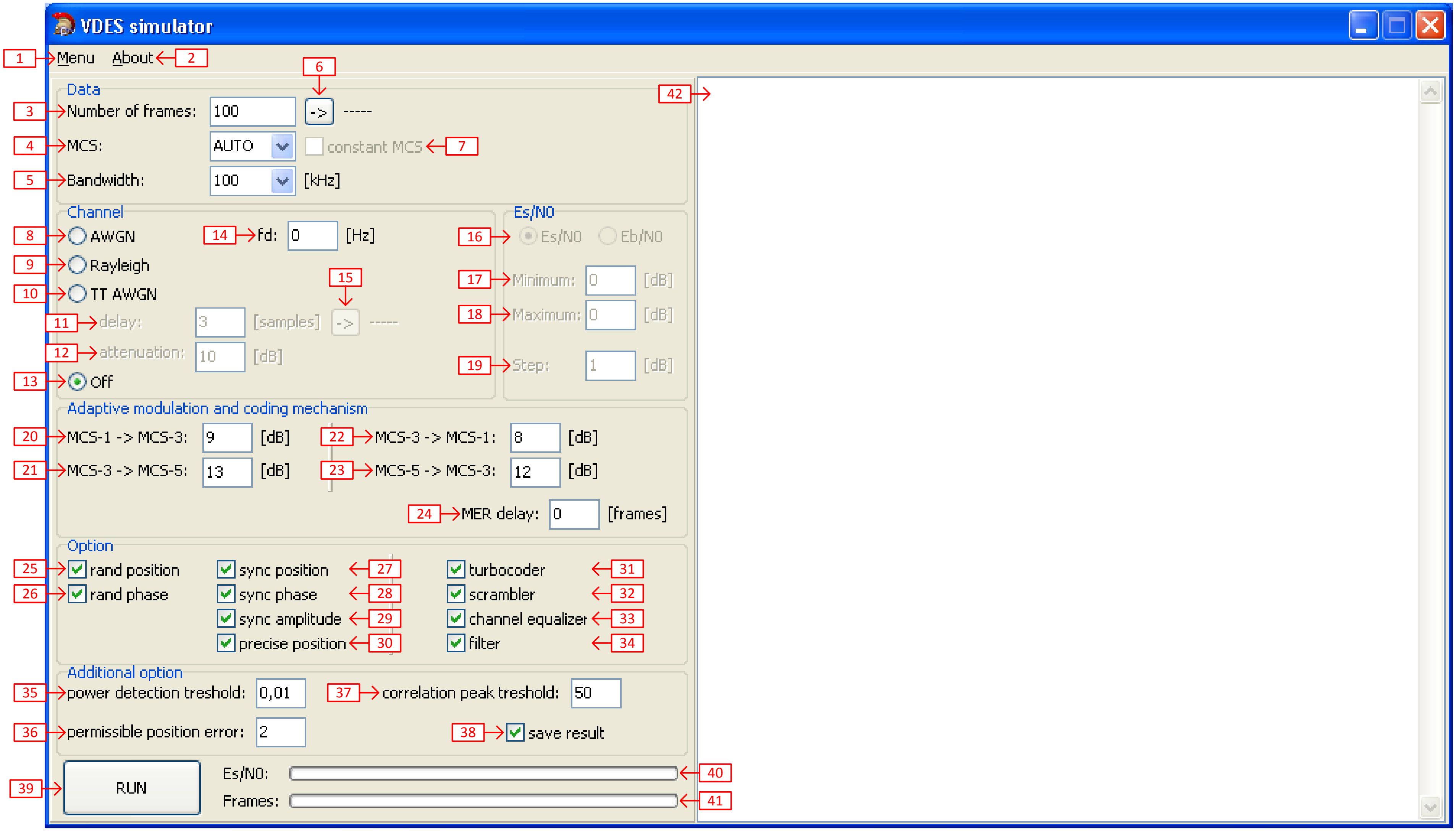

Fig. 2.2. The 'VDES simulator' window

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1) Menu – it is possible to open one of the six available windows
2) Simulator info –contains information about the EfficienSea2 project and the VDES software simulator
3) Number of transmitted frames
4) Modulation and coding scheme – it is possible to select one of the three available MCSs or set the automatic selection of MCS
5) Bandwidth – it is possible to select one of the three available transmission bandwidths
6) Transmission duration converter – it converts the number of frames into the transmission duration, presented in the format: [h:m:s:ms]
7) Checkbox that disables any modifications of the MCS and ensures that MCSs at the transmitter and receiver side will match
8) AWGN channel
9) Rayleigh channel
10) Two-path AWGN channel
11) Delay of the second path to the first path in two-path AWGN channel (expressed in the number of samples)
12) Delay of the second path to the first path in two-path AWGN channel (expressed in dB)
13) Channel with no noise and no fading – signal is transmitted without any additional distortions
14) Doppler frequency – deviation of the transmitter signal carrier from the receiver signal carrier
15) Conversion of the second path delay expressed in samples to delay expressed in time units
16) Selection of E_s/N_0 or E_b/N_0 – simulations will be performed either for E_s/N_0 or E_b/N_0
17) Minimum value of E_s/N_0 or E_b/N_0
18) Maximum value of E_s/N_0 or E_b/N_0
19) E_s/N_0 or E_b/N_0 step – a step by which E_s/N_0 or E_b/N_0 will be incremented in the simulation process
20) MER value at which MCS-1 will be changed to MCS-3 – only available if automatic MCS selection is enabled
21) MER value at which MCS-3 will be changed to MCS-5 – only available if automatic MCS selection is enabled
22) MER value at which MCS-3 will be changed to MCS-1 – only available if automatic MCS selection is enabled
23) MER value at which MCS-5 will be changed to MCS-3 – only available if automatic MCS selection is enabled
24) Delay of information about MER value change - only available if automatic MCS selection is enabled
25) Draw randomly signal’s position – checkbox that enables/disables random signal position
26) Draw randomly signal’s phase – checkbox that enables/disables random signal’s phase
27) Synchronize signal’s position - checkbox that enables/disables time synchronization
28) Synchronize signal’s phase - checkbox that enables/disables phase synchronization
29) Synchronize signal’s amplitude - checkbox that enables/disables amplitude synchronization
30) Determine exact signal’s position – checkbox that enables/disables precise signal’s position determination (only available if time synchronization is enabled)

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31) Checkbox that enables/disables turbocoder and turbodecoder
32) Checkbox that enables/disables scrambler and descrambler
33) Checkbox that enables/disables channel equalizer
34) Checkbox that enables/disables RRC filter
35) Signal detection threshold – minimum mean value of signal power at which time synchronization will be initiated
36) Frame position determination error – acceptable error of frame position determination (expressed in samples)
37) Correlation peak value – minimum value of the correlation peak at which the receiver will detect signal transmission
38) Checkbox that enables/disables writing the data to the csv file
39) Button that initiates simulation process
40) Progress bar - E_s/N_0 or E_b/N_0 value
41) Progress bar – number of transmitted frames
42) Displays simulation results

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2.3.2. Window: VDES simulator – modulation

The window ‘VDES simulator-modulation’ of the programme is shown in fig. 2.3.

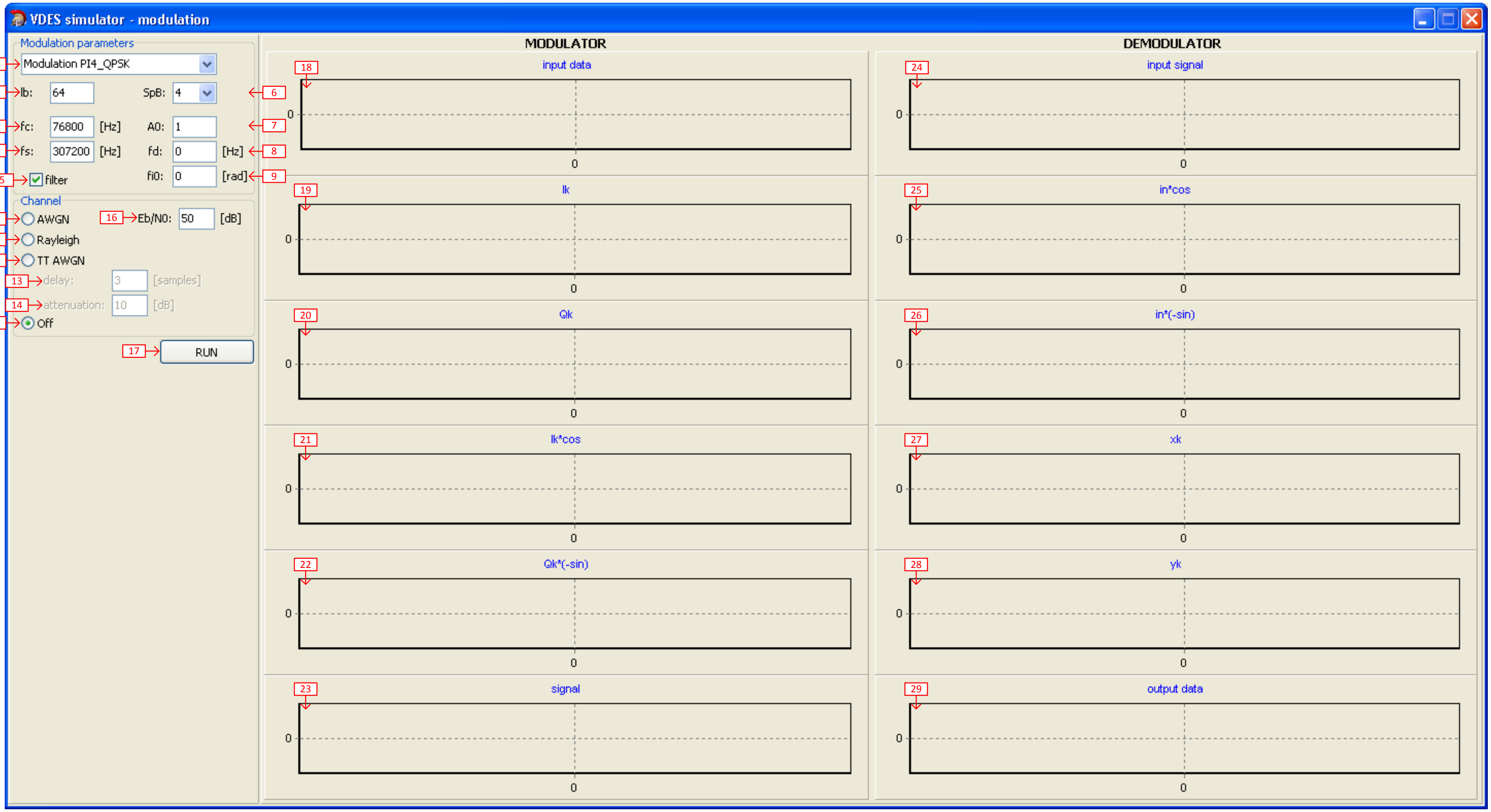

Fig. 2.3. Window: VDES simulator – modulation

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1) Modulation – selection of one of the available modulation schemes
2) Number of bits – number of random bits that will be modulated
3) Carrier frequency in the modulator and demodulator
4) Sampling frequency in the modulator and demodulator
5) Checkbox that enables/disables RRC filter
6) Number of samples per symbol
7) Signal's amplitude value in the modulator
8) Doppler frequency – deviation of the transmitter signal carrier from the receiver signal carrier
9) Modulated signal phase
10) AWGN channel
11) Rayleigh channel
12) Two-path AWGN channel
13) Delay of the second path to the first path in two-path AWGN channel (expressed in the number of samples)
14) Delay of the second path to the first path in two-path AWGN channel (expressed in dB)
15) Channel with no noise and no fading – signal is transmitted without any additional distortions
16) E_b/N_0 value
17) Button that initiates simulation process
18) Input data – bits fed into the modulator's input
19) Synphase component – odd input bits
20) Quadrature component – even input bits
21) Synphase component multiplied by the carrier
22) Quadrature component multiplied by the carrier
23) Modulated signal
24) Received signal (at the demodulator's input)
25) Synphase path – signal received multiplied by the cosine of the carrier frequency
26) Quadrature path – signal received multiplied by the sine of the carrier frequency
27) Symbol's location at the Re axis
28) Symbol's location at the Im axis
29) Bits received (after demodulation)

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2.3.3. Window: VDES simulator – spectrum

Window that displays modulated signal spectrum is shown in fig. 2.4.

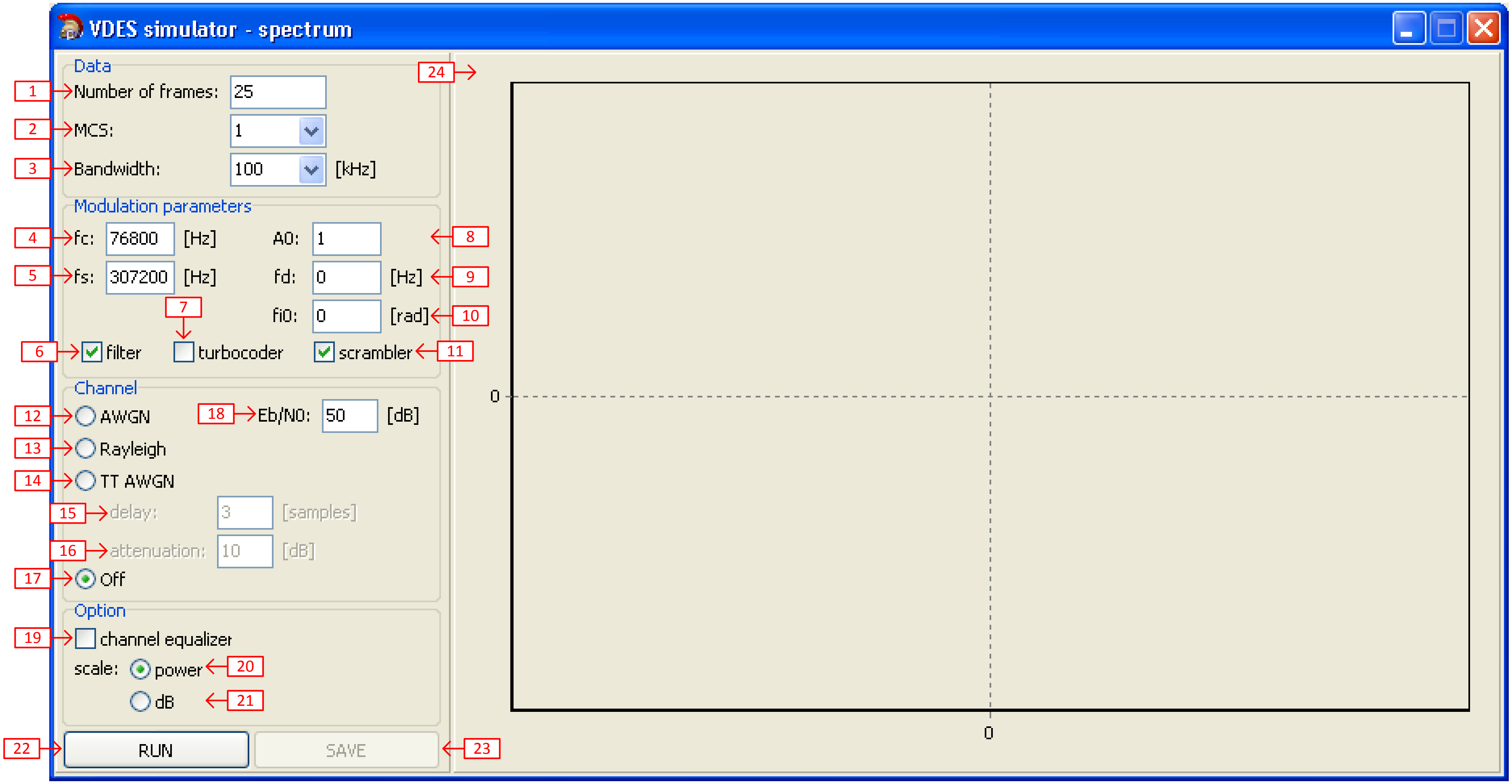

Fig. 2.4. Window: VDES simulator – spectrum

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1) Number of transmitted frames
2) Modulation and coding scheme – it is possible to select one of the three available MCSs or set the automatic selection of MCS
3) Bandwidth – it is possible to select one of the three available transmission bandwidths
4) Carrier frequency in the modulator and demodulator
5) Sampling frequency in the modulator and demodulator
6) Checkbox that enables/disables RRC filter
7) Checkbox that enables/disables turbocoder/turbodecoder
8) Amplitude of the transmitted signal
9) Doppler frequency – deviation of the transmitter signal carrier from the receiver signal carrier
10) Phase of the transmitted signal
11) Checkbox that enables/disables scrambler/descrambler
12) AWGN channel
13) Rayleigh channel
14) Two-path AWGN channel
15) Delay of the second path to the first path in two-path AWGN channel (expressed in the number of samples)
16) Delay of the second path to the first path in two-path AWGN channel (expressed in dB)
17) Channel with no noise and no fading – signal is transmitted without any additional distortions
18) E_b/N_0 value
19) Checkbox that enables/disables channel equalizer
20) OX axis scale – spectrum is displayed using the power unit
21) OX axis scale – spectrum is displayed in dB
22) Button that initiates the simulation process
23) Saves the spectrum into the graphic file and the text file
24) Spectrum of the modulated signal

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2.3.4. Window: VDES simulator – BER

Window for BER calculations and signal constellation display is shown in fig. 2.5.

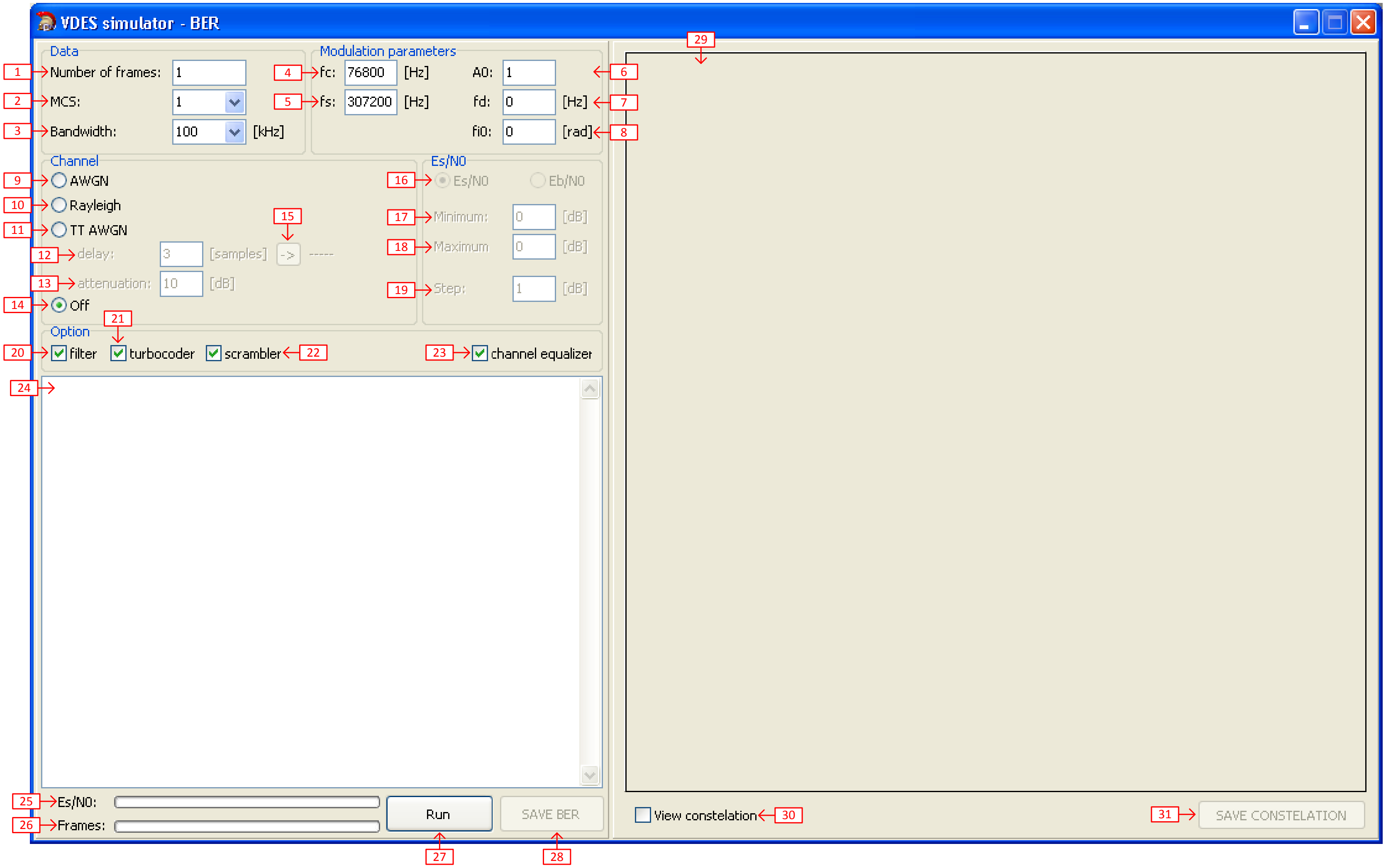

Fig. 2.5. Window: VDES simulator – BER

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1) Number of transmitted frames
2) Modulation and coding scheme – it is possible to select one of the three available MCSs or set the automatic selection of MCS
3) Bandwidth – it is possible to select one of the three available transmission bandwidths
4) Carrier frequency in the modulator and demodulator
5) Sampling frequency in the modulator and demodulator
6) Amplitude of the transmitted signal
7) Doppler frequency – deviation of the transmitter signal carrier from the receiver signal carrier
8) Phase of the transmitted signal
9) AWGN channel
10) Rayleigh channel
11) Two-path AWGN channel
12) Delay of the second path to the first path in two-path AWGN channel (expressed in the number of samples)
13) Delay of the second path to the first path in two-path AWGN channel (expressed in dB)
14) Channel with no noise and no fading – signal is transmitted without any additional distortions
15) Conversion of the second path delay expressed in samples to delay expressed in time units
16) Selection of E_s/N_0 or E_b/N_0 – simulations will be performed either for E_s/N_0 or E_b/N_0
17) Minimum value of E_s/N_0 or E_b/N_0
18) Maximum value of E_s/N_0 or E_b/N_0
19) E_s/N_0 or E_b/N_0 step – a step by which E_s/N_0 or E_b/N_0 will be changed in the simulation process
20) Checkbox that enables/disables RRC filter
21) Checkbox that enables/disables turbocoder/turbodecoder
22) Checkbox that enables/disables scrambler/descrambler
23) Checkbox that enables/disables channel equalizer
24) Simulation results
25) Progress bar - E_s/N_0 or E_b/N_0 value
26) Progress bar – number of transmitted frames
27) Button that initiates simulation process
28) Saves the data to the text file
29) Signal constellation display
30) Checkbox that enables/disables signal constellation display
31) Save constellation display to the graphic file

2.3.5. Window: VDES simulator – CCDF

Window for CCDF and PAPR calculation is presented in fig. 2.6.

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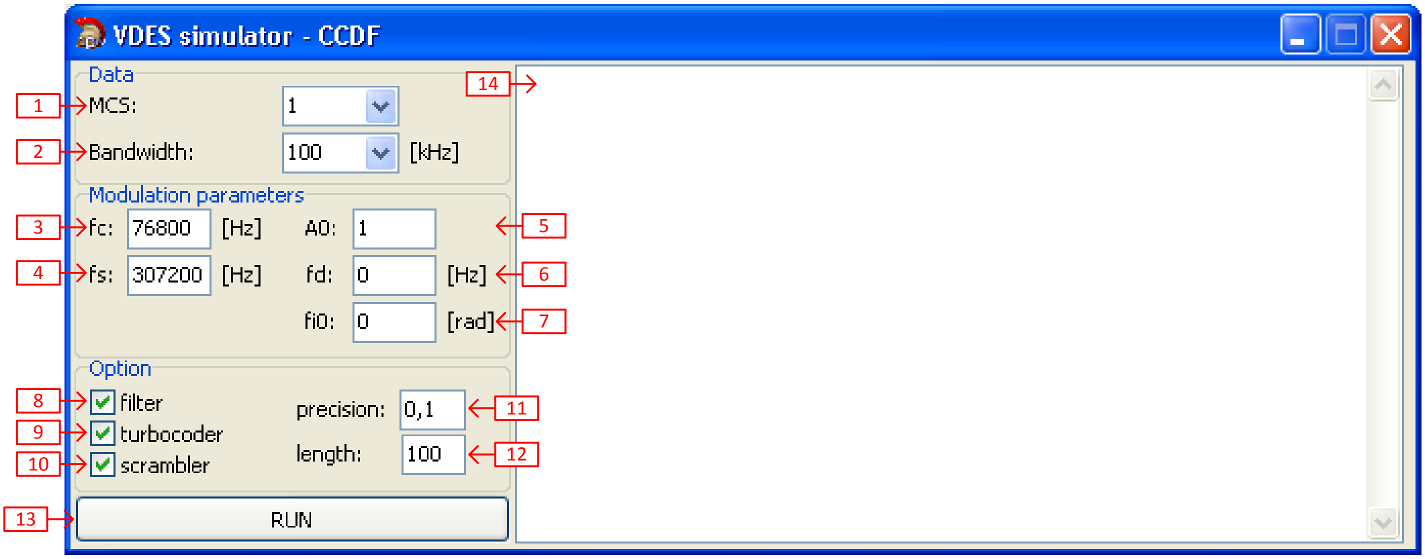

Fig. 2.6. Window: VDES simulator – CCDF

1) Modulation and coding scheme – it is possible to select one of the three available MCSs or set the automatic selection of MCS
2) Bandwidth – it is possible to select one of the three available transmission bandwidths
3) Carrier frequency in the modulator and demodulator
4) Sampling frequency in the modulator and demodulator
5) Amplitude of the transmitted signal
6) Doppler frequency – deviation of the transmitter signal carrier from the receiver signal carrier
7) Transmitted signal's phase
8) Checkbox that enables/disables RRC filter
9) Checkbox that enables/disables turbocoder/turbodecoder
10) Checkbox that enables/disables scrambler/descrambler
11) Required precision of the calculations
12) Length – number of the calculations
13) Button that initiates the calculations of CCDF and PAPR
14) Results display

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2.3.6. Window: VDES simulator – transmitter/receiver

The window where data is generated, saved/read to/from text file and demodulated is presented in fig. 2.7.

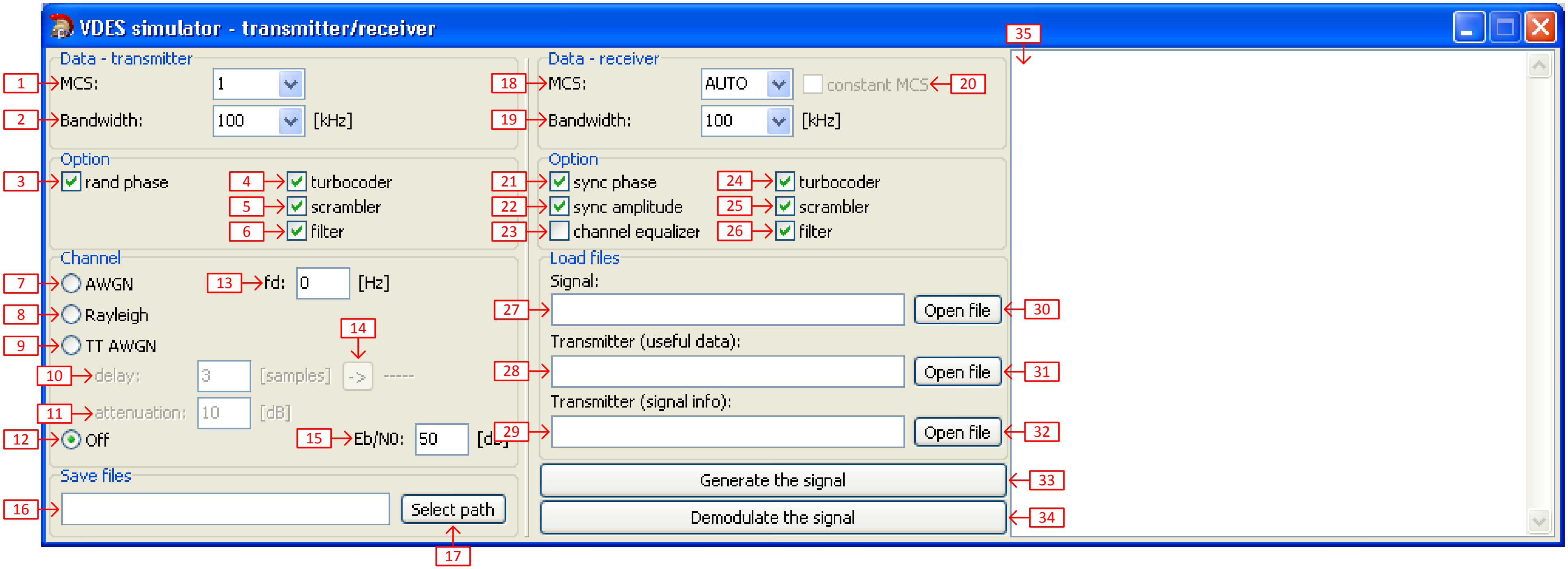

Fig. 2.7. Window: VDES simulator – transmitter/receiver

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1) Modulation and coding scheme – it is possible to select one of the three available MCSs or set the automatic selection of MCS (transmitter side)
2) Bandwidth – it is possible to select one of the three available transmission bandwidths (transmitter side)
3) Checkbox that enables/disables random drawing of the signal's phase
4) Checkbox that enables/disables turbocoder/turbodecoder
5) Checkbox that enables/disables scrambler/descrambler
6) Checkbox that enables/disables RRC filter
7) AWGN channel
8) Rayleigh channel
9) Two-path AWGN channel
10) Delay of the second path to the first path in two-path AWGN channel (expressed in the number of samples)
11) Delay of the second path to the first path in two-path AWGN channel (expressed in dB)
12) Channel with no noise and no fading – signal is transmitted without any additional distortions
13) Doppler frequency – deviation of the transmitter signal carrier from the receiver signal carrier
14) Conversion of the second path delay expressed in samples to delay expressed in time units
15) E_b/N_0 value
16) File path – location where the generated file will be saved
17) Select file path
18) Modulation and coding scheme – it is possible to select one of the three available MCSs or set the automatic selection of MCS (receiver side)
19) Bandwidth – it is possible to select one of the three available transmission bandwidths (receiver side)
20) Checkbox that disables any modifications of the MCS and ensures that MCSs at the transmitter and receiver will match
21) Synchronize signal's phase - checkbox that enables/disables phase synchronization
22) Synchronize signal's phase - checkbox that enables/disables phase synchronization
23) Checkbox that enables/disables channel equalizer
24) Checkbox that enables/disables turbocoder/turbodecoder
25) Checkbox that enables/disables scrambler/descrambler
26) Checkbox that enables/disables RRC filter
27) File path – location where the text file with the signal will be saved
28) File path – location where the text file with the useful data will be saved (to be used in the BER calculations)
29) File path – location where the text file with the signal information will be saved
30) Select the path for the file with the signal
31) Select the path for the file with the useful data
32) Select the path for the file with the signal information
33) Button that initiates signal generation
34) Button that initiates detection, synchronization, correction and demodulation of the selected signal

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35)Result of the simulation

2.3.7. Window: RRC Filter Designer

Window where RRC filter's coefficients are generated is shown in fig. 2.8.

Fig. 2.8. Window: RRC Filter Designer

1) Roll-off factor
2) Symbol's duration
3) Filter's length
4) Results of the calculations
5) Button that initiates calculations

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3. Simulation results

In the following chapter, the simulation results obtained using the software tool will be presented. Those results will demonstrate the performance of the VDE-TER physical layer in various scenarios.

3.1. Characteristics of BER and BLER for various MCSs

Below, the characteristics of bit error rate (BER) vs. Eb/N0 and block error rate (BLER) vs. Es/N0 for MCS-1, MCS-3 and MCS-5 in the AWGN channel have been presented. In each case, the results have been obtained for three channel bandwidth values: 25 kHz, 50 kHz and 100 kHz. The characteristics of bit error rate have been compared with the theoretical curves for QPSK (MCS-1), 8PSK (MCS-3) and 16QAM (MCS-5).

In order to generated the curves, the number of transmitted frames was sufficient to reliably obtain the BER equal to 10^{-6}.

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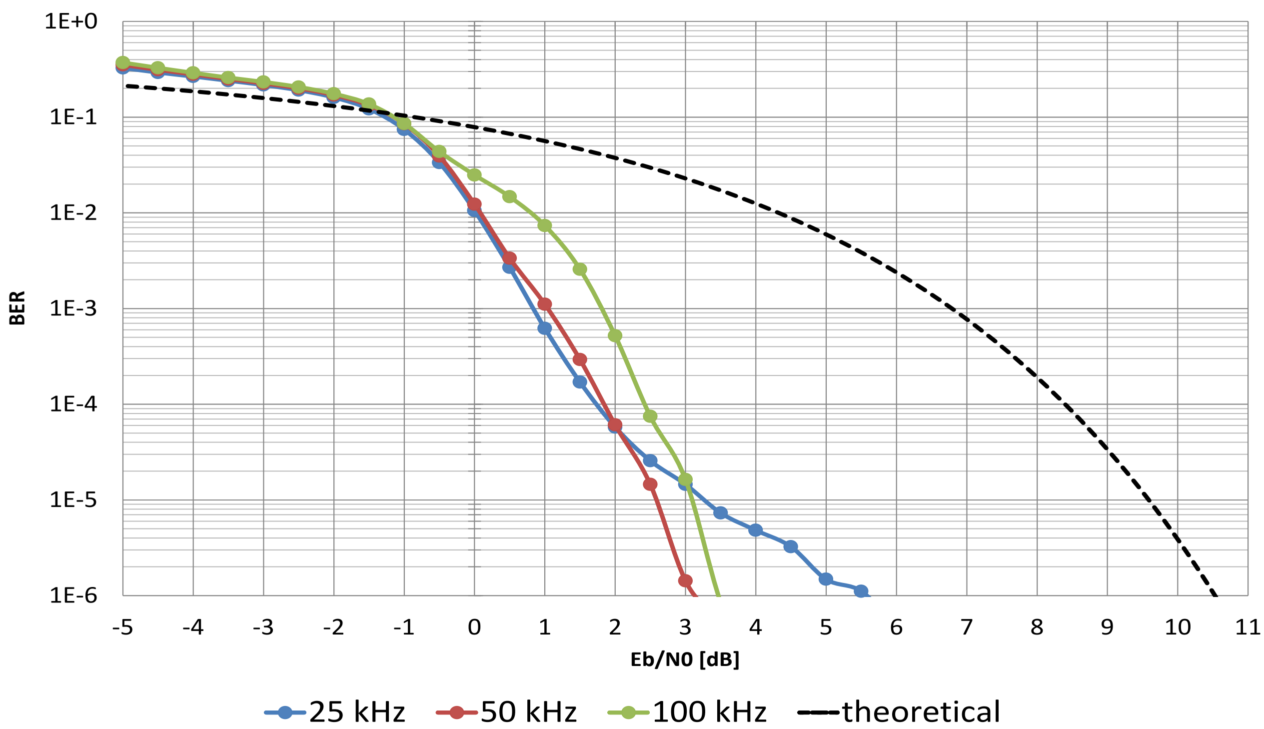

Fig. 3.1. BER vs. Eb/N0 for MCS-1 in the AWGN channel

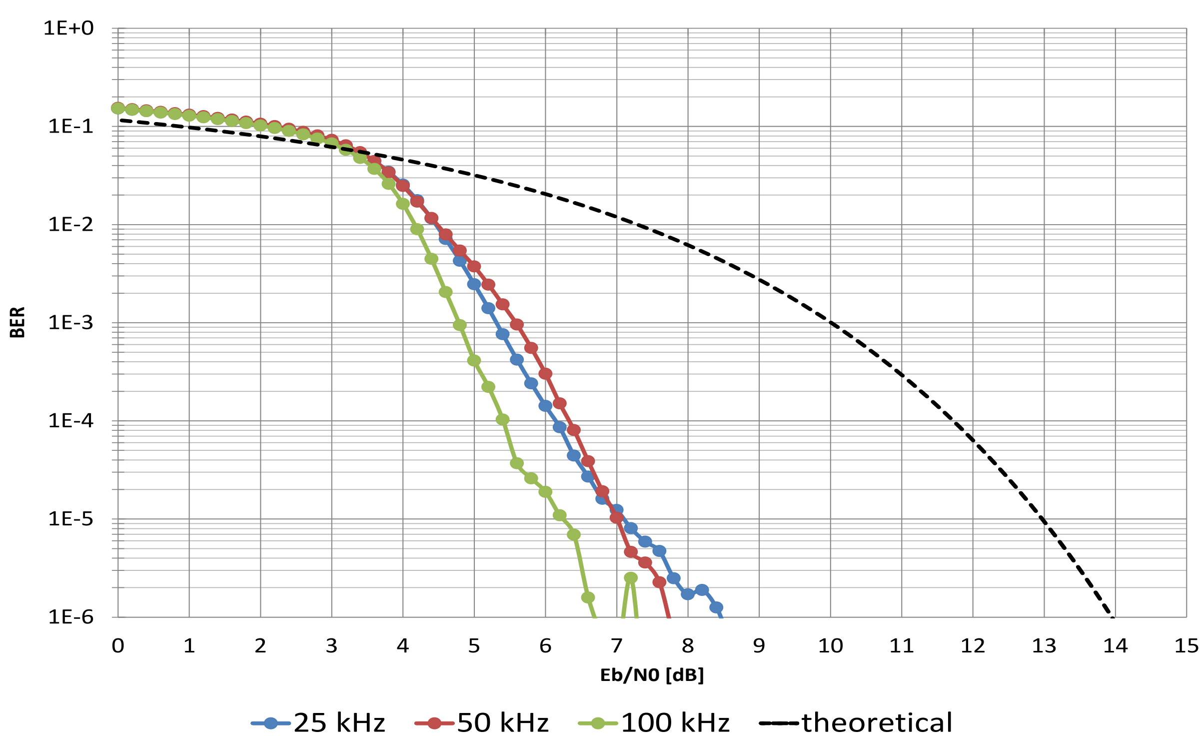

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Fig. 3.2. BER vs. Eb/N0 for MCS-3 in the AWGN channel

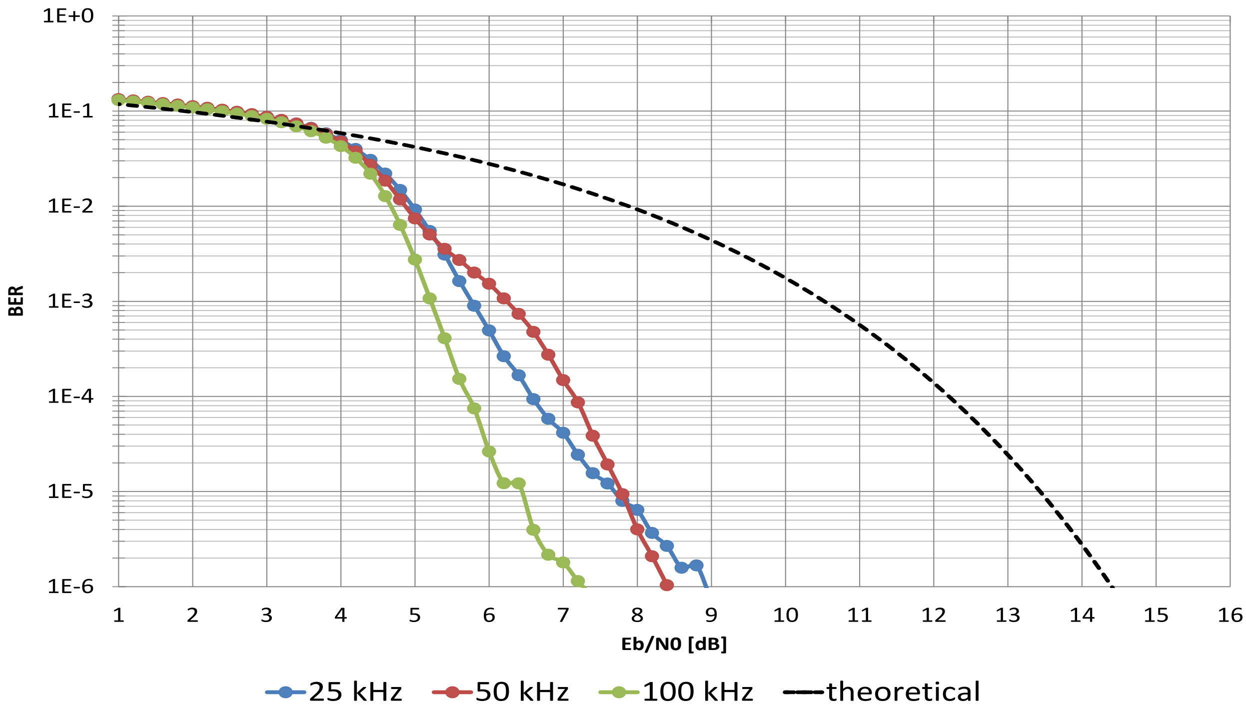

Fig. 3.3. BER vs. Eb/N0 for MCS-5 in the AWGN channel

In table 3.1, the coding gain observed for each of the analyzed MCS schemes have been gathered. The gain values have been calculated with respect to the theoretical BER curves, for the BER value of 10^{-6}.

Tab. 3.2. Coding gains for BER=10^{-6}

Modulation and coding scheme (MCS)	Coding gain [dB]		
	25 kHz	50 kHz	100 kHz
MCS-1	5	7	7,5
MCS-3	5,5	6	6
MCS-5	7,5	7,5	7,3

As we can see, generally the greatest coding gain can be achieved for the 100 kHz bandwidth, because in this case the data blocks are the longest, which improves the turbodecoding quality. On the other hand, the 100 kHz bandwidth requires highly reliable time synchronization, as one symbol comprises 4 signal samples. Consequently, any synchronization errors (e.g. a shift by one sample on the time scale) might result in transmission error. This issue is much less significant in the 50 kHz and 25 kHz bandwidths,

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because in those cases one symbol is comprised of 8 and 16 samples, respectively.

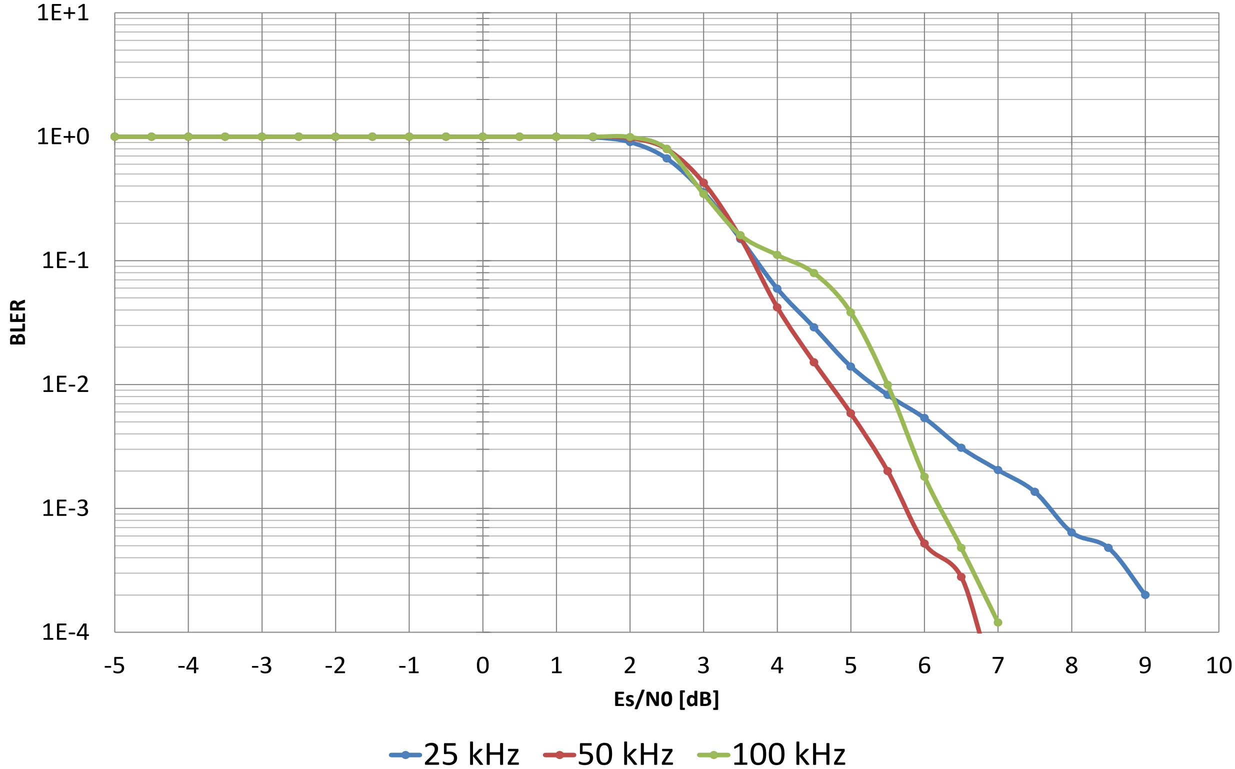

Fig. 3.4. BLER vs. Es/N0 for MCS-1 in the AWGN channel

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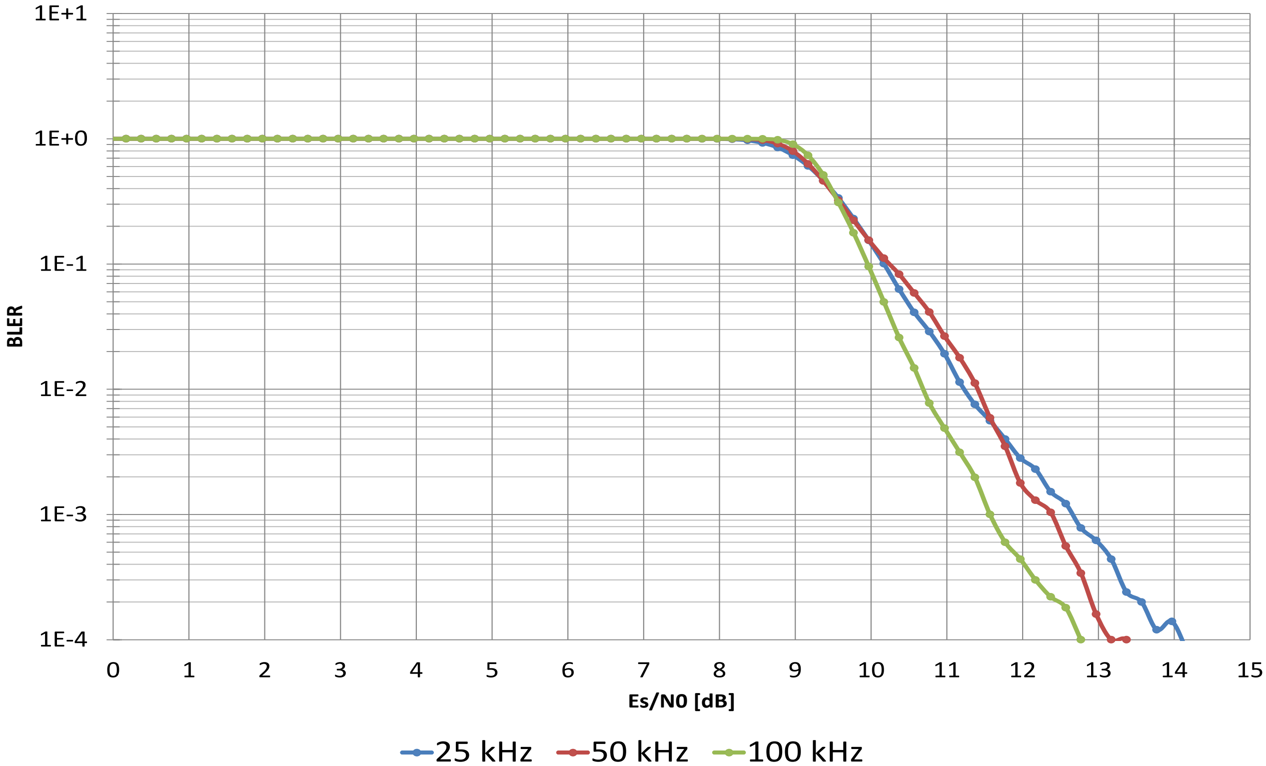

Fig. 3.5. BLER vs. Es/N0 for MCS-3 in the AWGN channel

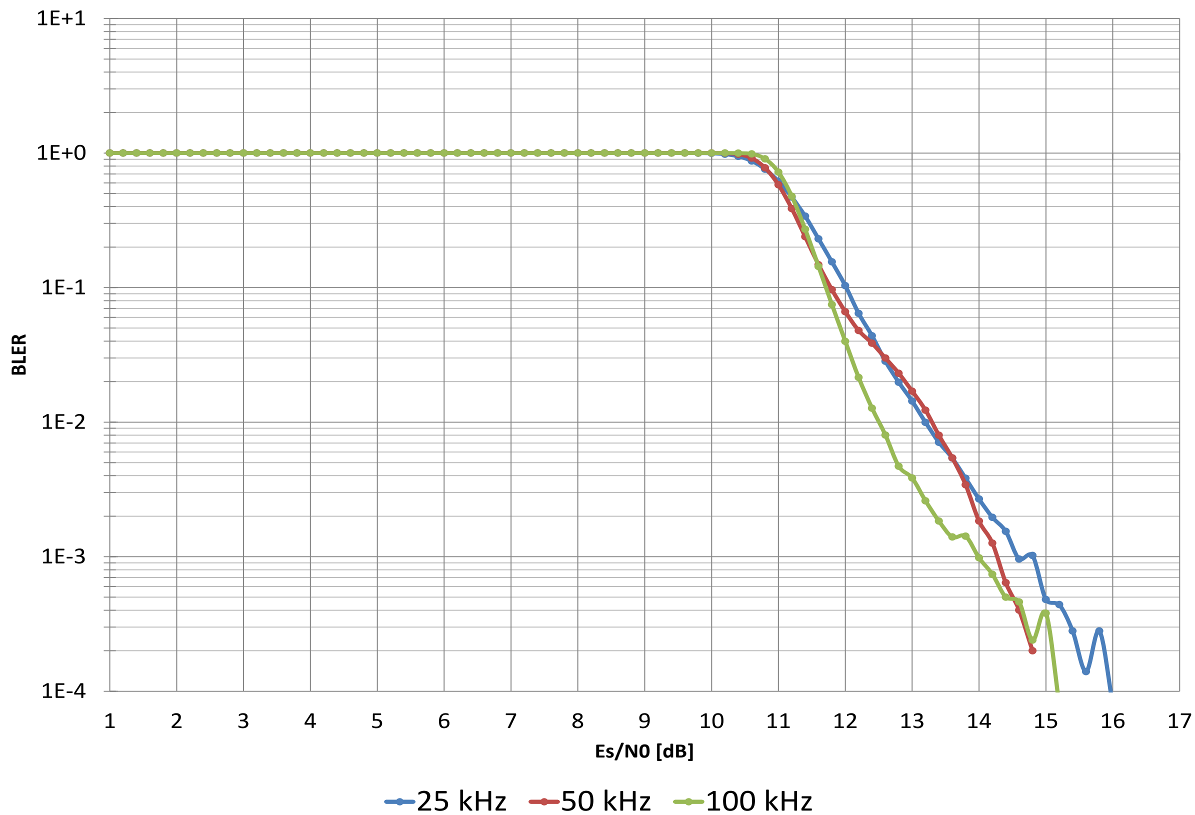

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Fig. 3.6. BLER vs. Es/N0 for MCS-5 in the AWGN channel

The block error rate characteristics indicate the Es/N0 values at which at least one block of data can be transmitted correctly. As we can see in figs. 3.4 – 3.6, in case of the MCS-1, if Es/N0 is less than 2.5 dB, no block can be send successfully. In case of MCS-3 and MCS-5, the respective Es/N0 threshold values are 9 dB and 11 dB.

3.2. The influence of synchronization error on transmission quality

In figs. 3.7 and 3.8, the characteristics of three parameters have been gathered as a function of Es/N0:

- Time synchronization error rate (denoted as 'sync time error' in the figures),
- Error of the 'signal info' field reception (denoted as signal info error) – the 'signal info' field carries the information about the current MCS scheme, so the erroneous reception of this field might result in incorrect signal demodulation,
- Block error rate (BLER).

The curves have been obtained for MCS-1 and MCS-3.

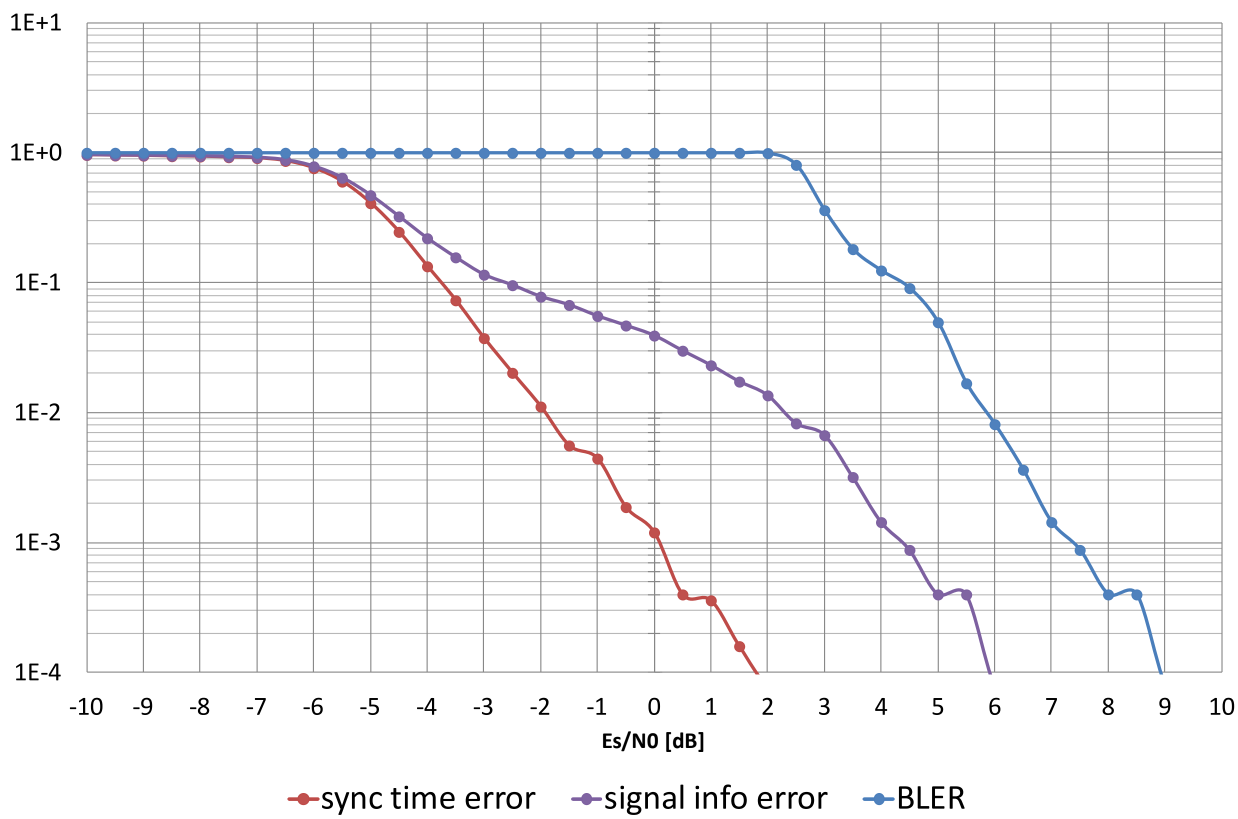

Fig. 3.7. Synchronization error rate for MCS-1

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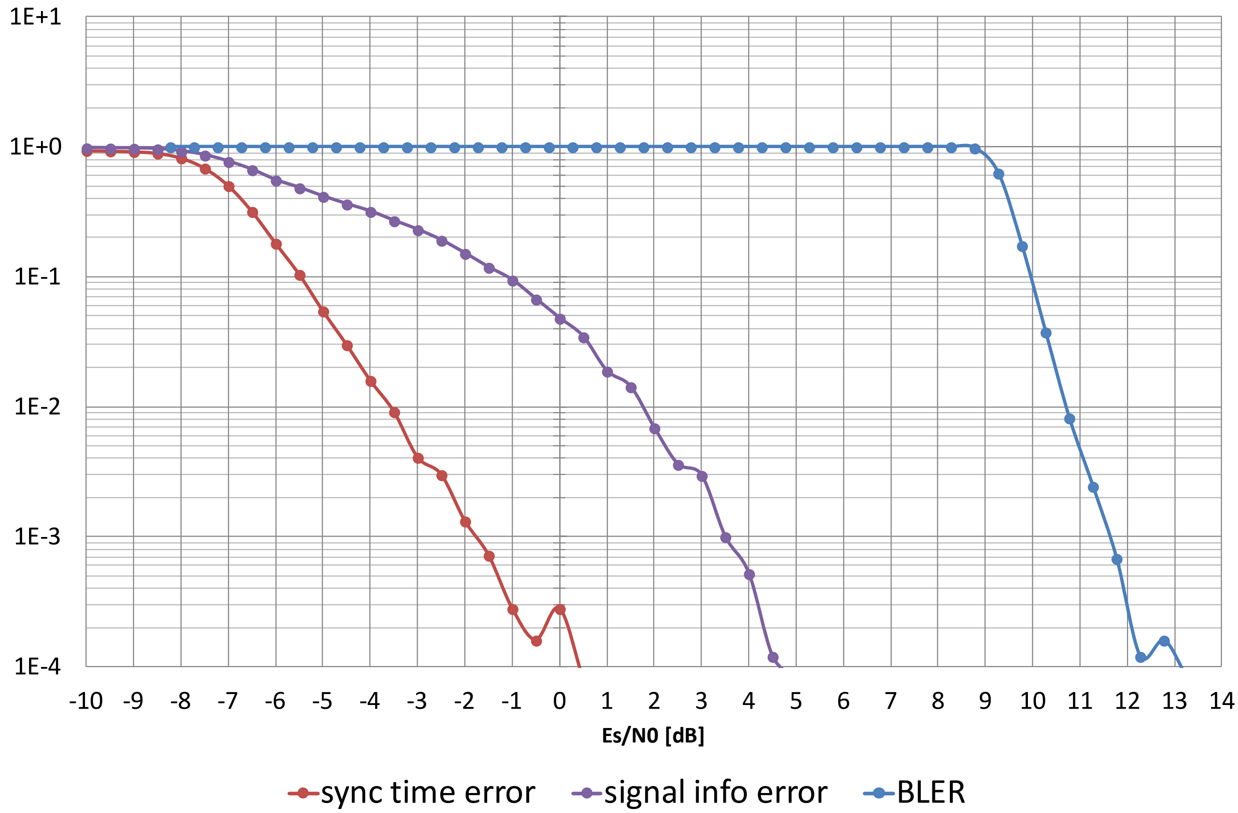

Fig. 3.8. Synchronization error rate for MCS-3

The above figures illustrate how synchronization error and errors of 'signal info' field reception affect transmission quality.

In the perfect scenario, there shouldn't be any sync and signal info errors when Es/N0 is high enough to send at least one block correctly (i.e. when BLER is less than 1). As we determined in the previous subchapter, this threshold value of Es/N0 is approx. 2.5 dB (for MCS-1) and 9 dB (for MCS-3).

In case of the MCS-1 (fig. 3.7), this perfect scenario is not achieved, but the results are still satisfactory. As we can observe, at Es/N0 = 2.5 dB, the signal info error is less than 10^{-2} and the sync error is less than 10^{-4}. Usually, it assumed the transmission is correct when BLER is less than 10^{-1}, and this condition is satisfied in the discussed figure.

The situation gets significantly better for the MCS-3. In this case, at Es/N0=9 dB, the signal info and sync errors are very low – actually close to zero (i.e. close to the ideal value). It is obvious that for MCS-5 even better results could be expected.

3.3. The influence of channel information delay on the achievable bit rates

Figures 3.9 – 3.11 illustrate the influence of the information about the channel state on the

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transmission rate. VDES system utilizes adaptive modulation, so the timely information about the current state of the radio channel is of paramount importance and lack of such information significantly affects the efficiency and performance of the system.

The characteristics below represent the bit rate vs. Eb/N0 in the AWGN channel and have been obtained for three bandwidth values: 25 kHz, 50 kHz and 100 kHz. Two cases of channel information delay have been considered: no delay (red bars) and 3 frames delay (blue bars).

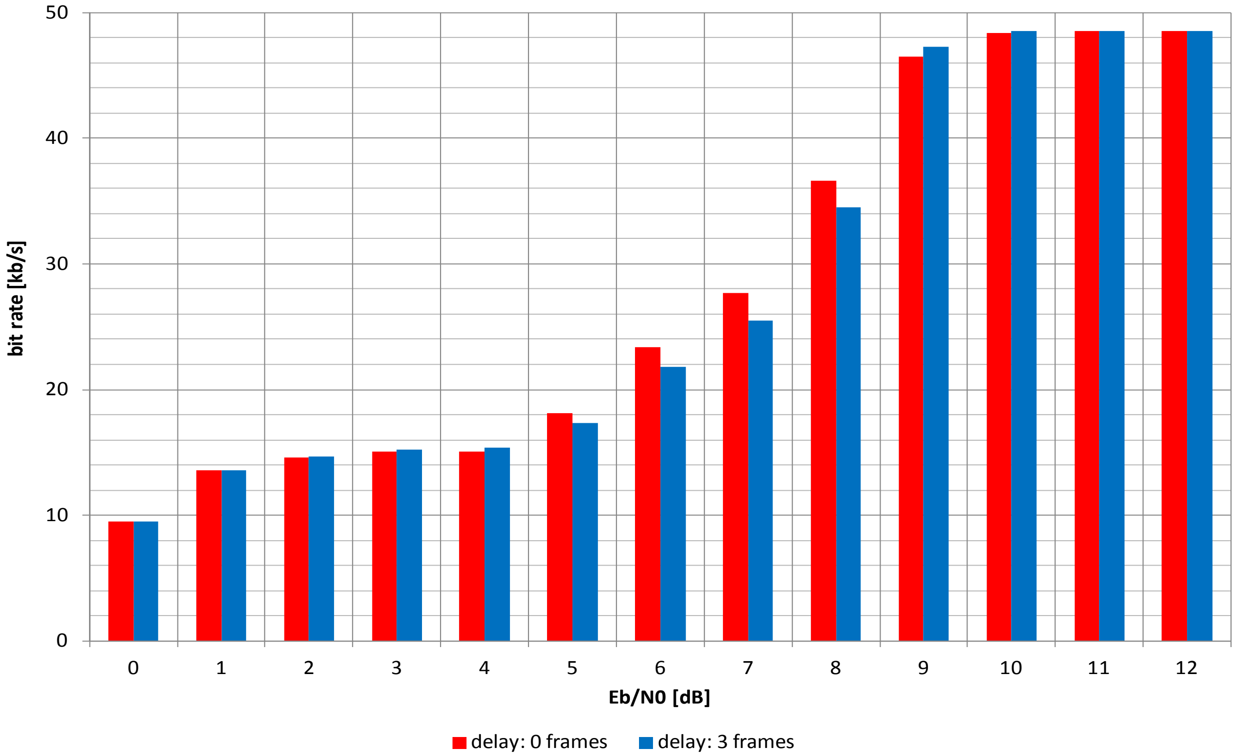

Fig. 3.9. Bit rate vs. Eb/N0 for 25 kHz AWGN channel

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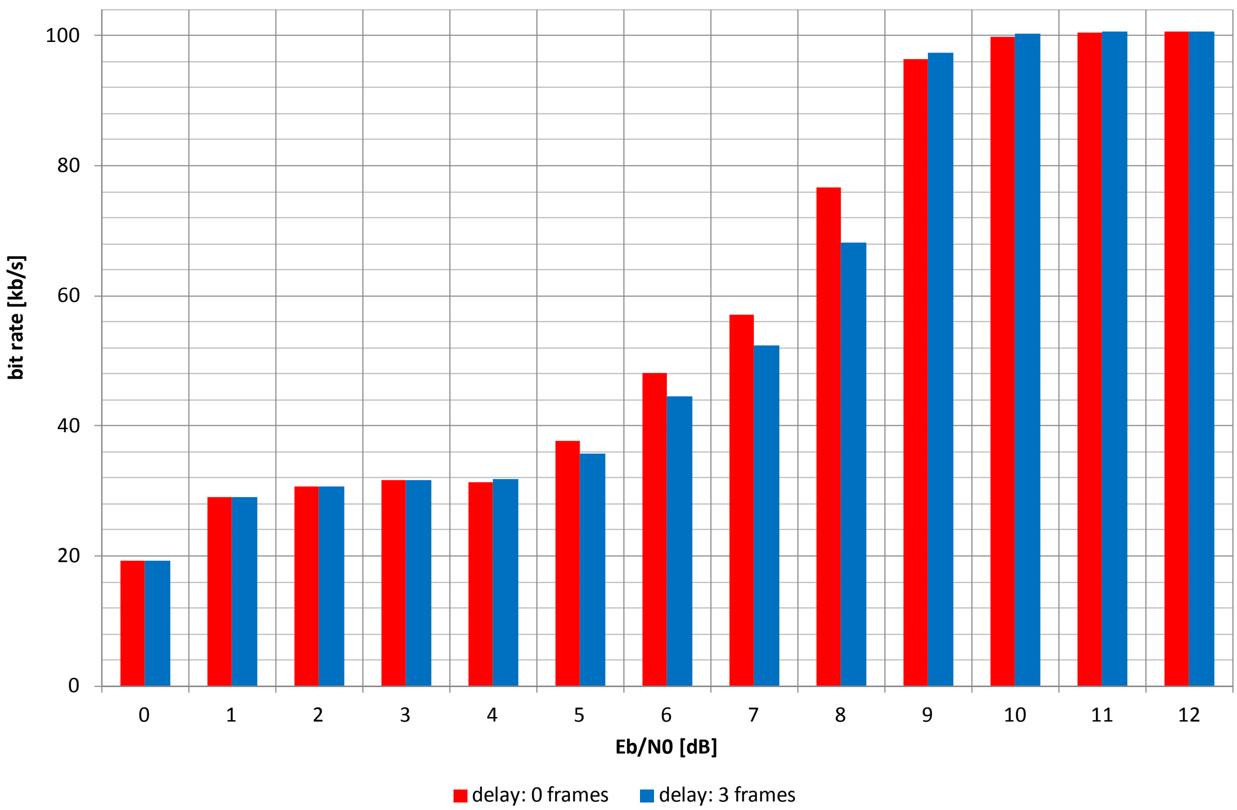

Fig. 3.10. Bit rate vs. Eb/N0 for 50 kHz AWGN channel

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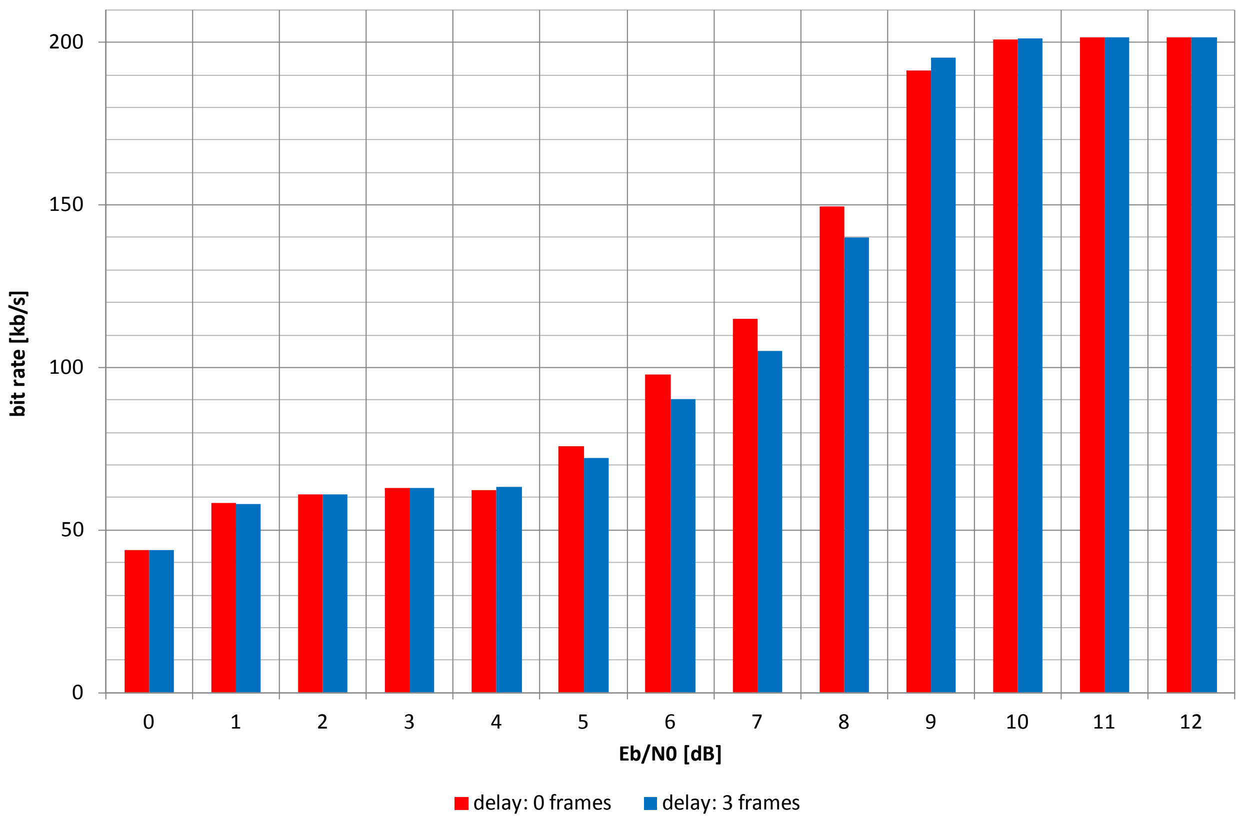

Fig. 3.11. Bit rate vs. Eb/N0 for 100 kHz AWGN channel

Obviously, as the Eb/N0 increases, so does the bit rate, which is mainly due to the adaptive modulation and coding algorithms. The better channel quality, the higher the MCS – and consequently: the higher the bit rate.

At the same, we can observe the channel state info delay negatively affects the bit rate for Eb/N0 from 5 dB to 9 dB. For other values of Eb/N0, the resulting bit rate values are almost identical and do not seen to be affected by the discussed delay. The above observation is true for every analyzed bandwidth value.

Those results show that in future stages of VDES development, a new MCS scheme could be introduced to increase achievable bit rates.

3.4. VDES signal spectrum

In the following subchapter, the calculated spectra of the VDES signal will be presented. In most cases, the simulations have been performed for the two-tap AWGN channel, whose characteristic is shown in fig. 3.12.

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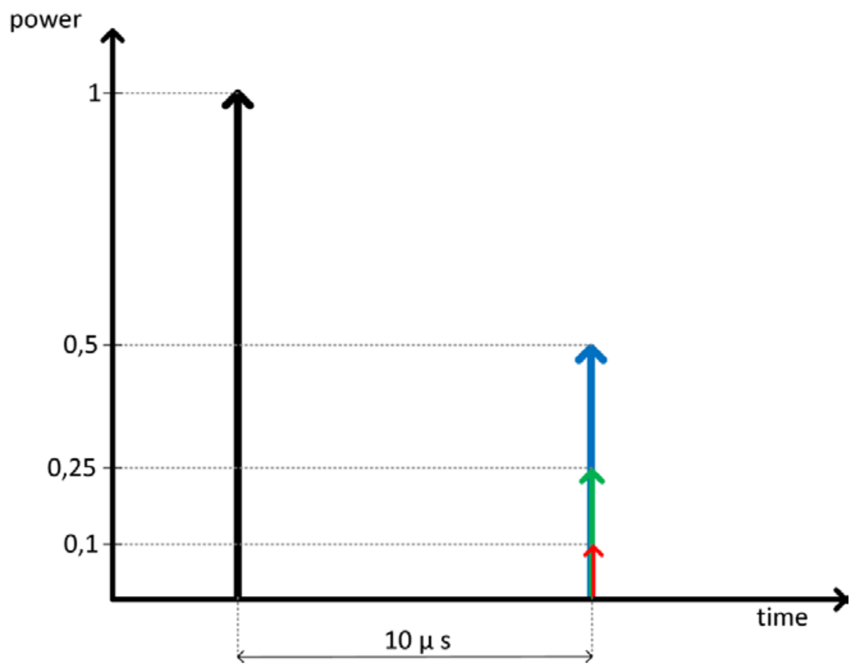

Fig. 3.12. Two-tap AWGN channel model

The model parameters:

- Delay between taps: approx. 10μs
- Attenuation of the second tap: 3 dB, 6 dB or 10 dB (for different cases and environments)
- Doppler shift: up to 5 kHz for 160 MHz

Figure 3.13 illustrates the VDES signal spectrum when no radio channel has been used (bandwidth: 100 kHz), whereas figures 3.14 – 3.16 represent the case of a two-tap channel with a second tap attenuation of 10 dB, 6 dB and 3 dB, respectively (bandwidth in all cases: 100 kHz).

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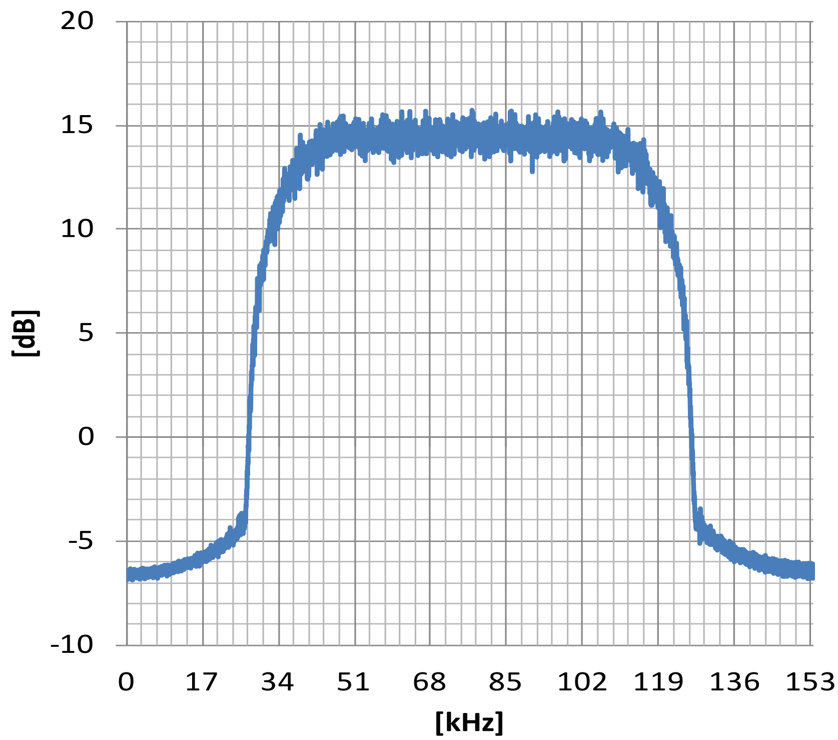

Fig. 3.13. VDES spectrum (no channel, bandwidth: 100 kHz)

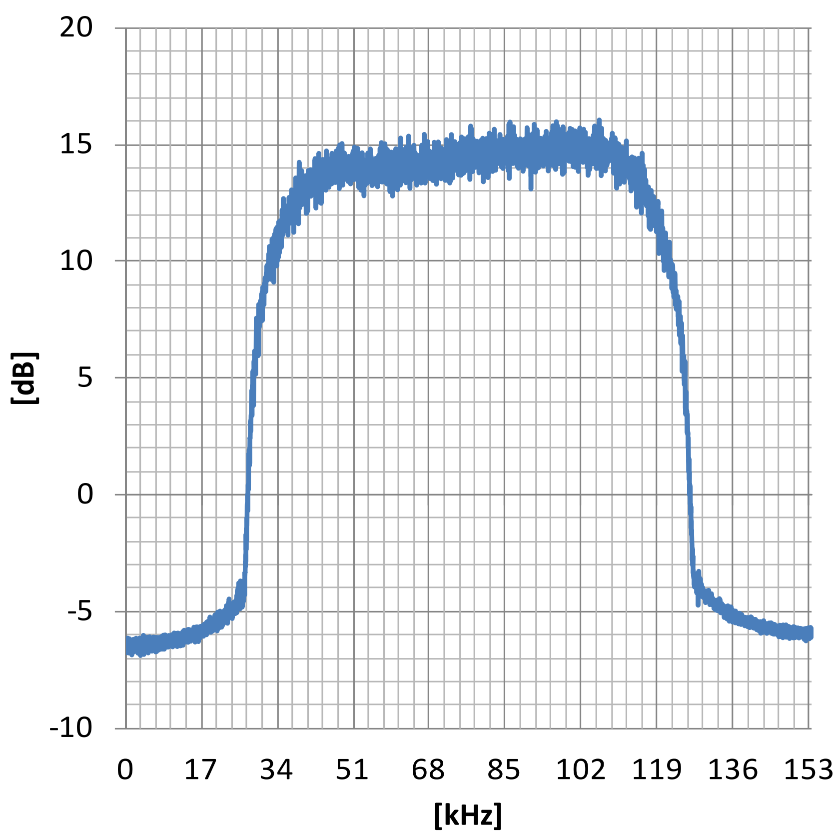

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Fig. 3.14. VDES spectrum (two-tap AWGN channel, second tap attenuation: 10 dB, bandwidth: 100 kHz)

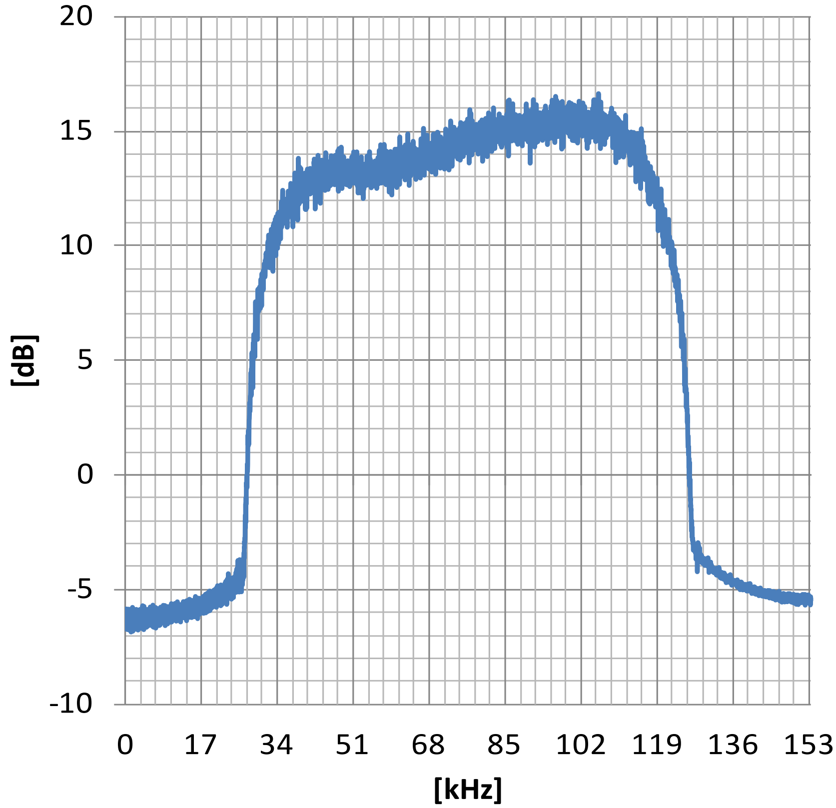

Fig. 3.15. VDES spectrum (two-tap AWGN channel, second tap attenuation: 6 dB, bandwidth: 100 kHz)

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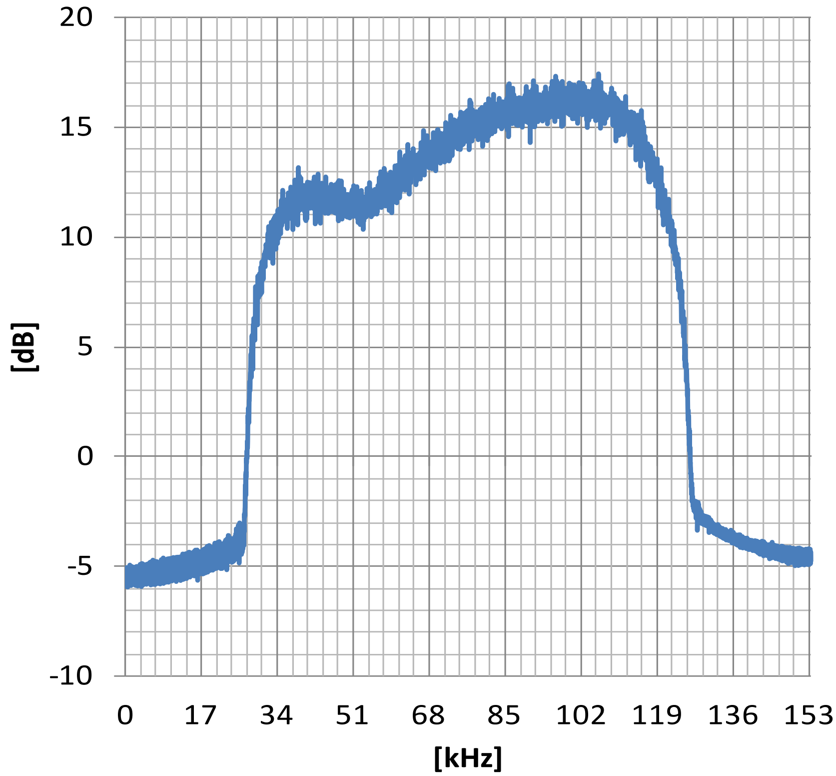

Fig. 3.16. VDES spectrum (two-tap AWGN channel, second tap attenuation: 3 dB, bandwidth: 100 kHz)

The following figures 3.17 - 3.19 compare the spectra achieved for the two-tap AWGN channel (second tap attenuation: 3 dB) for three different channel bandwidths: 25, 50 and 100 kHz.

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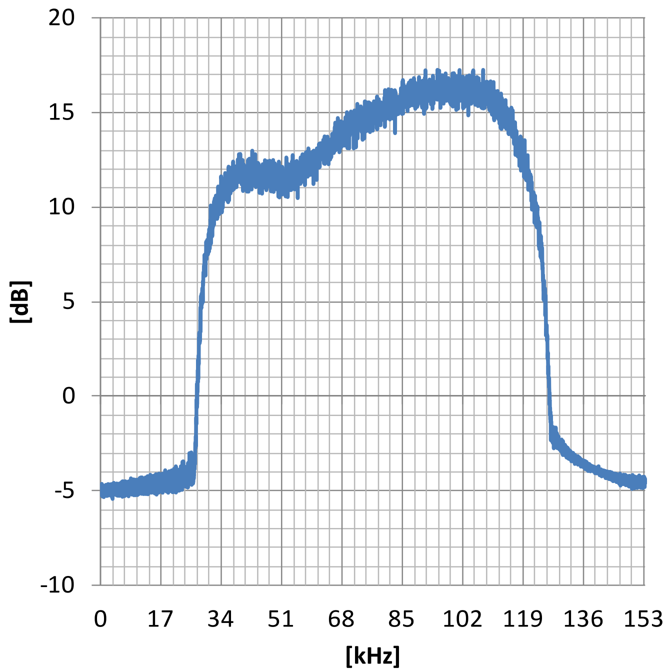

Fig. 3.17. VDES spectrum (two-tap AWGN channel, second tap attenuation: 3 dB, bandwidth: 100 kHz)

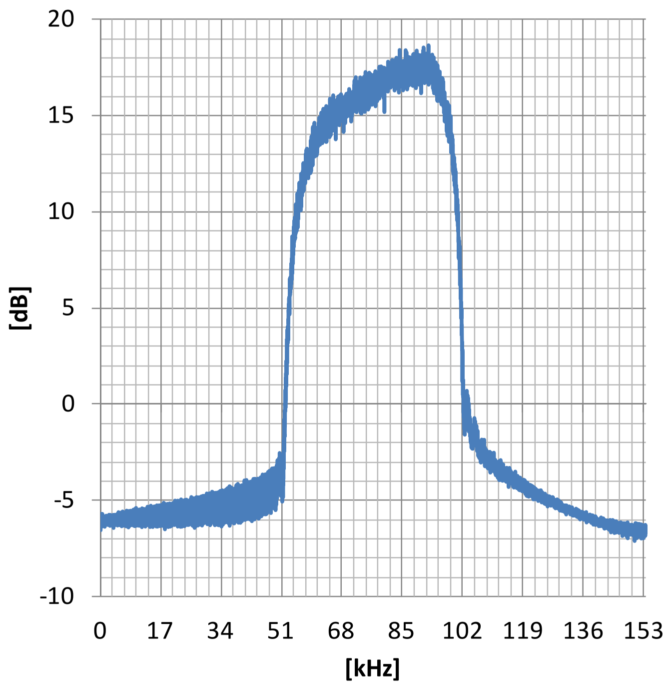

Fig. 3.18. VDES spectrum (two-tap AWGN channel, second tap attenuation: 3 dB, bandwidth: 50 kHz)

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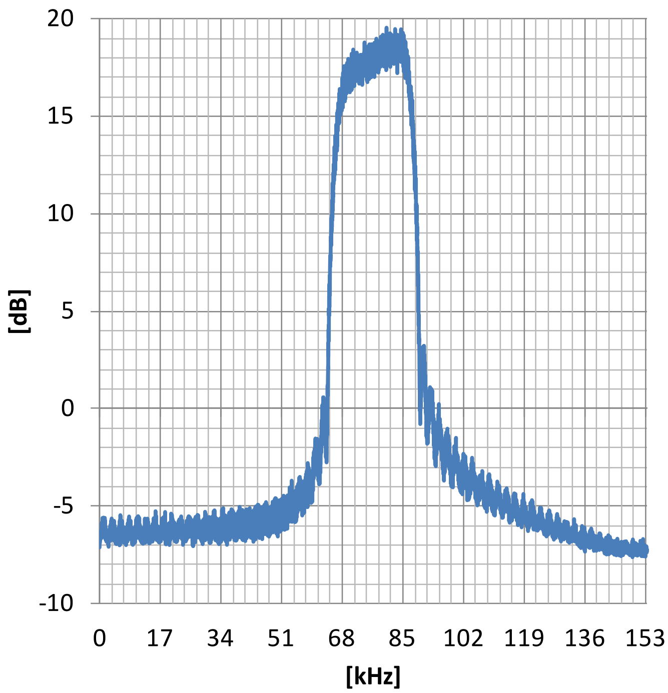

Fig. 3.19. VDES spectrum (two-tap channel, second tap attenuation: 3 dB, bandwidth: 25 kHz)

Figures 3.20-3.22 compare the spectra obtained for a two-tap AWGN channel (second-tap attenuation: 3 dB). Fig. 3.20 shows the spectrum of the transmitted signal, fig. 3.21 – the spectrum of the received signal and fig. 3.22 – the spectrum of received signal with channel equalizer.

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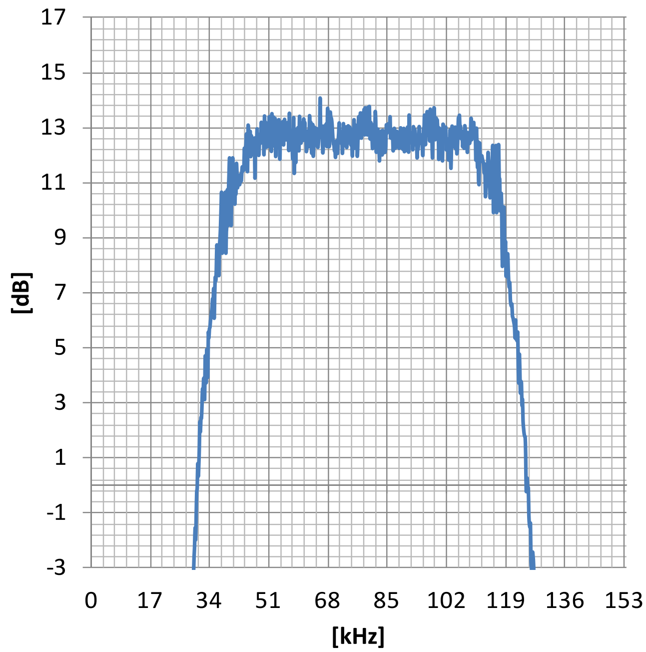

Fig. 3.20. VDES spectrum – transmitted signal (two-tap channel, second tap attenuation: 3 dB)

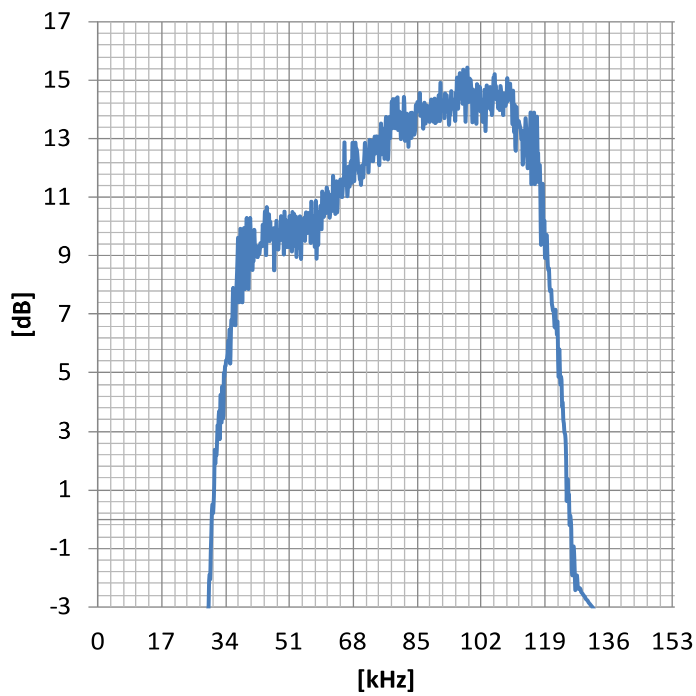

Fig. 3.21. VDES spectrum – received signal (two-tap channel, second tap attenuation: 3 dB)

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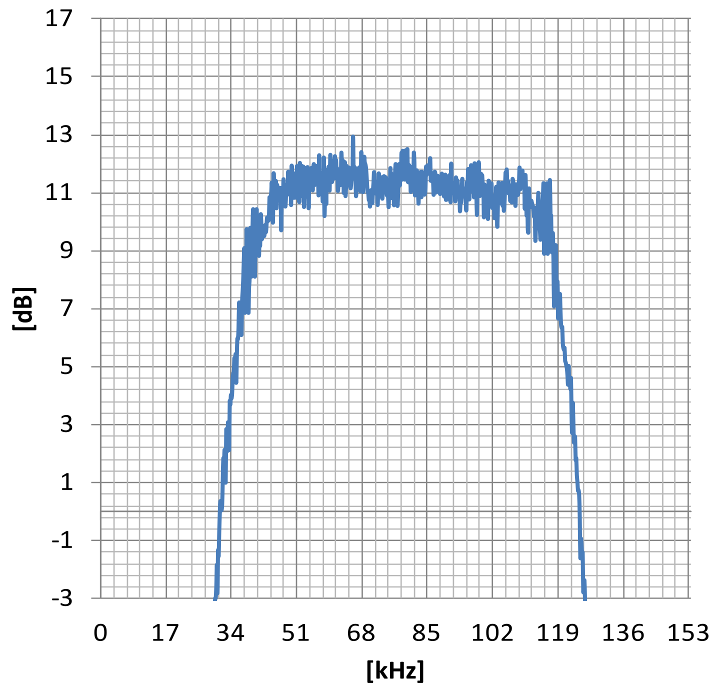

Fig. 3.22. VDES spectrum – received signal with an equalizer (two-tap channel, second tap attenuation: 3 dB)

The figures included in this section indicate the channel affects the radio signal differently, depending on the channel bandwidth. Generally, for 25 and 50 kHz the fadings are flat or almost flat, whereas in the 100 kHz bandwidth, the fadings are frequency selective. Consequently, the channel equalizer is mostly required for 100 kHz channels.

3.5. Constellations for various MCSs

In the following subchapter, the modulations constellations, associated with different MCS schemes, will be presented. In each case, the constellation will first be shown for the AWGN channel, then for two-tap AWGN channel without equalizer and finally for two-tap AWGN channel with equalizer.

In figs. 3.23 – 3.25, the mentioned characteristics will be shown for MCS-1 (QPSK modulation).

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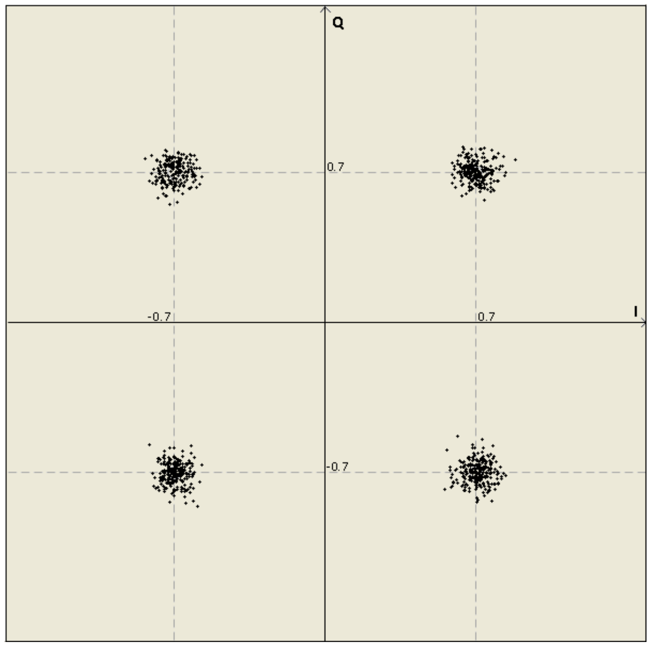

Fig. 3.23. MCS-1 signal constellation (AWGN channel without equalizer)

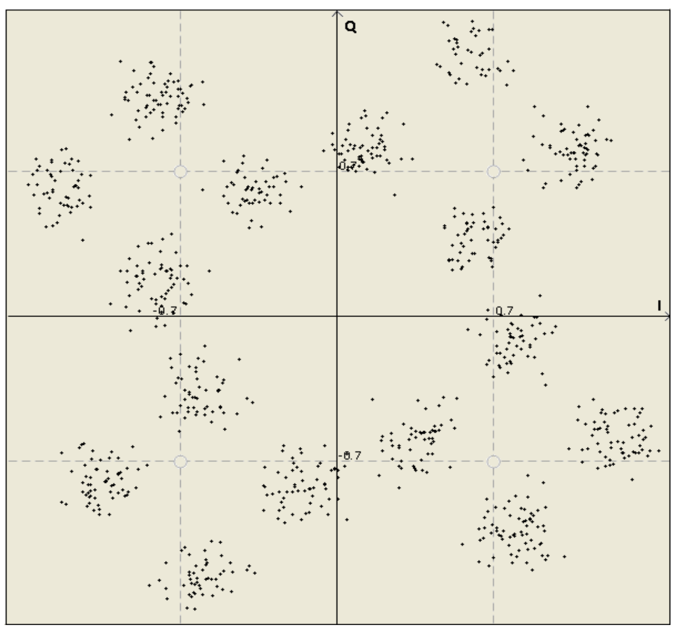

Fig. 3.24. MCS-1 signal constellation (two-tap AWGN channel without equalizer)

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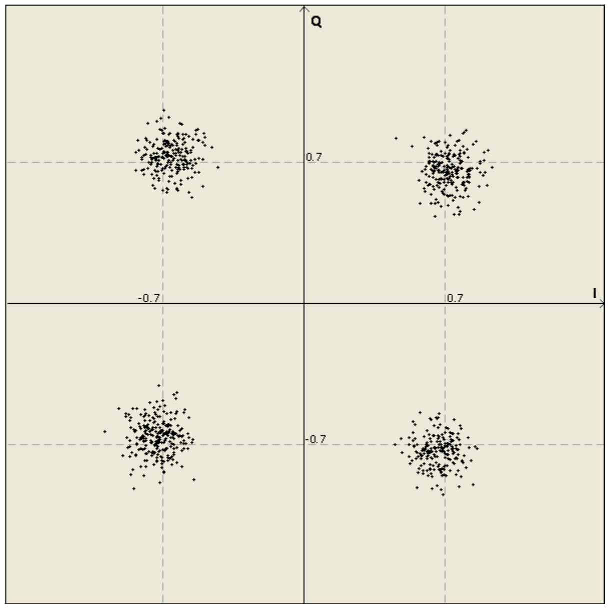

Fig. 3.25. MCS-1 signal constellation (two-tap AWGN channel with equalizer)

In figs. 3.26 – 3.28, the constellation characteristics will be shown for MCS-3 (8PSK modulation).

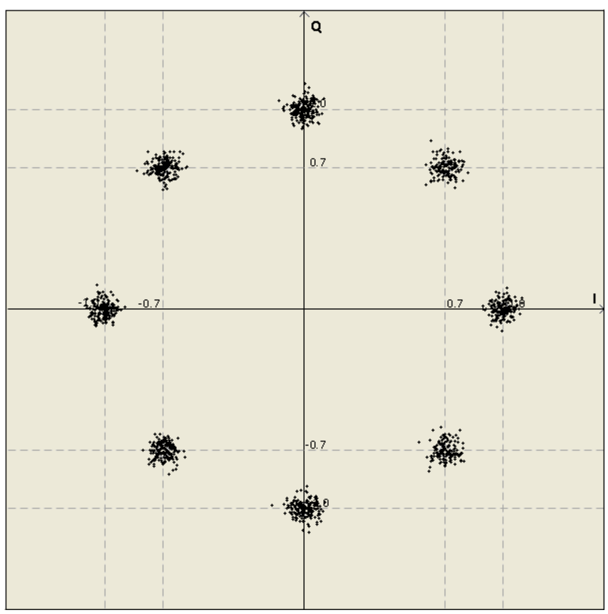

Fig. 3.26. MCS-3 signal constellation (AWGN channel without equalizer)

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Fig. 3.27. MCS-3 signal constellation (two-tap AWGN channel without equalizer)

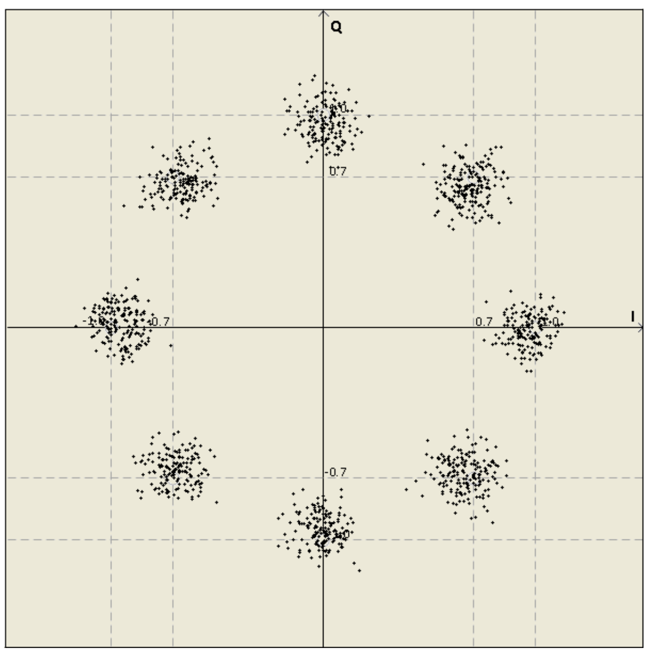

Fig. 3.28. MCS-3 signal constellation (two-tap AWGN channel with equalizer)

In figs. 3.29 – 3.31, the constellation characteristics will be shown for MCS-5 (16QAM modulation).

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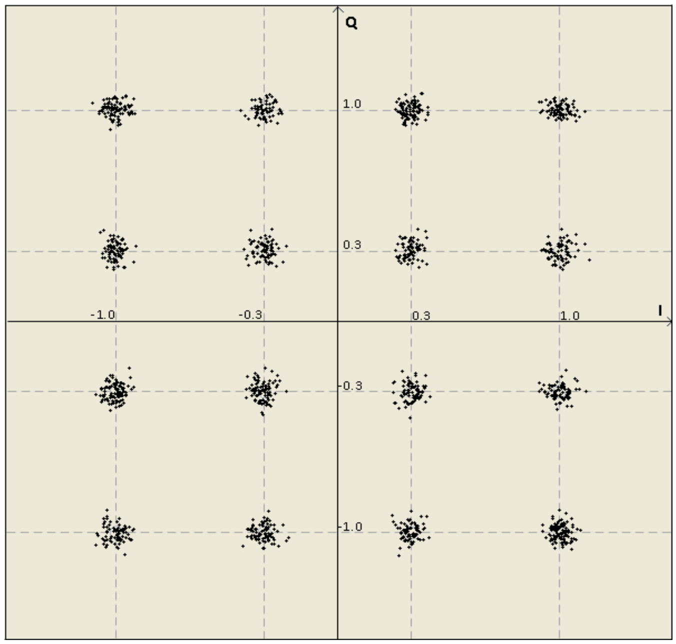

Fig. 3.29. MCS-5 signal constellation (AWGN channel without equalizer)

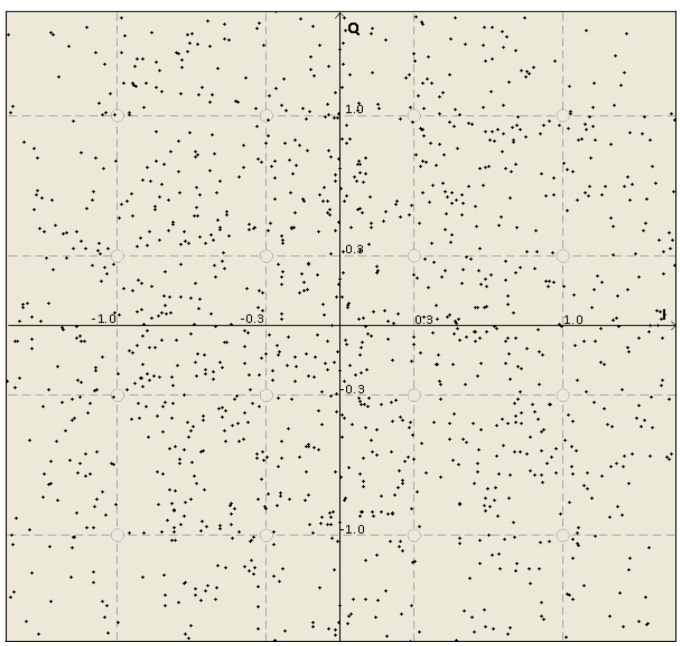

Fig. 3.30. MCS-5 signal constellation (two-tap AWGN channel without equalizer)

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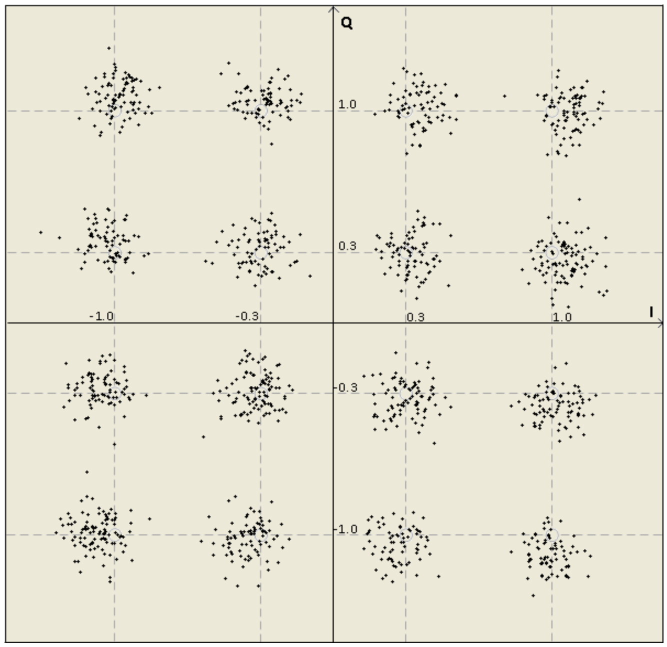

Fig. 3.31. MCS-5 signal constellation (two-tap AWGN channel with equalizer)

The figures included in this section mainly demonstrate the efficiency of the zero-forcing channel equalizer to be used in the VDES system. If the equalization is not used, the fading and intersymbol interference (ISI) strongly influence the signal and make the correct transmission almost impossible (see figs. 3.24, 3.27, 3.30). Obviously, this issue gets more serious when higher-order modulations are utilized (e.g. MCS-5). On the other hand, the signal constellations obtained when the equalizer was actually used show that the influence of ISI was substantially reduced. At the same time, we might also observe that using the equalizer will result in noise amplification; it is the drawback of this solution, but it is also fully expected and consistent with the general theory of the zero-forcing equalizer (see par. 1.2.7).

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