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Radio coverage provision of coastal marine zone using wireless broadband optical channel to support intensive navigation

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Abstract. **The model of a wireless broadband optical channel designed for communication between the coastal subsystem and an air repeater that provides coverage of the coastal sea area for the organization of intensive navigation, including the use of unmanned vessels is presented. It is shown that direct coast-to-ship data transmission using Wi-Fi and 4G/LTE technologies has a number of disadvantages for bays with complex coastal terrain. The use of a wireless optical channel in the "point-to-point" format between the coastal subsystem and the air transmitter makes it possible to provide high-quality radio coverage of the sea surface and provide information-intensive channels to ship systems. The results of modeling the wireless optical channel implemented using FSO (Free Space Optic) technology are presented. To increase the efficiency of using the spectrum of the transmitted data stream and the protection ratio of the wireless channel, 16QAM and OFDM are used.**

Keywords: **e-Navigation, wireless communication, optical communication, Free Space Optic technology**

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Contents

1. INTRODUCTION

One of the key trends in the development of commercial shipping nowadays is the use of such information technologies as e-Navigation and unmanned shipping, which have become key initiatives of the International Maritime Organization (IMO). According to the IMO's definition, e-Navigation is the harmonized collection, integration, exchange, presentation and analysis of marine information on board and ashore by electronic means to enhance berth to berth navigation and related services for safety and security at sea and protection of the marine environment [1].

e-Navigation infrastructure includes the following technical aspects [2]:

- communication and data exchange technologies, among which are terrestrial (3G/4G, WiMax, AIS) and satellite (Iridium, VSAT);
- ship-to-shore data transfer;
- transfer of information about the ship's routes from the ship to shore and back;
- transfer of navigational information from the coastal tracking station to the ship;
- hydrographic, hydrological and meteorological information or transfer from shore to ship;
- etc.

Also, Wi-Fi technology is promising for organizing broadband radio communication access when controlling ship traffic [3]. [4] presents an analysis of its use at a frequency of 2.4 GHz using UDP protocol as part of a stand-alone maritime meshed communication network. In [5] it is proposed to use long-range Wi-Fi technology in a marine wireless communication system for monitoring ships.

This article discusses the ways to organize effective coverage to ensure broadband radio access along a coastal area with a high density of ship traffic using Wi-Fi and 4G/LTE systems.

2. ANALYSIS OF DIRECT RADIOFREQUENCE COVERAGE ZONE ALONG SHIP-TO-SHORE LINE

First, we will analyze the case when it is necessary to set up broadband radio access within an extended bay with curved coastal terrain.

Selection of physical parameters of the environment was performed using Recommendation ITU-R P.527-4 "Electrical characteristics of the earth's surface" [6]. Physical environmental parameters were taken into account for seawater, soil and possible precipitation (rain, snow, fog, etc.). In accordance with Recommendations ITU-R P.527-4 [6], effective values of soil electrical characteristics are determined by the type of soil, its moisture, temperature, general geological structure and the frequency of incident electromagnetic radiation. Physical parameters of sea water and soil are accounted for in the calculation through determining their conductivity and dielectric constant, as well as their temperature dependence. Sea water parameters were selected from the graphs shown in **Fig. 1** for +20°C temperature.

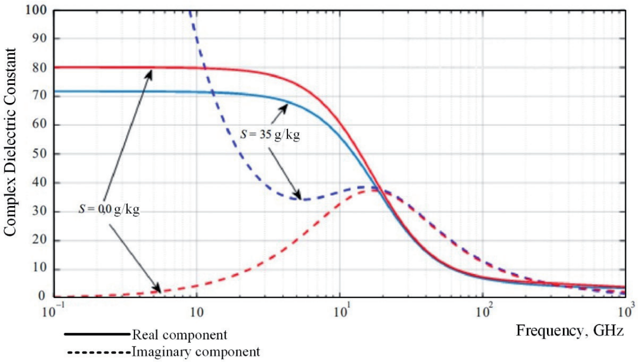


Fig. 1. *Relationship between complex dielectric constant of pure water and sea water and frequency at T = +20°C.*

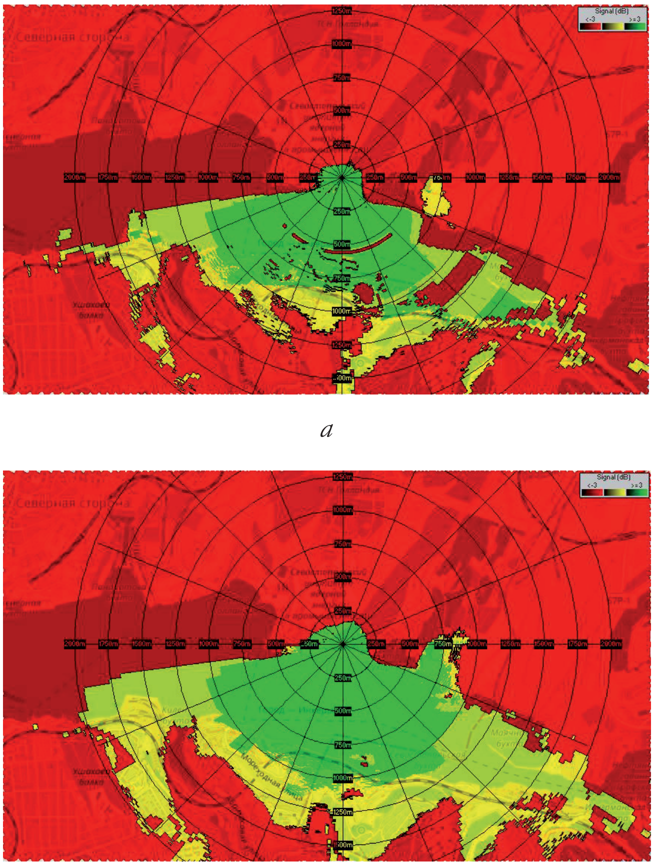
Fig. 2. *Sevastopol bay with coastal radio station.*

Weather conditions were taken into account as per recommendations given in [6], according to which the radio wave absorption coefficients within 2.4-2.5 GHz range do not exceed 0.1 dB/km in rain and fog of varying intensity, and 0.05 dB/km in oxygen and water vapors.

For simulation purposes, we used Sevastopol Bay (**Fig. 2**) featuring complex coastal terrain, with coastal radio system (CRS) installed as shown.

Initial data for simulation:

- coast height above sea level: 33 m;
- frequency range: 2.4-2.45 GHz;
- transmitter power: 23 dBm;
- receiver sensitivity: –65 dBm;
- radiation patterns (RP) of coastal and ship radio system antennas: circular in the
- H-plane, linear vertical polarization;
- antenna gain: 15 dBi for coastal radio system, 5 dBi for ship radio system.



a

b

Fig. 3. *Simulation results for Wi-Fi coverage with a ship antenna located 2 m (a) and 10 m (b) above the sea level.*

Fig. 3 shows simulation results for Wi-Fi coverage area when the coastal antenna is elevated by 1 m above the underlying surface and when the ship antenna is located 2 m (Fig. 3*a*) and 10 m (Fig. 3*b*) above the sea level. Green indicates reliable reception area, yellow indicates uncertain reception, and red indicates no radio signal.

In both cases considered, there are some areas on the sea surface where radio communication is missing. At the same time, as the height of the coastal antenna above the underlying surface increases, the number and extent of these zero-signal areas also increase.

For comparison purposes, we also simulated the coverage area of a 4G/LTE system with the following characteristics that differ from the previous case:

- frequency range: 1.92 — 2.17 GHz, Band 1, used in Russia;
- radio channel width: 5 — 20 MHz.

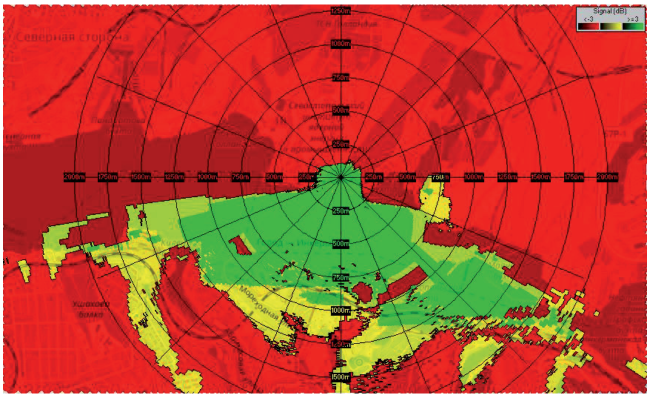


Fig. 4. *Simulation results for 4G/LTE coverage with a ship antenna located 2 m above the sea level.*

Fig. 4 shows simulation results for 4G/LTE coverage area when the coastal antenna is elevated by 1 m above the underlying surface and ship antenna is located 2 m above the sea level.

3. WIRELESS OPTICAL COMMUNICATION CHANNEL ARRANGEMENT ALONG SHORE-TO-REPEATER LINE

For a drastic and highly effective solution to the fading problem while maintaining the possibility of providing a data-intensive communication channel to a large number of moving marine objects, we have considered an option of using a basic repeater lifted into the air above the sea using an unmanned aerial vehicle (UAV) or an airship. At the same time, a network of repeaters can be arranged over the sea to solve various telecommunications problems. The most intensive communication channel will be the one along the base repeater-to-shore line. Increasing the data capacity of this channel is possible through the use of a wireless optical communication system.

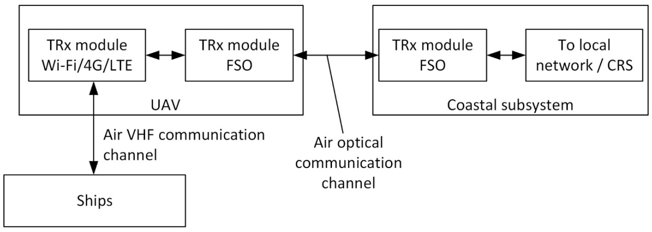


Fig. 5. *Arrangement of a remote broadband communication channel using FSO along the "Shore-to-UAV" line.*

Land-based wireless optical point-to-point communication systems (FSO, Free Space Optic) [7] operate at infrared, ultraviolet and ultraviolet frequencies of the optical spectrum. FSO systems use laser technology to transmit signals. **Fig. 5** presents the proposed arrangement of a remote broadband communication channel using FSO along the "Shore-to-UAV" line.

Fig. 6 shows the basic block diagram of an FSO system. Optical beamforming makes it possible to arrange long-distance communications using FSO systems. Initially, the source information is encoded. Optical source used in FSO systems must provide relatively high optical power over a wide range of operating temperatures. Important parameters of an optical transmitter in FSO systems are the size, power and quality of the beam, which determine the laser intensity and the minimum divergence obtained from the system [8]. Front part of the receiver contains optical filters with a lens for collecting and focusing the received beam onto a

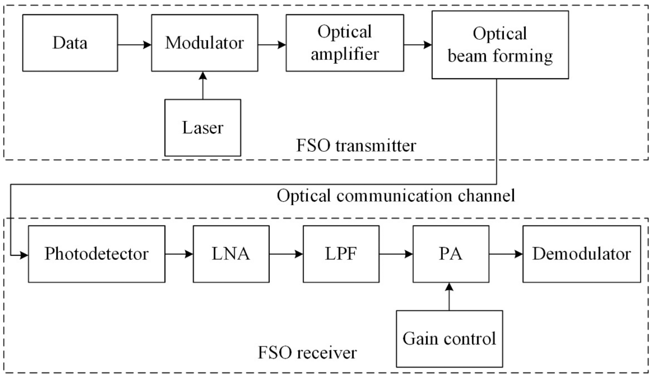


Fig. 6. *Basic block diagram of an FSO system.*

photodiode. The photodiode output current is then converted to voltage. A low pass filter is used to limit thermal and background noise levels. Finally, a demodulator performs the necessary demodulation to obtain the original data transmitted.

One of the main limitations of using a wireless optical communication channel as part of high-speed digital telecommunication radio systems is the potentially large downtime of these systems in adverse weather with limited visibility. The issue of comparing atmospheric attenuation of optical signals of different wavelengths is discussed in [9] and others. An extensive search in the literature and some calculations of the total scattering of light on spherical particles show that 1550 nm, 850 nm and 785 nm are virtually equally attenuated in fog.

In [10], the influence of the communication channel on the linear attenuation of the optical signal at various optical wavelengths is studied. Linear attenuation along the path can be calculated using the following expression

$$\sigma = \frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-q},$$

where σ is the atmospheric attenuation (or scattering) coefficient; V is visibility (km); q is size distribution of scattering particles: $q = 1.6$ for high visibility ($V > 50$ km); $q = 1.3$ for average visibility ($6 > V > 50$ km); $q = 0.6V + 0.34$ for visibility in haze ($1 > V > 6$ km); $q = V - 0.5$ for visibility in fog ($0.5 > V > 1$ km); $q = 0$ for visibility in fog ($0.5 > V$ km).

Table 1 shows relationship between the atmospheric attenuation coefficient and

Table 1

Relationship between atmospheric attenuation coefficient and visibility range and atmosphere conditions

Visibility range, km	σ, dB/km at λ = 785 nm	σ, dB/km at λ = 785 nm	Weather conditions
0.05	340	340	Fog
0.2	85	85	
0.5	34	34	
1	14	10	Mist
2	7	4	
4	3	2	
10	1	0.4	Clear
23	0.5	0.2	

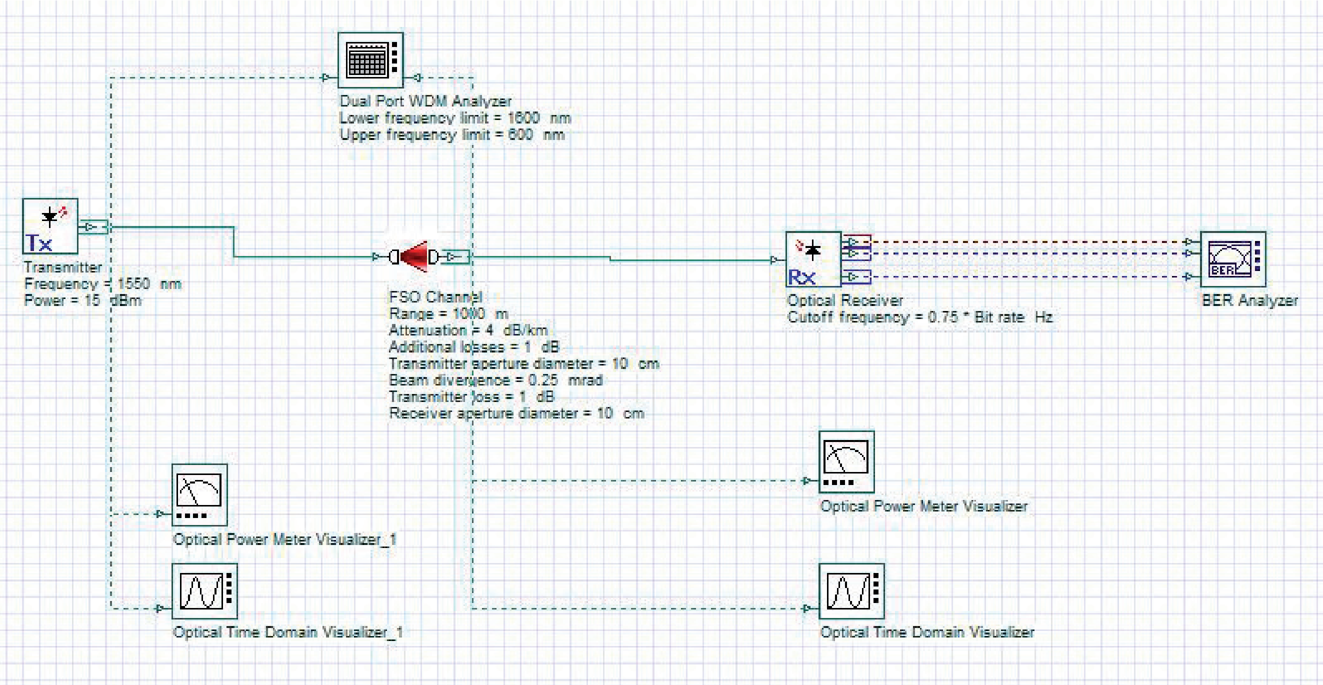


Fig. 7. *FSO wireless channel simulated using CAD software.*

visibility range and atmosphere conditions.

A simplified model for arranging a wireless optical communication channel of an FSO system is shown in **Fig. 7**, where the optical carrier is simulated by a linear digital sequence with NRZ encoding.

Allowable length of the communication channel was determined for the following parameters:

- optical radiation wavelength: 1550 nm;
- data transfer rate: 1 to 10 Gbit/s;
- σ_1 = 4 dB/km and σ_2 = 85 dB/km.

Results of the analysis are presented in **Fig. 8** as eye diagrams.

To increase noise immunity of a wireless optical communication channel and energy efficiency of using the signal spectrum band, we will consider the use of QAM and OFDM.

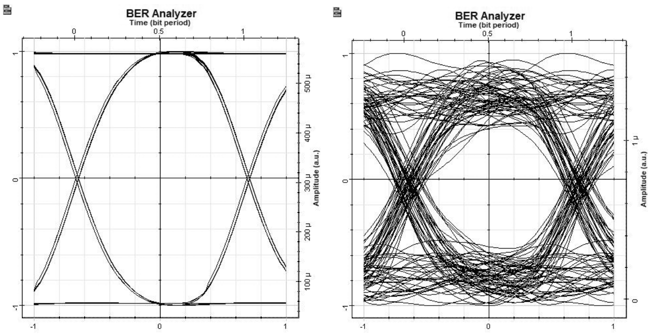
Calculations of OFDM signal parameters for various telecommunication systems (TCS) are presented in **Table. 2.**

OFDM method uses various modulation techniques to encode several information bits in one discrete signal state (symbol). Thus, IEEE 802.11a standard uses binary and quadrature phase shift keying (BPSK and QPSK), while IEEE 802.11b standard uses binary (BDPSK) and quadrature (QDPSK) differential phase shift keying. Maximum modulation levels are as follows:

Table 2

QFDM signal parameters for various telecommunication systems

TCS	Channel width, MHz	FFT size	T_{sym}, μs	Δf_{car}, kHz
LTE(4G)	20	1024, 2048	66.7	15
Wi-Fi 4	20, 40	64.128	3.6 (with short intervals) 4 (with long intervals)	312.5
Wi-Fi 5	20, 40, 80, 160	64, 128, 256, 512	3.2	312.5
Wi-Fi 6	20, 40, 80, 160	64, 128, 256, 512, 1024, 2048	12.8	78.125



a *b*

Fig. 8. *Eye diagrams for the basic FSO model of the communication channel at a wavelength of 1550 nm, attenuation in the communication channel of 85 dB/km, data transfer rate of 1 Gbit/s: distance 150 m, Q=614 (a); distance 420 m, Q=6 (b).*

- 64-QAM as per IEEE 802.11n (Wi-Fi 4) standard;
- 256-QAM as per IEEE 802.11ac Wave 2 (Wi-Fi 5) standard;
- 1024-QAM as per IEEE 802.11ax (Wi-Fi 6) standard.

The second option for setting up a remote broadband communication channel using FSO is shown in Fig. 7. Here the FSO provides high-speed transmission of a digital data stream with OFDM between the coastal subsystem and UAV, the repeater of which provides the required coverage area for the joint operation of a group of unmanned surface watercrafts.

Fig. 9 shows QAM and OFDM based FSO system for the source digital data flow.

FSO system model parameters:

- Data transfer rate: 10 Gbit/s;
- QAM modulation of the digital signal:

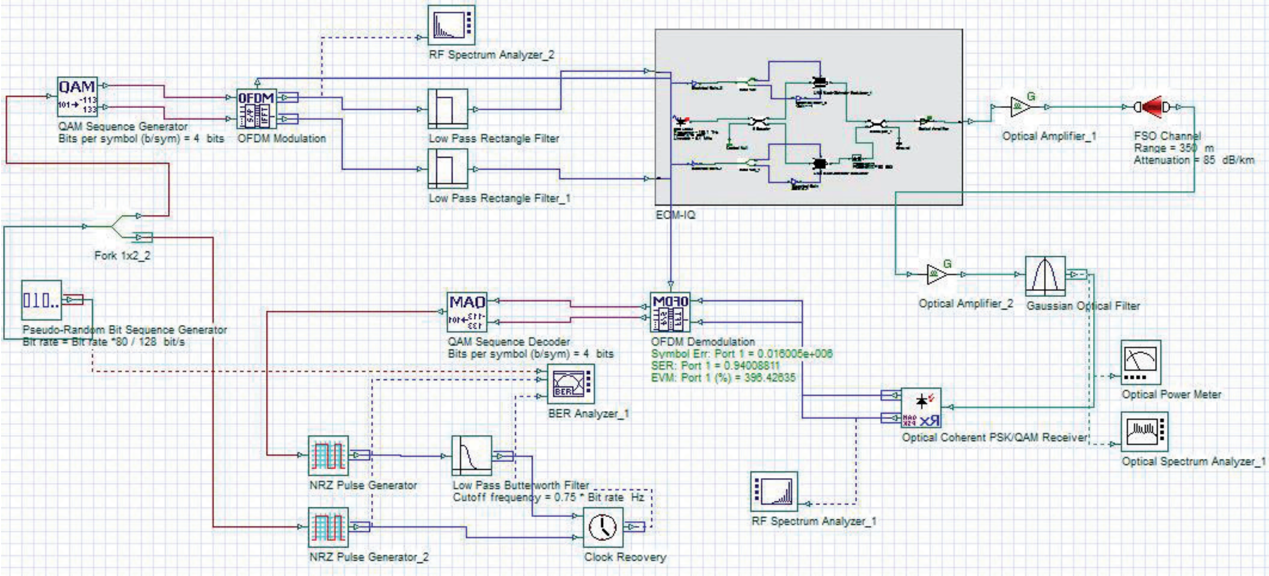


Fig. 9. *Simulation of FSO system using QAM and OFDM*

16QAM;

- anti-noise coding: Gray code;
- OFDM parameters:
- number of subcarriers: 128;
- number of prefix points: 10;
- numbers of information subcarriers: 25 to 104.
- pilot signals on subcarriers with numbers: 25, 44, 64, 84, 104.

Simulation shown in Fig. 9 uses a subcircuit of the quadrature electro-optical modulator model (**Fig. 10**), made

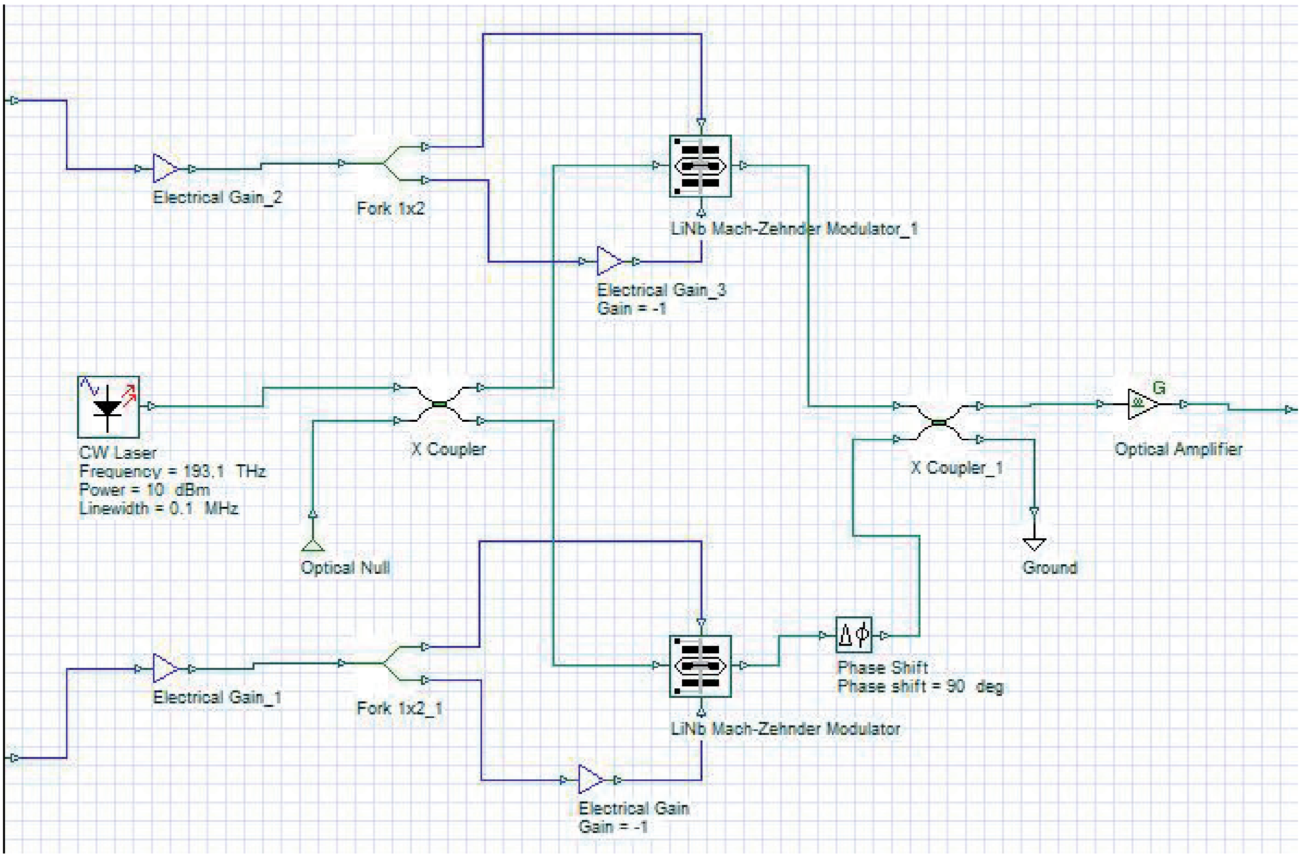


Fig. 10. *Subcircuit of a quadrature electro-optical modulator simulation.*

using two Mach-Zehnder electro-optical modulators.

In the circuit, I-Q control signals are supplied to two channels; at the output of one of the modulators, the optical signal is phase shifted by 90°.

Since a coherent optical circuit of the communication channel is used to build the FSO, a coherent optical receiving module is used as a receiver, at the input of which a bandpass optical filter with a bandwidth of 25 GHz is installed. **Fig. 11** shows an eye diagram for a 350 m long optical communication channel with a linear absorption in the atmosphere of 85 dB/km.

Energy characteristics of the FSO system are adjusted by two erbium fiber amplifiers (Optical Amplifier_1 and Optical Amplifier_2 — in Fig. 9), the gain of which can be altered to adjust the budget value of the optical path of the FSO system along the air route of the required length.

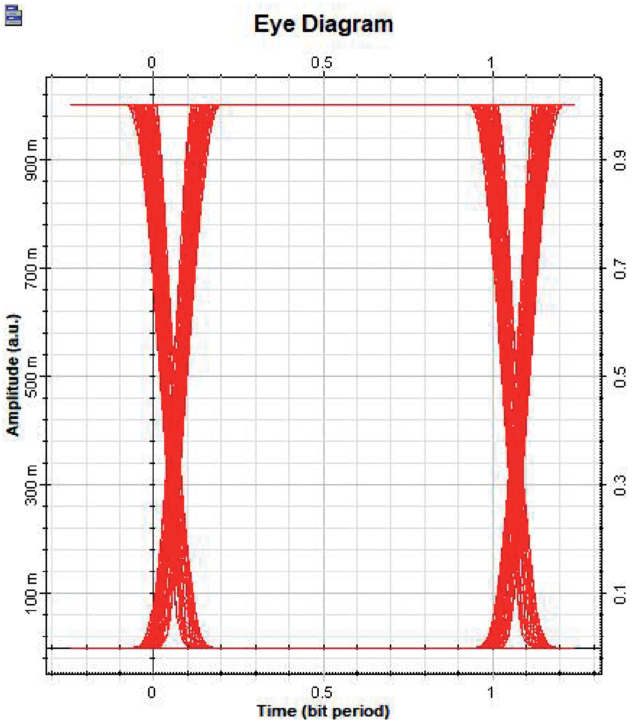


Fig. 11. *Eye diagrams as plotted by BER_Analyzer_1 (see Fig. 9).*

4. CONCLUSION

As shown above, use of wireless optical communications along the shore-to-reference repeater line is a promising advanced technique for organization of shipping in the coastal area. From shore to the repeater, a digital data flow with 16QAM and OFDM is transmitted in the optical carrier sideband. The repeater performs radio exchange with ships. The repeater itself is placed on an unmanned aerial vehicle or on an airship.

It is proposed to arrange an optical channel using FSO technology, which allows data to be transmitted at high speed over a long distance. Simulation of an optical system transmitting path was based on an approach where the optical carrier was simulated in quadrature using two electro-optical modulators, thus the wireless FSO system was coherent. In the transmitter block of the FSO TRx module, this eliminates the need to transfer the modulated digital signal to an RF subcarrier to modulate the laser intensity. In this case, it is not necessary to use a synchronous microwave detector in the receiving unit of the FSO TRx module. Such use of optical communications makes it possible to increase the capacity of radio channels provided to ships, significantly increase the electromagnetic compatibility of various radio systems, and create a secure communication channel.

It has been shown that in unfavorable weather conditions on the air route between the shore and the reference repeater with a length of more than 300 m, it is possible to transmit data at a speed of at least 10 Gbit/s, which will make it possible to set up a network of air repeaters to solve future e-Navigation objectives as well as to implement maritime Internet of Things.

REFERENCES

1. E-Navigation Strategy Implementation Plan – Update 1 (MSC.1/Circ.1595) [Online] Available: https://iho.int/uploads/default/m/s/msc-circ1595-e-navigation-strategy-implementation-plan-update-1-secretariat.pdf, access data 12.10.2023.
2. Pinsky AS. E-Navigation and unmanned navigation. *Transport of the Russian Federation*, 2016, 4(65):50-54, (in Russ.).
3. Skvarnik IS, Sovkova OI, Statsenko LG, Turmov GP. Wireless broadband access technologies: assessing the feasibility of application for vessel traffic control. *Bulletin of the FEFU Engineering School*, 2019, 4(41):113-124, (in Russ.).
4. Ali H-F, Kexiong Z, Yaling Y, Majid M. A Self-Sustaining Maritime Mesh Network. *Proc. of United States National Committee of URSI National Radio Science Meeting* (USNC-URSI NRSM), 2019:1-2. DOI: 10.23919/USNC-URSI-NRSM.2019.8713132.
5. Zainuddin Z, Wardi, Nantan Y. Applying Maritime Wireless Communication to Support Vessel Monitoring. *Proc. of 4th International Conference on Information Technology, Computer, and Electrical Engineering* (ICITACEE), 2017:158-161. DOI: 10.1109/ICITACEE.2017.8257695.
6. Recommendation ITU-R P.527-4. Electrical characteristics of the earth's surface. International Telecommunication Union. [Online] Available: https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.527-4-201706-S!!PDF-R.pdf, access data 12.10.2023.
7. Uysal M, Nouri H. Optical wireless communications – an emerging technology. *Proc. of 16th International Conference on Transparent Optical Networks* (ICTON), 2014:7. DOI: 10.1109/ICTON.2014.6876267.
8. Khalighi M, Uysal M. Ali Survey on free space optical communication: a communication theory perspective. *IEEE Communication Surveys & Tutorials,* 2014, 4(16):2231-2258. DOI: 10.1109/COMST.2014.2329501.
9. Szajowski PF, Nykolak G, Auborn JJ, Presby HM, Tourgee GE, Korevaar E, Schuster J, Kim II. 2.4 km free-space optical communication 1550 nm transmission link operating at 2.5 Gb/s – experimental results. *Proc. of SPIE Conf. Optical Wireless Communications,* 1999:29-40. DOI:

10.1117/12.338979.

10. Kim II, McArthur B, Korevaar EJ. Comparison of laser beam propagation at 785 nm and 1550 nm in fog and haze for optical wireless communications. *Proc. of SPIE Conf. OpticaI Wireless Communications,* 2001: 26-37. DOI: 10.1117/12.417512.