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Practical aspects of design of the wireless underwater optical communication system for telecommunication applications

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Abstract: **The overview of the principles of organizing underwater wireless optical communication is presented in the paper. The basic features of the optical communication system design with the usage of laser and LED emitters working in the visible range, as well as using various types of modulation, are considered. A comparative review of the developments of underwater wireless optical communication systems, operating at distances up to one hundred meters and with data transfer rates up to tens of Gbit/s, is presented. In addition, a comparative review of design of underwater optical modems is considered. It is shown, that the further prospect of their development is the combination of various methods of underwater wireless communication, including the use of MIMO technology.**

Keywords: **underwater optical communication, optical communication in the visible range, optical modem for underwater communication, underwater communication system**

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Contents

1. INTRODUCTION

In modern telecommunication systems, the several approaches are used to organize wireless underwater communication.

Acoustic underwater communication (UAWC) is considered as the most popular method of underwater wireless communication because of the low values of the attenuation of acoustic waves under water (about 0.1-4 dB/km). Disadvantages of UAWC are the low acoustic wave propagation speed (1500 m/s) and limited UAWC bandwidth (kHz), which leads to the multipath phenomenon, large time delay, and bulky acoustic antennas [1]. For example, in [2], a UAC system with a data transfer rate of 60 Kbit/s with 32 QAM is considered This UAC system can communicate at a depth of 100 m and at a distance of 3 km horizontally. In order to achieve high data transfer rates without the need for complex calculations, many researchers have widely used orthogonal frequency division multiplexing (OFDM) in underwater acoustic communication [3].

Underwater radio communication (URWC) is used to organize high-speed data transmission over short distances. Electromagnetic waves are affected by temperature, salinity and depth, which leads to a strong weakening of electromagnetic waves and limits the range of signal propagation in water. Due to the high electrical conductivity of water in microwave range, it is difficult to implement URWC on communication lines with a length of more than 10 m [4] in the ranges of meter and shorter waves (in the 2.4 GHz range, the attenuation of radio waves in salt water is about 169 dB/m). For such communication lines, a large power of transmitters (more than 100 watts) is required [5]. In the DV (30-300 kHz) and SDV (3-30 kHz) bands, the attenuation of the electromagnetic wave can be considered low enough to provide reliable communication at a distance of many kilometers. URWC systems in the DV range are used in underwater military systems or when creating communication lines between ground and underwater objects [6]. The main disadvantages of such systems include complex design requirements for very large antennas and low data transfer rates.

*Underwater communication using magnetic inductio*n (UWMIC), as a promising replacement of traditional acoustic systems and radio communications, has attracted considerable attention [7], due to its inherent qualitative amplitude-frequency response of the channel, low propagation delay and relatively low energy consumption [8]. UWMIC involves the transition from traditional unidirectional antennas to multidirectional MI-antennas. There is also a great research interest in the currently available approaches to expanding or reusing the available frequency bands to increase the capacity of the underwater MI channel [7].

Underwater optical communication (UOWC) is based on the use of a visible part of the optical spectrum. UOWC is characterized by a large available bandwidth, which can help to realize high data transfer rates, and has the advantages of low power consumption, low cost and compact size. The complex underwater environment has a serious impact on the propagation of light under the water. Absorption, scattering and turbulence are the dominant harmful effects that degrade the optical transmission characteristics at low temperatures. Underwater transmission of optical waves in the 450-500 nm band (blue and green) has the least attenuation for pure seawater or transparent ocean (0.4 dB/m) compared to other bands. In this band the attenuation effect caused by the interaction of photons with water molecules and other particles is limited. The 520-570 nm band (yellow-green) is suitable for coastal ocean or turbid waters in ports (11 dB/m).

In the underwater environment, a chlorophyll substance absorb blue and red light. These and other colored dissolved organic substances (CDOMS) increase the turbidity of water and reduce the distance of light propagation. The concentration of CDOM varies depending on the depth of the water medium, thereby changing the corresponding light attenuation coefficients. The total absorption in seawater can be determined taking into account a complex of factors according to the formula [9]

$$a(\lambda) = a_w(\lambda) + a_f c_f exp(-k_f \lambda) + \\ + a_h c_h exp(-k_h \lambda) + a_c (c_c)^{0,622},$$

where $a_w(\lambda)$ – an absorption coefficient in pure water; a_f – a partial absorption coefficients of fulvic acids; c_f – a fulvic acid concentration; k_f

– an exponential coefficient of fulvic acids; a_h – a humic acid absorption coefficient; c_h – a humic acid concentration; k_h – an exponential coefficient of humic acid; a_c – a chlorophyll absorption coefficient; c_c – a chlorophyll concentration.

Due to the complexity of the water environment, the implementation of UOWC systems requires reliable underwater devices. The performance and service life of UMPC devices are largely influenced by the current, temperature pressure and salinity of seawater. The power consumption of the system's transmitter, taking into account the capacity of the batteries, determines the battery life.

The main disadvantage of optical communication is that the range is limited to a distance of about 1-100 meters, because of the water parameters and suspended particles in the water, where the light is either attenuated or scattered. Another disadvantage is that optical communication usually requires a line of sight from the transmitter to the receiver.

Fig. 1 shows a generalized comparison of available wireless underwater communication technologies [10].

Therefore, the generalization of the results of UOWC developments for communication and information transmission systems has a great practical interest.

2. APPROACHES TO THE CONSTRUCTION OF UNDERWATER WIRELESS OPTICAL SYSTEMS

In practice, the technology of "optical communication in the visible range" (VLC) is widely used for the organization of wireless underwater optical communication, as the most promising. Due to the rapid development of LED lighting, the cost of the component is decreasing. However, some of the problems that need to be solved are listed below:

– an integration of the VLC system with existing communication standards;

– a problem with interference from the ambient light source;

– a VLC must correctly support handover in coverage areas;

– an application of error correction methods to improve the performance of the communication system.

As the number of VLC devices increases, there will be interference between different VLC devices. The Electronic Information Technology Industry Association has developed the 802.15.7 standard, which is the standard established by the IEEE for the physical layer and the MAC layer [11]. The objectives of this standard are:

– providing access to hundreds of terahertz frequency bands;

– providing protection against electromagnetic interference;

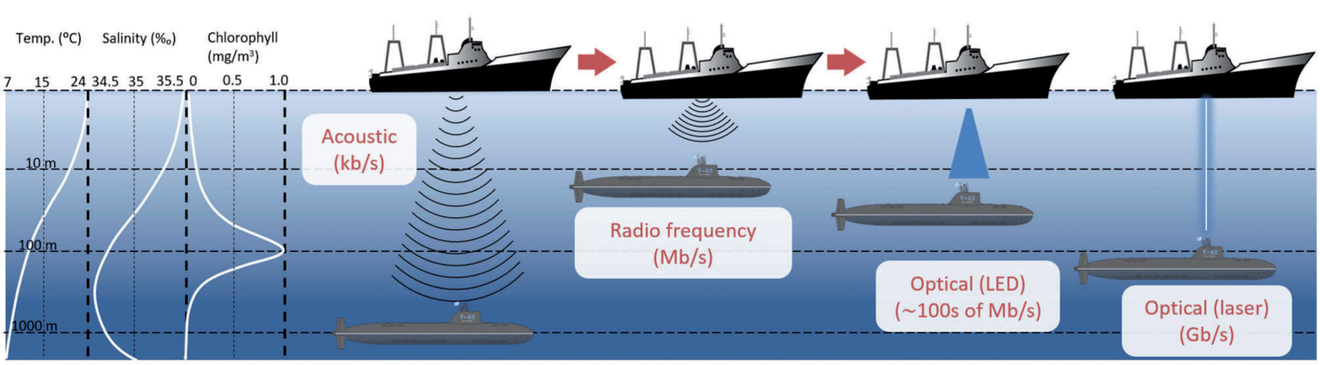

Fig. 1. *Comparison of available wireless underwater communication technologies.*

– provision of additional services that complement the existing visible light equipment;

– the VLC-connection that prescribes a forward error correction (FEC) scheme, a form of modulation and a data transfer rate;

– a channel access mechanism, since visibility range support also describes channel access, as well as the time period when contention for the network environment (contention access period, CAP) and the competition-free time period (CFP);

– the physical layer specifications: the optical projection, TX-RX, RX-TX cycle time, flicker and dimming.

The three different types of devices used by VLC are: mobile objects, a mobile equipment, and the infrastructure [12]. VLCs can be used indoors [13,14], in identification and location systems [15], in communication systems in transport [16], and are used for the organization of wireless underwater communication channels [17].

The VLC system mainly consists of two components: an optical transmitter (Tx) and an optical receiver (Rx). After preprocessing and encoding, the binary bit stream directly simulates the emission of the light source. To increase the transmission rate and the efficiency of the spectrum, high-order coding modulation methods are used.

The implementation of extended and high-speed underwater communication lines using laser diodes (LD) as a source of optical radiation has been considered in a number of papers [18, 19]. However, due to the narrow directional pattern of LD in the underwater environment, problems arise with the positioning of the receiving and transmitting paths. At the same time, the additional beam expansion or other solutions are used to achieve the required technical characteristics of the UOWC.

Therefore, the most common type of radiation sources in the UOC structure are light-emitting diodes (LEDs) [20], which provide many advantages: a safety for the eyes, the long service life, a low power consumption, the possibility of simultaneous lighting and communication. Since LEDs are characterized by a wide directional pattern, they solve the problem of positioning, which allows the use of simpler and more compact UOWC systems. Large divergence angles and a relatively small frequency band of LED modulation limit their use in terms of data transmission range and speed: for example, for communication between underwater vehicles and nodes of underwater wireless sensor networks, etc.

A comparison of the characteristics of LD and LED used in VLC is presented in **Table 1**.

To increase the efficiency of using the LED modulation range, it is customary to investigate methods of digital compression of the signal spectrum, for example, due to quadrature amplitude modulation (QAM) and multiplexing with orthogonal frequency division (OFDM) [21]. The following types of modulation are also used:

– the multilevel pulse-amplitude modulation (PAM), which is characterized by a simpler structure, more flexible implementation and less computational complexity [22];

– the amplitude manipulation without returning to zero (NRZ-OOK) as is the

Table 1

Comparison of LD and LED characteristics used in VLC.

Light source	Transverse dimensions, mm^2	Modulation bandи	Power, Watt
LED	0.1-1	~ 10 МГц	> 1
LD	< 0.2	10-20 ГГц	> 1

most intuitive and simple modulation scheme suitable for light communication;

– the phase-pulse modulation (PPM);

– the frequency manipulation (FSK);

– the digital pulse interval modulation (DPIM) is a method of isochronous pulse-time modulation, in which data is encoded as a series of discrete time intervals, or time intervals between adjacent pulses. The length of the symbol is variable and is determined by the information content of the symbol. To avoid symbols in which the time between adjacent pulses is zero, an additional guard interval can be added to each symbol immediately following the pulse.

When modulations are modified, a discrete multi-tone transmission is used (DMT) [23].

The key element of the VLC receiving path of the system is a photodetector that converts the energy of the received optical radiation into a photocurrent. VLC receivers use different types of photodiodes, such as:

– the semiconductor pin photodiode (PIN PD): high-speed contact photodiodes have a fast reaction time, low cost, single gain and high resistance to ambient light; the main type of noise is thermal;

– the avalanche photodiode (APD): APD has a high intrinsic current gain and high quantum efficiency (70-90%). The main type of noise is shot noise. APD requires high bias voltage and complex control circuits; the quantum efficiency of APD depends on the thickness of the material, for example, in the range of 400-500 nm, silicon has very low sensitivity. Therefore, the contact photodiode seems to be a more promising technology at shorter wavelengths than APD for the UOWC system [12];

– the photomultiplier (PMT), which is the type of vacuum lamp that is very sensitive to light, has a large photocurrent gain, low noise, high frequency response and large overall dimensions compared to photodiodes; PMT requires a high supply voltage (about 100 V) and have a high cost, also have a fragile design.

The main requirements for photodetectors in the VLC system are:

– the high quantum efficiency; the output photocurrent can be as large as possible to create a certain incident optical power;

– the sufficiently high response rate for use in a high-speed broadband system;

– the noise level should be as low as possible;

– a low level of nonlinear distortion;

– small size and long service life.

3. OVERVIEW OF THE DEVELOPMENT OF UNDERWATER VLC SYSTEMS

A comparative analysis of the characteristics of various options for building VLC systems designed for the organization of UOWC is considered below.

A comparison of the characteristics of VLC systems, the transmission path of which is implemented on the basis of laser diodes, is shown in **Table 2**.

Table 2

Comparison of the characteristics of VLC systems with laser diodes

Source	Photo-detector	Modulation	Distance, m	Data transfer rate, Gbit/s	Reference
Laser diode (LD)	Avalanche photodiode	NRZ-OOK	7	2.3	[24]
		PSK/QAM	64	5	[25]
			8	1	
		QAM-OFDM	5.4	4.8	[26]
		OAM-OOK	2.96	3	[27]
		OOK	20	1.5	[28]
		OFDM	1.7	14.8	[29]
		NRZ-OOK	34.5	2.7	[30]
		OFDM	21	5.5	[31]
		NRZ-OOK	34.5	2.7	[32]
	PIN-photodiode	16-QAM	3	0.05	[33]
		OOK	1.6	0.1	[34]

A comparison of the characteristics of VLC systems, the transmission path of which is implemented on the basis of light-emitting diodes, is shown in **Table 3.**

Analysis of recent publications shows that today LED arrays are increasingly popular in the design of UOWC transmission modules [50]. LED arrays with increased optical power can provide a sufficiently long data transmission distance under the water. In addition, LED arrays with a relatively large light spot in the receiving plane can reduce the influence of turbulence and inhomogeneities in the UOWC channel.

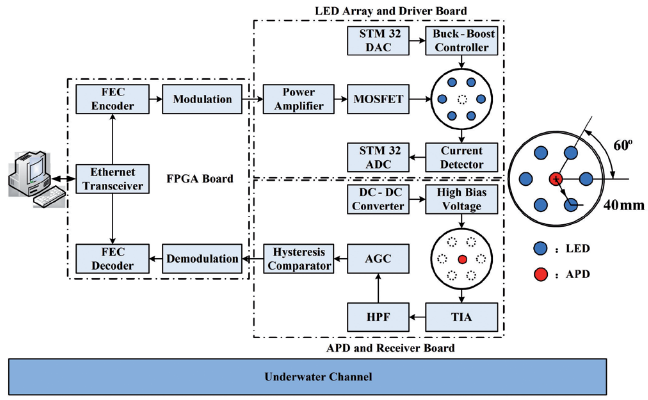

Fig. 2. *Block diagram of the VLC receiving and transmitting module of the UOWC system.*

Table 3

Comparison of the characteristics of VLC systems with light-emitting diodes

Type of trans-mitter	Recei-ver Type	Modula-tion	Dis-tance, м	Data transfer rate	Refe-rence
521 нм LED	2 PIN PD	64-QAM-DMT	1.2	2,175 Gbit/s	[35]
470 нм LED array	PMT	OOK	8	19 Gbit/s	[36]
RGBYC LED	PIN PD	64QAM-DMT bit-loading-DMT	1.2	14.81-15.17 Gbit/s	[37]
Blue LED	PIN PD	64 QAM DMT	1.2	3.075 Gbit/s	[38]
Blue LED	MPPC	PPM	46	~ MHz	[39]
458 нм LED	PIN PD array (2×2)	32 QAM DMT	1.2	20.09 Gbit/s	[40]
LED (4×4) array	PIN PD	PS-bit loading DMT	1.2	20.09 Gbit/s	[41]
450 нм LED	PIN PD	16QAM OFDM	3	50 Mbit/s	[42]
450 нм LED array	APD	video broad-cast	10	1 Mbit/s	[43]
450 нм LED	APD	PAM4	5	1.25 Gbit/s	[44]
450 нм LED	APD	GS-8QAM OFDM	3.6	2,2 Gbit/s	[45]
448 нм LED	APD	OOK	118	25 Mbit/s	[46]
480 нм LED	APD	DPIM	30	1,2 Mbit/s	[47]
470 нм LED	APD	DPIM	50	2,28 Mbit/s	[48]
Blue LED	APD	NRZ-OOK	11.5	235 Mbit/s	[49]
445 нм LED	APD	2FSK	14.5	1 Mbit/s	[50]

A typical example of the block diagram of the VLC receiving and transmitting module of the UOWC system [50] is shown in **Fig. 2**.

Depending on the number of LEDs in the grid, LEDs can be connected in series, in parallel, or in a combined way. In a serial line, usually no more than 10 LEDs are included.

The modern way to improve the reliability of UOWC systems is to use the multiple-input multiple-output (MIMO) technology [51]. The system characteristics of MIMO wireless optical communication using spatial modulation (SM-OMIMO) in the OWC of free space [52] and wireless indoor environment [53] have already been studied. It has been shown that the SM can help to achieve improved spectral efficiency and is more resistant to high channel correlation compared to conventional MIMO using a code with repetitions [51]. In addition, SM has the advantage of implementation, since it requires only a low complexity detection algorithm [54]. However, for realization of UOWC, it is still not clear to what extent the SM-OMIMO methods can provide a gain, because the channel attenuation will be more severe in an underwater environment.

Using a typical equal power absorption algorithm (PAA) [55], receivers can only determine the intensity of signals, but cannot determine the position of the activated transmitter. To negate the limitations associated with high channel correlations, power imbalance (PI) technology on transmitters has recently been introduced. In [56], an optimal power distribution was proposed for a spatially modulated VLC system with OFDM for the case of a simple MIMO structure with two transmitters. Expressions for the power distribution coefficient for four transmitters are obtained in [57]. In most recent reference sources related to the SM system, a simple pulse-amplitude modulation scheme is used, including OOK [55] and the pulse-amplitude modulation (PAM) [57]. In [58], UOC MIMO using spatial modulation (SM-UOMIMO) and the flag two-amplitude pulse positional modulation (FDAPPM) is considered [59].

4. OVERVIEW OF THE DESIGN OF UNDERWATER OPTICAL MODEMS

The practical implementation of various approaches to the design of UOWC receiving and transmitting equipment, taking into account existing data transmission protocols, is presented on the market of underwater optical modems. Comparative characteristics of the developments of underwater optical modems are presented in **Table 4**.

Table 4

Comparative characteristics of the development of underwater optical modems

Organization	Light source	Data transfer rate	Dis-tance, м	Refe-rence
WHOI (2005)	LEDs	10 Mbit/s	100	[60]
Laurentian Univ. (2009)	LED	1 Gbit/s	20	[61]
MIT (2010)	LEDs	2.28 Gbit/s	50	[62]
Maritime Technology and Research (2017)	LD	100 Mbit/s	2	[63]
Dalian Univ. Of Technology (2018)	LD	100 Mbit/s	4.8	[64]
Tsinghua Univ. (2018)	LED	235 Mbit/s	11.5	[49]
MIT Lincoln Lab. (2019)	LED	1 Gbit/s	20	[65]
Sonardyne (2019)	LEDs	10 Mbit/s	150	[66]
Nanjing Univ. of Posts and Telecommunica-tions (2020)	LEDs	1 Mbit/s	10	[67]
KAUST (2020)	LD	1.2 Mbit/s	2	[68]
KAUST (2021)	LED	1.5 Mbit/s	0.6	[69]
KAUST (2022)	LED	2.5 Mbit/s	5	[70]

The prospect of the development of underwater communication modems is associated with the combination of two or more different methods of underwater communication. This approach is often used for ocean mooring with sensors on an anchor cable and wireless mobile communication. Hybrid systems can take advantage of each method and therefore increase the reliability of the system. Today, one of the most important tasks of hybrid systems is an adaptive and smooth transition from one communication environment to another, which makes the system more complex and requires protocols and algorithms to understand the environment in a hybrid system [71]. Many underwater vehicles used hybrid communication systems, which included both acoustic and optical systems [72]. Choosing the appropriate communication channels in response to changing traffic load and weather conditions, presented in [73], the hybrid optical-acoustic underwater wireless communication system that minimizes network power consumption and provides high data transfer rates in underwater applications. Compared with conventional optical-acoustic methods, the proposed approach allows saving up to 35% of electricity.

5. CONCLUSION

VLC optical technologies are widely used for the organization of underwater wireless telecommunication systems, which provide unique opportunities for high-speed communication, including the organization of promising underwater networks of the

Internet of Things. The developed component optical base (lasers, LEDs and various types of photodiodes) is well adapted to solve the problems of UOWC design using VLC technologies and make it possible to find the most effective combinations to implement the various technical tasks. Various types of digital modulation, noise-proof coding and MIMO technologies can significantly increase the efficiency of using the frequency band of communication channels, the reliability of data transmission over long distances at different states of the communication channel in terms of transparency, heterogeneity, the content of various organic substances, etc. Modern UOWCS make it possible to get data transfer rates from Mbit/s up to tens of Gbit/s for distances from several to hundreds of meters. Numerous studies in the field of VLC design for various UOWCS have determined the production and active improvement of underwater optical modems with data transfer rates from 1 Mbit/s to 2 Gbit/s at distances up to 150 m. Further development of underwater modems is associated with the combined use of various methods of underwater communication.

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