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IMPULSE ULTRAWIDEBAND WIRELESS COMMUNICATION SYSTEM OF THE TERAHERTZ FREQUENCY BAND

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Abstract *– The article considers the possibility of developing a wireless telecommunication system of the terahertz band (THz), in which an impulse radio ultrawideband signal (IR-UWB) is used as an information carrier. Variants of the transmission and reception path constructions of the THz IR-UWB wireless communication system (WCS) are considered, taking into account the technical characteristics of the THz devices available on the telecommunication market. One of the main results is the block diagram of the IR-UWB WCS of the terahertz range development of the point–to–point type based on the heterodyning method. It is also important that already existing technical implementations of some THz blocks (subharmonic mixer, waveguides, antennas, etc.) of the transmitter and receiver devices allow us to determine which devices of the WCS require designing. The calculation of the energy budget of the THz IR-UWB WCS line for various types of IR-UWB signal modulation was also carried out, which made it possible to estimate the distance between corresponding stations under different conditions of the electromagnetic wave propagation environment. The proposed version of the radio communication system is of the point-to-point type using IR-UWB signal in the terahertz range. An assessment of the potential distance between the corresponding line-of-sight stations for different conditions of EMF propagation and types of performed IR-UWB modulation was carried out, which shows that for the ideal case of EMF propagation with an increase in the operating frequency, an increase in distance is observed, which is obviously because energy losses EMF in free space with increasing frequency is compensated by increasing the directivity of the transmitting and receiving antennas.*

Анотація *– У статті розглядається можливість розробки імпульсної надширокосмугової телекомунікаційної системи терагерцового діапазону (ТГц), в якій носієм інформації є імпульсний надширокосмуговий сигнал (ІНШС). Розглянуто варіант побудови трактів передачі та прийому ТГц імпульсної надширокосмугової системи радіозв'язку (ІНШСР) з урахуванням технічних характеристик ТГц-пристроїв, представлених на телекомунікаційному ринку. Одним із основних результатів є блок-схема ІНШСР терагерцового діапазону типу «точка – точка» на основі методу гетеродинування. Важливо зазначити, що вже існують технічні реалізації деяких ТГц-блоків (субгармонійний змішувач, хвилеводи, антени тощо) передаючого та приймального пристроїв, що дозволяють визначити, які пристрої надширокосмугової системи радіозв'язку потребують проєктування. Проведено розрахунок енергетичного бюджету ТГц-лінії для різних типів модуляції ІНШС, що дає змогу оцінити відстань між відповідними станціями за різних умов середовища поширення електромагнітних хвиль. Запропонований варіант системи радіозв'язку є типом «точка-точка» з використанням ІНШС у терагерцовому діапазоні. Проведено оцінку потенційної відстані між відповідними станціями прямої видимості для різних умов розповсюдження електромагнітних хвиль (ЕМХ) та типів виконаної модуляції ІНШС, яка показує, що для ідеального випадку розповсюдження ЕМХ зі збільшенням робочої частоти спостерігається збільшення відстані, що пов'язано з тим, що втрати енергії ЕМХ у вільному просторі зі збільшенням частоти компенсуються збільшенням спрямованості передавальної та приймальної антен.*

Introduction

Currently, considerable attention is paid to the problem of using impulse radio ultrawideband signals (IR-UWB) in wireless communication systems (WCS). Such signals have a number of advantages over radio systems using narrowband and wideband signals based on sinusoidal carriers [1].

However, the use of IR-UWB signals in the USA and Europe is subject to restrictions, respectively, by the USA Federal Communications Commission and the European Community Communications Administration, related to the frequency band and spectral density per radiated power. According to recommendations, the frequency range for the IR-UWB signals emission is limited to 3.1…10.6 GHz band, and the maximum power density of these signals should not exceed -41.3 dBm/MHz. The restriction was introduced to prevent interference with narrowband radio systems (primarily systems of mobile cellular radio communication and global satellite navigation system GPS) that jointly use the specified frequency range and neighboring bands, i.e., to ensure electromagnetic compatibility of radio electronic devices (RED) of various radio systems. The specified limitations allow realizing the potential of IR-UWB signals only at distances of up to ten meters [2].

At the same time, attention is rapidly growing in the world to the development of the 0.1…3 THz band, which, firstly, is poorly developed for wireless communication; secondly, it has a tremendous information capacity; thirdly, it is unlicensed in most countries of the world [3, 4]. A significant number of leading Western technical companies specializing in the development of microwave devices, such as SAGE Millimeter, VivaTech, Virginia Diodes, Radiometer Physics GmbH, etc., have already mastered the serial development of the main parts of transmitters, receivers, and antennas of the terahertz range at frequencies up to 325 GHz. That opens the possibility of REDs development for THz WCS based on its typical blocks, such as amplifiers, mixers, frequency multipliers, synthesizers, filters, detectors, decouplers, dividers, and power adders, etc.

Therefore, one of the options for realizing the potential of IR-UWB signals at greater distances between the corresponding REDs, than can be ensured due to the presence of restrictions on the spectral density of radiation power in the range of 3.1…10.6 GHz, can be the option of using IR-UWB of signals as a carrier of information in the THz WCS. At the same time, the IR-UWB signal generation in the transmitter of the RED directly in THz is possible either by the method of photon mixing of optical signals on a special photodiode or by radio electronics methods by frequency heterodyning of the IR-UWB signal generated in the microwave range into the THz range [5-8]. Reception of the THz signal can be realized based on the use of receivers of direct amplification or superheterodyne reception.

I. Problem Formulation

Let us formulate and justify the main requirements for the developing THz IR-UWB WCS, as well as determine and justify the requirements and parameters of individual nodes of its transmission and reception path:

1) Corresponding stations №1 and №2 of the THz IR-UWB WCS located within the line-of-sight at a distance which should be at least 1 km.

2) To ensure simultaneous two-way data exchange between corresponding stations, the line-of-sight radio line connecting these stations must work in duplex mode.

3) In wireless communication, frequency duplex (FDD) is the most straightforward implementation. Therefore, we will choose the FDD as the primary type of duplex, which will involve the use of two separate frequency bands in the THz range for signal transmission in the direction from station №1 to station №2 and from station №2 to station №1. According power losses in atmospheric gases [9], the most suitable and promising frequency ranges for designing high-speed ultrawideband wireless telecommunication sys-

tems are Δf_1 = 110...170 GHz and Δf_2 = 220...310 GHz, so we will choose exactly these frequency bands for THz IR-UWB WCS under development.

4) In most cases, high-speed wireless communication systems (for example, radio relay communication systems) are stationary (immobile), so THz IR-UWB WCS, which is being developed is also expected to be performed in a stationary version.

5) The data rate of a point-to-point WCS must be at least 1 Gbit/s in both transmission directions.

6) The output power of the WCS radio transmitter is determined by the structure of its output stage. In the case of using an optoelectronic converter based on the UTC photodiode of the Japanese company NTT Electronics of the IOD-PMF-14001 brand, the output power for the operating frequency range of 110...170 GHz is P_{out} = -9...-6 dBm, and the UTC photodiode of the brand IOD-PMJ-13001 for the operating frequency range of 280...380 GHz, it is P_{out} = -18...-11 dBm [10]. In the case of using an output power amplifier in the form of an amplifier module, for example, brand MGA 2101, which is intended for operation in the frequency range of 220…325 GHz, the maximum output power at the saturation point is P_{out} = 0 dBm [11].

7) The receiver sensitivity of the WCS will be primarily determined by the bandwidth of the receiving path and its noise temperature. The calculated value of this parameter for a satellite radio communication system based on IR-UWB signals for the frequency band 70…170 GHz is $7.45{\cdot}10^{-10}$ W or -61.3 dBm [12]. Therefore, in the future, we will focus on this sensitivity value, the more accurate value of which will be determined at the stage of energy calculation of the WCS.

8) The input interface of the station terminal must be made in the form of a Gigabit interface Ethernet type 1000BASE-T (electrical interface based on twisted pair of the 5th, 6^{th}, or 7th categories) or 1000 BASE-LX (optical based on single-mode fiber).

9) The quality of information transmission (bit error, minimum signal-to-noise ratio at the input of the receiver demodulator) will be determined by the type of reception (coherent or incoherent) and the type of modulation used.

II. Block diagram of a THz IR-UWB WCS based on the method of heterodyning of ultrawideband signals into the terahertz range

The generalized structural diagram of the point-to-point pulse ultra-broadband radio communication system of the terahertz range based on the method of heterodyning IR-UWB signals in the terahertz range is presented in Fig. 1. The structural diagrams of corresponding stations №1 and №2, to which subscriber terminals №1 and №2 are connected, are similar so that we will consider the principle of operation of station №1.

The principle of station №1 operation in the data transmission mode is as follows. The electrical signal of the Gigabit network interface of Terminal №1 in the form of a sequence of digital pulses with a speed of 1 Gbps through a twisted pair enters the receiving channel of the Ethernet to IR-UWB signal converter.

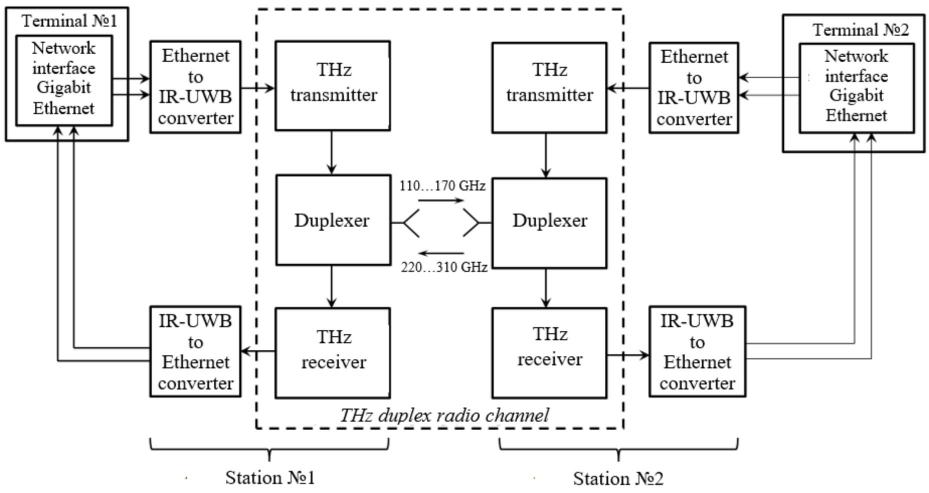


Fig. 1. Generalized block diagram of a point-to-point THz IR-UWB WCS based on the heterodyning method

In the converter, the following operations occur sequentially (Fig. 2): 1) conversion of the input electrical pulses from a symmetrical interface to an asymmetrical one (coaxial or microstrip); 2) generation of trigger pulses with sharp edge for IR-UWB oscillator (the logical "1" corresponding to the start-up pulse of positive polarity and the logical zero to the start-up pulse of negative polarity when using BPSK modulation or zero amplitude when using OOK modulation); 3) generation of IR-UWB signals in the form of a Gaussian monocycle with a duration of no more than 1 ns.

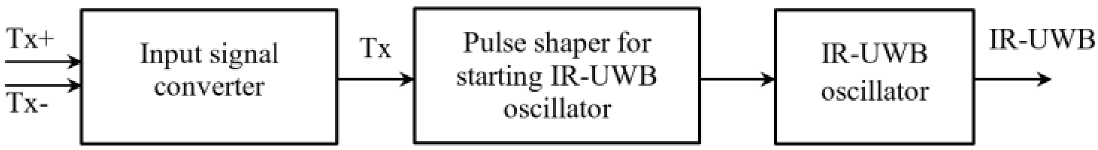


Fig. 2. Block diagram of the Ethernet to IR-UWB signal converter

From the output of the IR-UWB signal generator, the signal enters the input of the THz transmitter path (Fig. 3), in which the following transformations take place: 1) amplification of the IR-UWB signal to the required level by a wideband amplifier (if necessary); 2) mixing IR-UWB with the carrier harmonic oscillation of the transmitter local oscillator (heterodyne), which for the frequency range of 110...170 GHz should have a nominal value of $f_{\text{het.TX1}}$ = 65 GHz when using a subharmonic diode mixer; 3) IR-UWB bandpass filtering by a septum-type bandpass waveguide filter with a passband of 110...170 GHz at the level of -3 dB, built based on a rectangular waveguide WR6.5, which has cross-sectional dimensions of 1.651x0.8255 mm^2, 4) amplification of the IR-UWB signal to the required level of output power (if necessary).

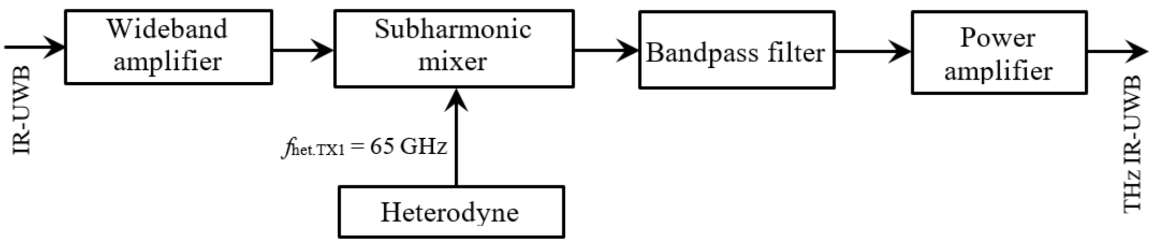


Fig. 3. Generalized structural diagram of the transmitter THz IR-UWB signal generation in 110…170 GHz band

The WR6.5 SHM subharmonic mixer (Fig. 4) of the Virginia Diodes company can be used as a subharmonic mixer of the transmitter and has the following parameters [13]:

- RF (signal) input : 110…170 GHz;
- input LO (heterodyne): 55…85 GHz;
- IF input (intermediate frequency): 0...24 GHz;
- conversion loss: 7 dB ;
- local oscillator level: +3...+6 dBm ;
- maximum input power: -10 dBm.
- noise temperature: 400…800 K.

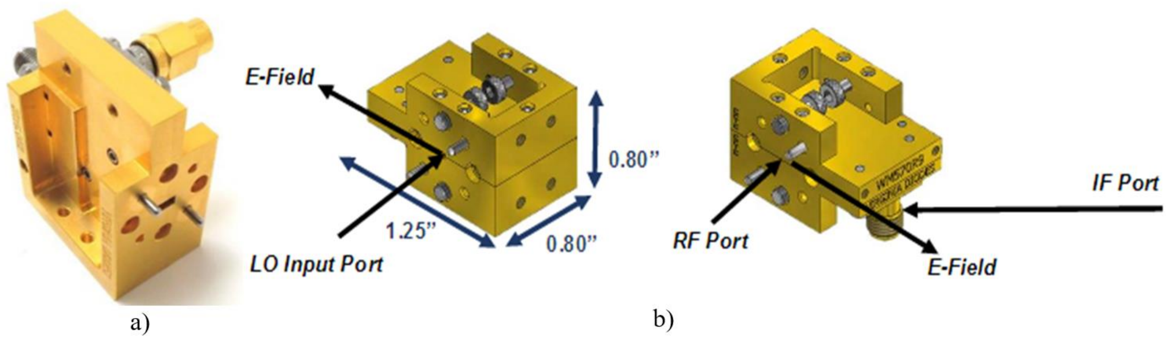
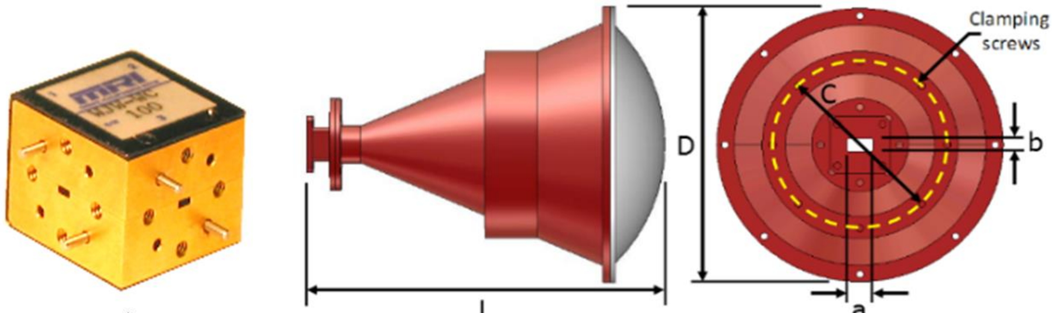


Fig. 4. Types of subharmonic mixer
a) photo of a subharmonic mixer; b) linear dimensions (in inches) of the body of the WR6.5 SHM subharmonic mixer

Therefore, the input IR-UWB signal of the wideband amplifier in transmitter shown in Fig. 4, must have a maximum frequency spectrum width no more than 24 GHz in order to use the subharmonic mixer brand WR6.5 SHM. The VTBPF-06 waveguide filter of the VIVATECH company with a bandwidth of 110...170 GHz can be used as a bandpass filter of the THz transmitter [14].

THz IR-UWB signal through the rectangular waveguide WR-6.5 enters the frequency duplexer and then passing to antenna which radiates THz electromagnetic waves in the direction of the corresponding Station №2. In this case, the duplexer is the easiest to implement based on a ferrite circulator (Fig. 5,a), for example, WJD-XC brand of the Microwave Resources company[15], which is designed for operation in the range of 110…170 GHz, providing a gap between the shoulders at the level of 18…20 dB and direct losses of about 1.3…1.5 dB. As an antenna (Fig. 5,b), a pyramidal horn antenna of the ANT-SGH-110-170 brand of the NSI-MI Technologies company can be used, designed for operation in the range of 110-170 GHz, which has a gain of 24.7 dB, or LHA-30-WR06 lense horn antenna of the ANTERAL company with a gain factor of 30 dB or a conical horn antenna with a gain factor of about 47 dB [16].

Considering that for Stations №1 and №2, the transmitters operate in the 110...170 GHz band, and the receivers operate in the 220...310 GHz band, it is challenging to use a standard transceiver antenna both in the transmission and reception modes. This is because the single-mode WR6.5 waveguide feeder operation on the main EMW H_{10}, which connects the output of the duplexer with the input of the antenna in the transmission mode of the IR-UWB signal, will be maintained at a frequency of up to 181.6 GHz.



a) b)

Fig. 5. Examples of ferrite circulator and LHA
a) Ferrite circulator of the 110-170 GHz frequency range; b) LHA-30-WR06 lens horn antenna from ANTERAL: L = 33 mm, D = 37 mm, range 110...150 GHz, gain coefficient 29..32 dB, the beamwidth of the antenna pattern is 5° in E-plane and 6° in the H-plane

At the same time, the WR6.5 waveguide in the reception mode will function in the presence of the higher types of EMW, i.e., in addition to the H_{10} wave, the H_{20}, H_{01} waves, etc., will be excited in it. That will lead to a loss of THz IR-UWB signal power received from the corresponding station. In addition, a duplexer based on the WJD-XC ferrite circulator [15] is designed for operation in the 110…170 GHz band. When operating in the range of 220...310 GHz, it will not provide the necessary parameters of transmission losses and separation between the arms of the circulator. Based on the aforementioned, for THz IR-UWB WCS operation at such very high frequencies, it is advisable to use its own antenna for transmitting and receiving devices.

The block diagram of THz IR-UWB WCS of the "point-to-point" type with the separate antennas in the transmission and reception parts of corresponding stations is presented in Fig. 6.

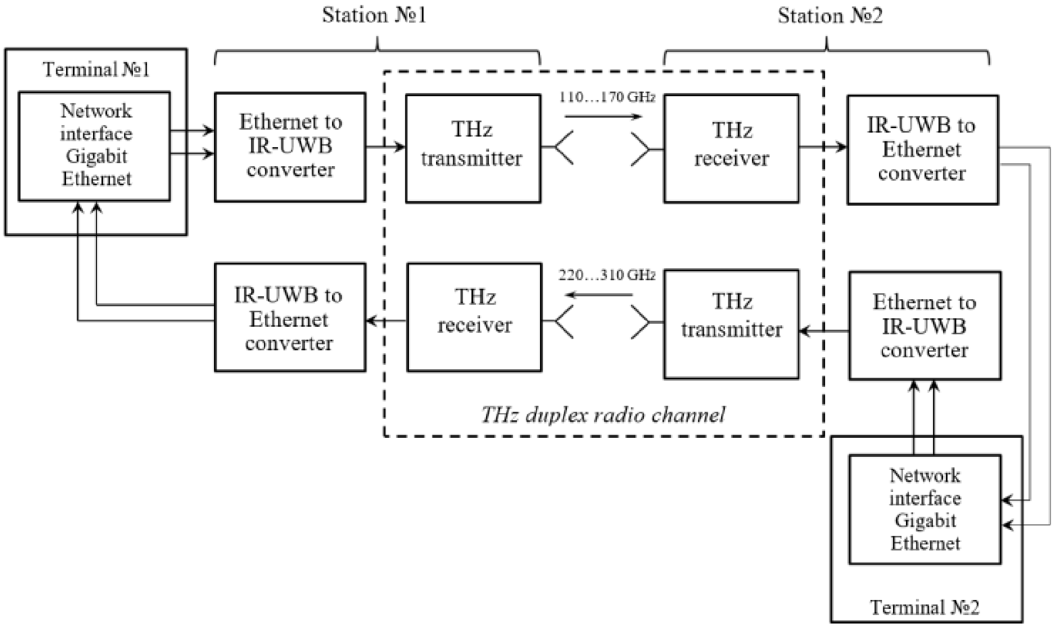


Fig. 6. Generalized block diagram of a point-to-point THz IR-UWB WCS with application of separate antennas in the transmission and reception parts of corresponding stations

According to Fig. 7, EMW of the 220...310 GHz band from Station №2 reaches the receiving antenna of Station №1 and excites currents in it, which inputs the THz receiver via the waveguide feeder line. As a receiving antenna in the 220...310 GHz band, for example, one can use the SAR-2507-03-S2 pyramidal horn antenna of Sage Millimeter, which has a gain factor of 23.5...25 dB, 11.1x9.3mm² aperture dimensions, width of the main lobe 9° in the E-plane and 10° in the H-plane, waveguide flange for rectangular waveguide WR3 or pyramidal horn antenna SGH-26-WR03 of ANTERAL, which has a gain factor of 26 dB, aperture dimensions of 11x8 mm².

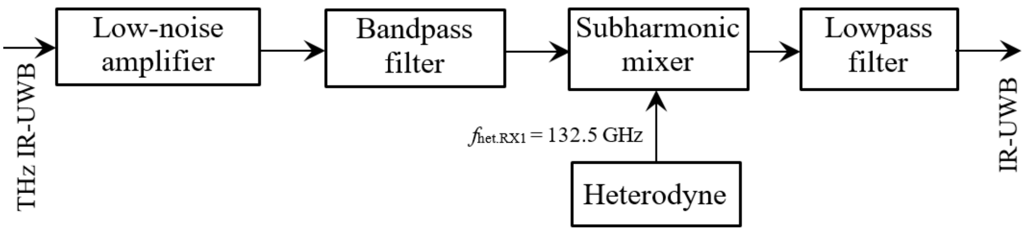


Fig. 7. Generalized block diagram of the THz receiver for receiving the THz IR-UWB signal and its conversion into an IR-UWB signal

As a feeder waveguide for connecting the THz receiver to the antenna a rectangular WR3 waveguide can be used which has cross-sectional dimensions of 0.863x0.4318 mm² and designed for operation in the 220-330 GHz frequency band. The cut-off frequency of such waveguide is 174 GHz for the main wave H_{10} and cut-off frequency of the first wave of higher type (H_{20}) is 348 GHz.

In the receiver of station №1 (Fig.1, Fig.6) according to Fig.7 THz IR-UWB signal:

– if necessary, it is sent to a low-noise amplifier of the 220...310 GHz band, where it is amplified by 10…15 dB;

– passes through a bandpass filter with a bandwidth of 220...330 GHz, which is designed for pre-filtering the received THz IR-UWB from noise signal, especially from the THz IR-UWB signal emitted by the transmitting antenna of station;

– enters to the radio-frequency input of the subharmonic diode mixer which operates in the downconverter mode; at the same time, the harmonic signal from the receiver local oscillator (heterodyne) with the frequency $f_{het.RX1}$ = 132.5 GHz will be sent to the heterodyne input of this mixer;

– the downconverted IR-UWB signal is filtered from other signals by a low-pass filter, the cut-off frequency of which is defined as $f_{LPF.RX.Cut\text{-}off} = f_{max}\text{-}2f_{het.RX}$=310-265=45 (GHz).

Next, the IR-UWB signal is sent to the IR-UWB signal converter to Ethernet signal, the block diagram of which is shown in Fig. 8.

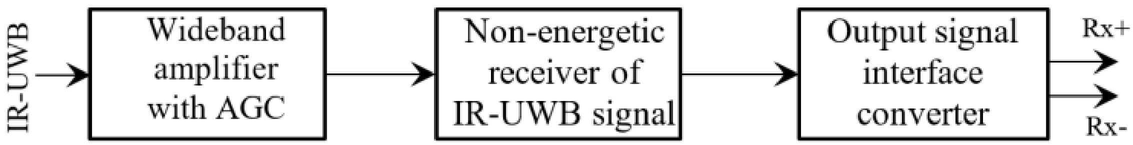


Fig. 8 Block diagram of the IR-UWB signal converter to Ethernet signal

According to Fig. 8, IR-UWB from the output of the THz receiver enters the wideband amplifier with automatic gain control, in which it is amplified to the level at which the normal operation of the "non-energetic" receiver of the IR-UWB signal, which included after the amplifier, is ensured. In a non-energetic IR-UWB receiver the IR-UWB signal is demodulated to the level of logical zero or logical one [17]. A pulse sequence at a speed of 1 Gbps from the output of IR-UWB receiver is sent to the output signal interface converter, which converts this digital pulse sequence into an electrical signal of an asymmetric interface of Gigabit Ethernet technology. Accordingly, the converted signal inputs via a twisted pair to the receiving channel of the subscriber terminal.

The principle of operation of Station №2 with connected subscriber terminal №2 can be described similarly, with the only difference being that the THz transmitter will operate in the 220...310 GHz band and the THz receiver – in the 110...170 GHz band.

III. Mathematical model of a THz IR-UWB WCS

The choice of the time duration of the IR-UWB signal based on the fact that the data rate via wireless channels should be V = 1 Gbps.

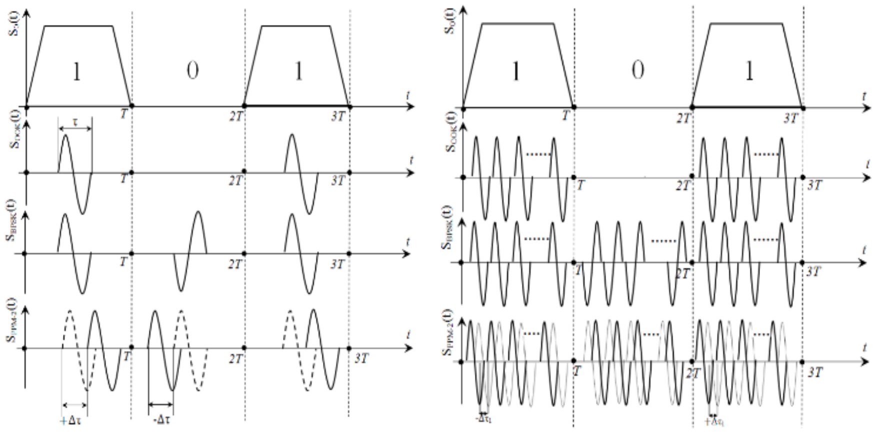
At the data transmission rate V of the digital stream entering to THz transmiter from the network interface of terminal or vice versa, the duration of one element (bit) of information, i.e., a logical "0" or a logical "1" should not exceed

$$T = \frac{1}{V} = 10^{-9}\,(\text{s}). \tag{1}$$

When a logical "0" or logical "1" pulse reaches the Ethernet to IR-UWB converter of the transmission path IR-UWB signals are formed at its output, and the following options are possible:

1) Logical "0" or logical "1" is transmitted using one IR-UWB pulse signal (Fig. 9,a) with different types of modulation.

2) Logical "0" or logical "1" is transmitted using several IR-UWB pulse signals (Fig. 9,b) with different types of modulation.



a) b)

Fig. 9. Transmission of an data sequence of logical "1" or logical "0"
a) when using one or b) several IR-UWB pulse signals with OOK, BPSK, and OOK modulation

The second method of transmission is more promising because, firstly, it allows to reduce the output power of the transmitter, and secondly, in the future, allows to ensure the multi-channel mode of operation of the WCS by representing the logical "0" and logical "1" with the address codes of the corresponding subscriber.

In paper [18], it is shown that when transmitting a logical "0" or a logical "1" by several IR-UWB signals in the form of a monocycle, the ratio of the bit energy to the noise spectral density is determined by the ratio

$$\frac{E_b}{N_0} = \frac{E_S N}{N_0} = \frac{P_S}{P_N} N, \tag{2}$$

where E_b is the required value of the energy of one monopulse (monocycle) at reception, N_0 is the white noise power spectral density, P_S is the power of the monopulse signal, P_N is the power of the noise, N is the number of monopulses per one information bit.

In logarithmic form, the ratio can be presented as

$$\left(\frac{P_S}{P_N}\right)_{dB} = \left(\frac{E_b}{N_0}\right)_{dB} - 10\lg N. \tag{3}$$

Therefore, increasing the number (N) of IR-UWB pulse signals at the time interval of one bit transmission reduces the required signal-to-noise ratio at the input of the THz receiver.

Currently, IR-UWB oscillators based on semiconductor devices (avalanche transistor, tunnel diode, step recovery diode) allow the generation of IR-UWB signals with the shortest duration of 50...150 ps. With such a short duration of the IR-UWB signal, it is quite difficult to form an IR-UWB signal with an amplitude exceeding several hundred millivolts. At the same time, the lower and upper limit of the frequency spectrum of the IR-UWB signal at the level of – 3 dB, according to [19], will be:

$$f_L = 0{,}319 f_c, \quad f_H = 1{,}922 f_c, \tag{4}$$

where f_c is the central frequency of the spectrum determined by the ratio

$$f_c = \frac{1}{\tau}. \tag{5}$$

At τ = 50 ps, we get f_L = 6.38 GHz, f_H = 38.44 GHz.

At τ = 125 ps, we get f_L = 2.55 GHz, f_H = 15.38 GHz.

From formula (5) and calculations, it can be seen that the width of the spectrum of the IR-UWB signal at the -3 dB level will be Δf =32.06 GHz at τ = 50 ps, and in the second case not less than Δf =12,83 GHz. When using subharmonic frequency conversion of the IR-UWB signal in the THz transmitter, the specified frequency band must be doubled since the spectrum of the THz IR-UWB signal will have upper and lower sidebands. Accordingly, it will be necessary to increase the bandwidth of the THz receiver which in turn leads to an increase in the level of inherent noise of the receiving tract. If the calculations are based on the level of -10 dB, then the indicated bandwidths will be even larger.

In this work, in accordance with the above, we assume that τ = 200 ps. Then f_L = 1.6 GHz, f_H =9.61 GHz, 2Δf = 16 GHz.

For the case when using OOK, BPSK, M-PAM modulations, the number of monocycles with a duration of 200 ps, which correspond to one information bit, will be equal to

$$N_1 = \frac{T}{\tau} = \frac{10^{-9}}{0.2 \cdot 10^{-9}} = 5. \tag{6}$$

When using multi-position PPM modulation to ensure the possibility of determining the fact which information bit ("0" or "1") is transmitted, each bit must be transmitted with a smaller number of IR-UWB signals than for OOK, BPSK, M-PAM. Let each bit, i.e., logical "0" or "1" when using PPM modulation, be represented by two IR-UWB signals with a duration of 200 ps, i.e., $N_2 = 2$.

When designing a "point-to-point" WCS based on IR-UWB signals application, it is necessary to consider the attenuation of EMW energy of the THz band in the atmosphere, which increases with increasing frequency, as it directly affects the data transmission distance. The main components of this attenuation are [9]:

– attenuation due to weakening of the radio signal by hydrometeors;

– attenuation due to radio signal absorption in gases;

– attenuation due to the influence of antenna directional diagrams.

The purpose of calculating the energy budget of THz IR-UWB WCS is to determine the maximum distance between corresponding stations with different types of IR-UWB signal modulation, which ensures the necessary bit error rate (BER).

Bit errors are the main source of the deterioration of communication quality, which is manifested in the distortion of speech in telephone channels, the unreliability of information transmission, or the reduction of the data transmission rate. Bit errors are characterized by statistical parameters and standards, which are determined by the corresponding probability of fulfilling these standards. The latter are divided into long-term and operational standards, the first of which are determined by ITU-T recommendations G.821 and G.826, and the second – M.2100, M.2110, and M.2120 recommendations. Thus, according to M.2100 [19], the quality of the digital path is divided into three categories according to the error criterion:

–normal – BER $< 10^{-6}$;

–reduced – $10^{-6} \le$ BER $< 10^{-3}$ (pre-abnormal state);

–unacceptable – BER $\ge 10^{-3}$ (abnormal state).

Let's assume that BER = 10^{-6}. As it was said earlier, when transmitting IR-UWB signals, the following types of modulation can be used: OOK, BPSK, PPM, PAM.

In Fig. 10 a), a graph presented of the BER dependence for OOK and BPSK modulation from E_b/N_0 [18]. According to this graph, at BER=10^{-6}, the necessary ratio E_b/N_0 = 14.25 dB with OOK modulation and E_b/N_0 = 10.5 dB with BPSK modulation.

According to Fig.10 b), at BER = 10^{-6} E_b/N_0 = 10.25 dB for 2-PAM modulation, E_b/N_0=14.25 dB for 4-PAM modulation, E_b/N_0 =18.5 dB for 8-PAM, E_b/N_0 =14.5 dB for 2-PPM modulation, E_b/N_0=11.5 dB for 4-PPM modulation, E_b/N_0 = 10 dB for 8-PPM modulation, E_b/N_0 = 9 dB for 16-PPM modulation, E_b/N_0 = 8 dB for modulation 32-PPM , E_b/N_0 = 7.5 dB for modulation 64-PPM.

Then, according to expression (3), taking into account Fig. 10, at T = 1 ns (corresponding to a data transmission rate of V=1 Gbps), we will obtain the following required values of the signal-to-noise ratio $(P_S/P_N)_{dB}$ at the receiver input, presented in Table 1.

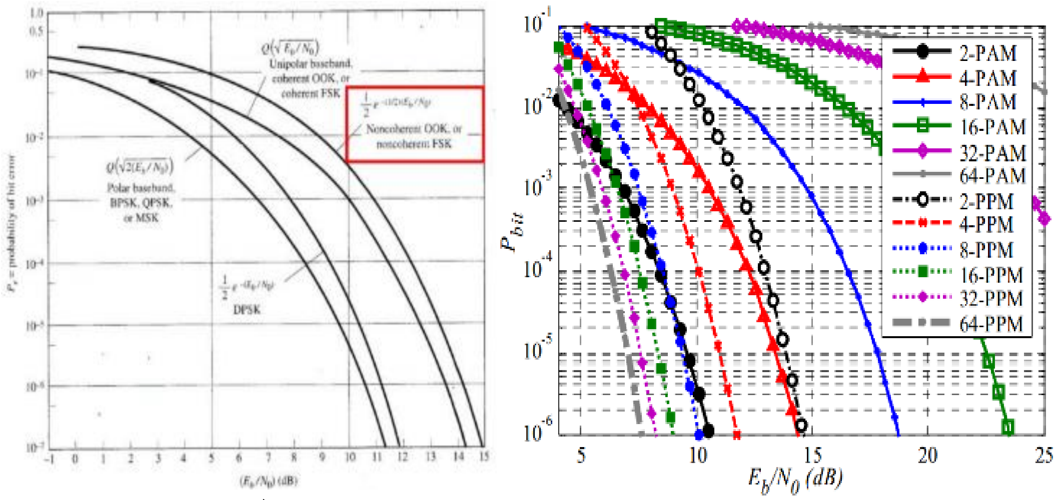


Fig. 10. The graph of the dependence of the BER on the ratio E_b/N_0 for: a) OOK, BPSK modulations; b) M-PAM and M-PPM modulations

The calculation of the THz IR-UWB WCS energy budget was performed for three possible options, depending on the type of conditions:

– ideal conditions (only free space attenuation is taken into account);

– conditions are close to real ones (attenuation in the atmosphere and attenuation in free space are taken into account);

– adverse conditions (attenuation in rain with intensity I = 35 mm/h is added to real conditions).

For all three cases, the calculation was performed for different central frequencies of the two bands 110…170 GHz and 220…310 GHz, when the frequency band of the THz IR-UWB signal is equal to Δf = 30 GHz.

Table 1. Dependence of the $(P_S/P_N)_{DB}$ Ratio from Signal Modulation Method

Modulation method	$(E_b/N_0)_{dB}$ = 10 dB at BER=10^{-6}	N	$(P_S/P_N)_{dB}$, dB
OOK	14.25	5	7.26
B PSK	10.5	5	3.51
2-PAM	10.25 _	5	3.26
4-PAM	14.25	5	7.26
8-PAM	18.25	5	11.26
2-PPM	1 4.5	2	11.5
4-PPM	11.5	2	8.5
8-PPM	10	2	7
16-PPM	9	2	6
32-PPM	8	2	5
64-PPM	7.5	2	4.5

The methodology for calculating distance R between corresponding stations of WCS assumes solving of the next transcendental equation

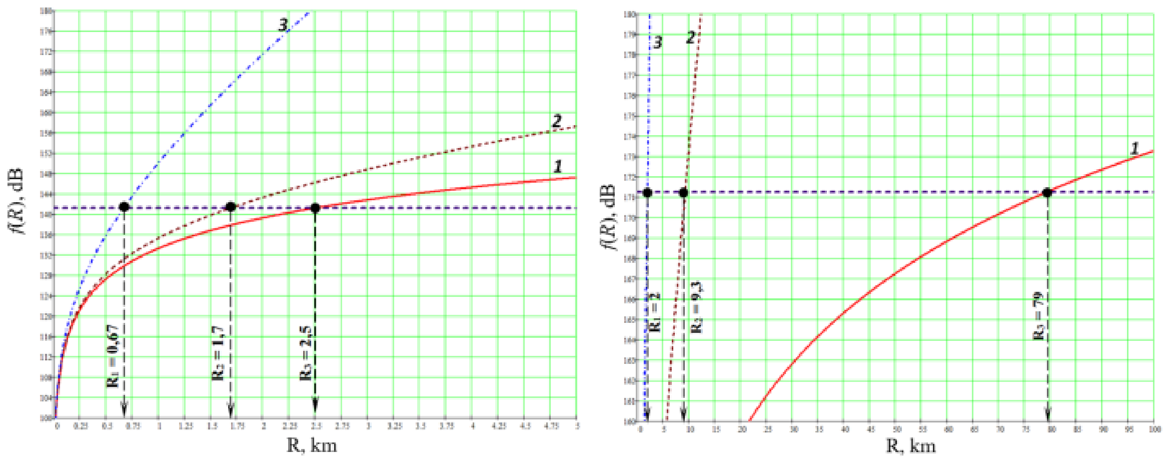
$$f(R)=C\,, \tag{7}$$

where $f(R)=L_{0[\text{dB}]}(R)+L_{\text{atm[dB]}}(R)+L_{\text{rain[dB]}}(R)$ is a function of total attenuation between corresponding stations, which includes free-space attenuation $L_{0[\text{dB}]}(R)$, total atmospheric losses in vapor and dry air $L_{0[\text{dB}]}(R)$, and attenuation in the rain $L_{\text{rain[dB]}}(R)$ which depends on distance R (in kilometers); C is the constant, which equals to

$$C=P_{\text{TX[dBW]}}+G_{\text{TX[dB]}}+G_{\text{RX[dB]}}-P_{\text{N[dBW]}}-\left(P_S/P_N\right)_{\text{[dB]}}, \tag{8}$$

where $P_{\text{TX[dBW]}}$ is THz transmitter output power, dBW; $G_{\text{TX[dB]}}$ and $G_{\text{RX[dB]}}$ are the gains of transmitting and receiving antennas, respectively, dB; $\text{P}_{\text{N[dBW]}}$ is the thermal noise power in the receiver, dBW; $(P_S/P_N)_{\text{[dB]}}$ is the required signal-to-noise ratio at the receiver input according to Table 1, dB.

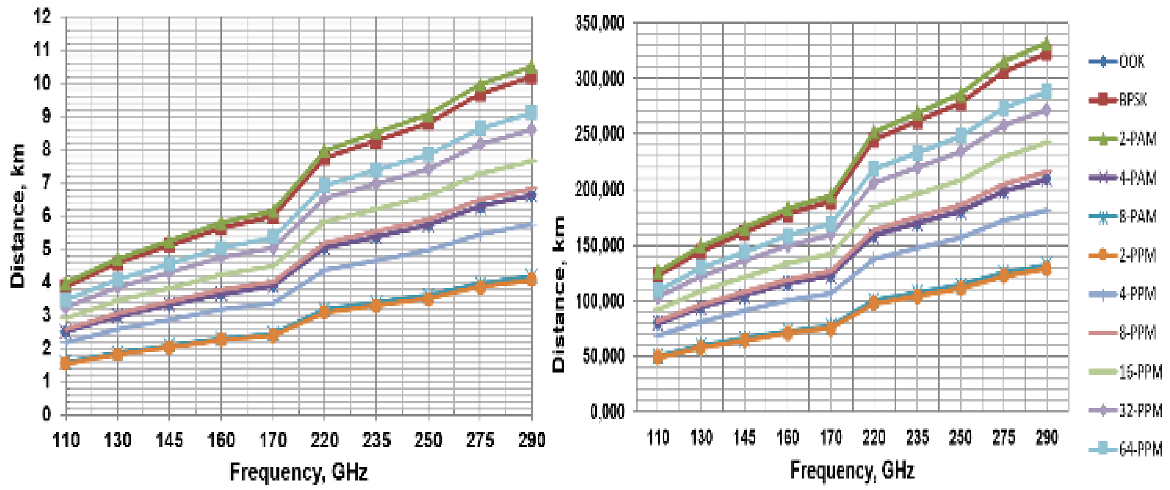
The equation (7) solution is possible either graphically or analytically using numerical methods. As an example, Fig. 11 shows the algorithm for finding distances between corresponding stations for three states of the EMW propagation environment (1 – ideal case, 2 – no rain, 3 – with rain) using a graph of the dependence of total losses *f*(*R*) from the distance *R*, constructed according to the expression (7) at a THz transmitter power of 50 μW and OOK modulation for a frequency of 110 GHz.



a) b)

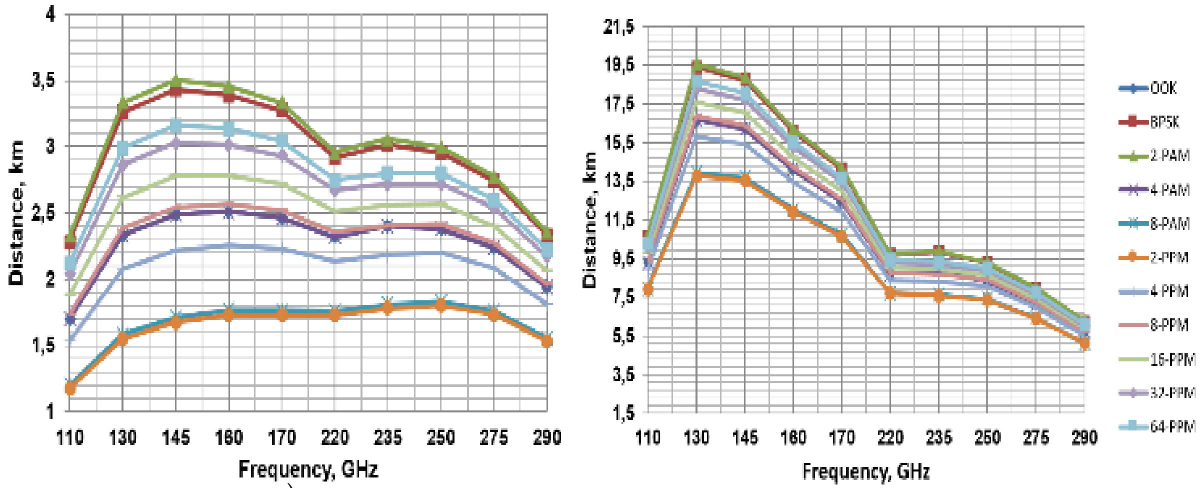
Fig. 11. Finding distances between corresponding stations for three states of the EMW propagation environment (1 – ideal case, 2 – no rain, 3 – with rain) using a plot of total loss *f*(*R*) versus distance *R* for the frequency of 110 GHz and modulation OOK at a transmitter power of: a) 50 μW (-13 dBm); b) 50 mW (+17 dBm)

Figures 12-14 show calculated graphical dependences of distance between corresponding stations of the THz IR-UWB WCS from the operating frequency for the case of the same antennas usage with the aperture diameter D = 0.3 m.



a) b)

Fig. 12. Graphs of the dependence of the range of the wireless telecommunication system on the frequency and different types of modulation of 50 μW for the ideal case of EMW propagation at the THz transmitter power: a) 50 μW (-13 dBm); b) 50 mW (+17 dBm)



a) b)

Fig. 13. Graphs of the dependence of the range of the wireless telecommunication system on the frequency and different types of modulation of 50 μW for the case of EMW propagation without rain at the THz transmitter power: a) 50 μW (-13 dBm); b) 50 mW (+17 dBm)

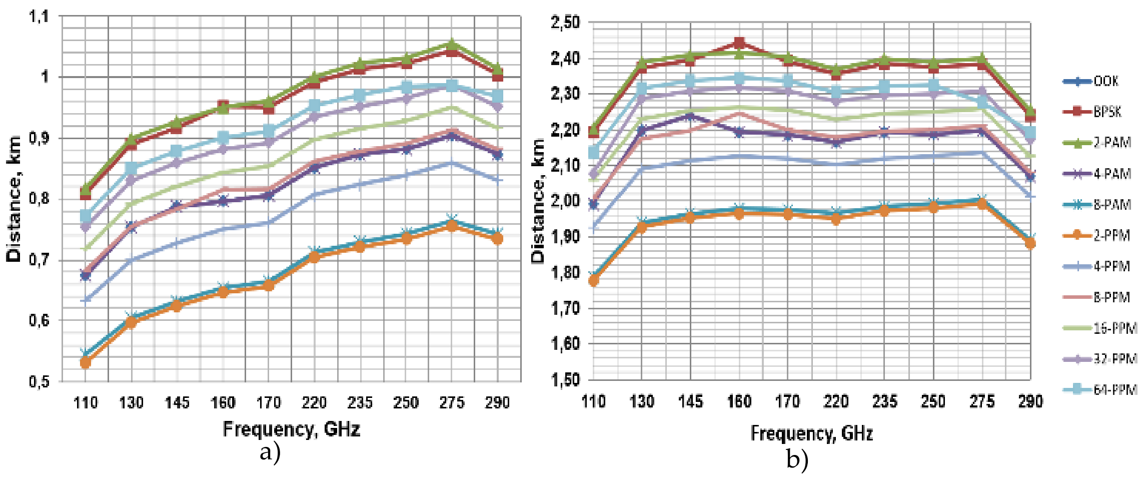


Fig. 14. Graphs of the dependence of the range of the wireless telecommunication system on the frequency and different types of modulation of 50 μW for the case of EMW propagation for the case of EMW propagation in rain at the THz transmitter power: a) 50 μW (-13 dBm); b) 50 mW (+17 dBm)

Conclusion

The variant of the WCS using IR-UWB signals in terahertz band has been proposed. An assessment of the potential distance between corresponding stations of line-of-sight WCS was carried for different conditions of EMW propagation and types of IR-UWB signal modulation performed, which shows that:

1) For the ideal case of EMW propagation, with an increase in the operating frequency, an increase in distance is observed, which is obviously due to the fact that energy losses in free space with an increase in frequency are compensated by an increase in the directivity of the transmitting and receiving antennas.

2) The maximum distance between the stations:

– in the absence of rain (that is, considering the losses in atmospheric gases) with the transmitter power P_{TX} = 50 μW is about r_{max} = 3.5 km at the frequency 145 GHz;

– in the absence of rain with the transmitter power P_{TX} = 50 mW is about r_{max} = 19.5 km at a frequency of 130 GHz;

– in the presence of rain with a precipitation intensity of rain I = 35 mm/h with the transmitter power P_{TX} = 50 μW is about r_{max} = 1.5 km at the frequency of 275 GHz;

– in the presence of rain with a precipitation intensity of rain I = 35 mm/h with the transmitter power P_{TX} = 50 mW is about r_{max} = 2.45 km at a frequency of 160 GHz.

This article will be useful for engineers and developers of terahertz wireless communication systems.

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