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# WIRELESS TERAHERTZ COMMUNICATIONS WITH SPECTRAL MODULATION OF ULTRA-WIDEBAND NOISE SIGNALS

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An ultra-wideband wireless communication system based on continuous carrier noise signals with low radiation level for digital information transfer in terahertz frequency range has been investigated. Autocorrelation and spectral methods of processing received ultra-wideband noise signals with coded spectral modulation are considered. The error probability on bit of transmit information versus the energetic signal to noise ratio at the receiver input is theoretically analyzed for different bit rate performance and frequency band of carrier noise signals. The proposed terahertz wireless communication system is characterized by high interference immunity and information transmission reliability under conditions when the amplitude of desired signal becomes lower then the interference level. The range of radio communication at low radiation power of ultra-wideband carrier noise signals is evaluated. The performed investigations confirm the development possibility of prospective ultra-wideband systems of noise communication.

## Introduction

The problem of prospective wireless personal area and intellectual networks [1—2] development in the terahertz frequency range can be successfully solved by implementation of high-velocity ultra-wideband systems of radio communication with low level of radiation. One of the prospective development areas of wireless personal area networks with spread spectrum technology is using complex noise signals with high information capacity [3—6]. The terahertz frequency range is currently of great interest for foundation of high-velocity interference-immunity communication. The successful development of the terahertz frequency range can be achieved by implementation of prospective information and telecommunication technologies, efficient methods of transmitting, receiving and processing broadband signals, including ultra-wideband chaotic noise signals [7, 8].

For optimal signal processing in systems of noise communication, an exact copy of coherent reference noise signal is required. The recovery of reference noise signal with frequency bandwidth over 1,000 MHz through local generator disposed in receiver is currently impossible. In communication systems with unknown properties of wideband signals or propagation channels, the transmitted reference methods are used. These methods are based on selection of informational and referenced signals on spectrum, time delay or on orthogonal polarizations with subsequent transmission of separated signals along the propagation channels [3, 6]. The method of ultra-wideband noise communication with coded spectral modulation using the delay channel diversity has been developed in [7, 8].

Transmitted reference methods are used in wideband communication systems in order to significantly simplify the structure of receivers as well as the whole transmission lines. In this case, at simultaneous transmission of informational and referenced signals through wireless communication line, the recovery of reference signal copy in the receiver by means of local generator is not required. The phase exact synchronization of referenced and informational signals at relative transmission is also not needed. The receiver synchronization is performed with lower requirements according to fed bit stream [3].

Therefore, it is justified to develop the terahertz ultra-wideband communication system based on combination of transmitted reference methods and spread spectrum technology with coded spectral modulation [2] in the transmitter.

In this paper, we propose the efficient spread spectrum technology at inserting the information in transmitter and spectral modulation in the receiver to enhance the throughput, interference immunity, electromagnetic compatibility and environmental safety of radio communication systems at the low level of radiated power. Formation, modulation, demodulation and processing of ultra-wideband noise signals in the transceiver are performed in the centimetre band [7, 8]. A semiconducting converter transfers carrier frequency of ultra-wideband signals into the terahertz range in the transmitter and exercises the reverse decreasing the frequency in the receiver. To carry out the correct up-and-down frequency transformation of ultra-wideband noise signals, it is important to maintain the thin spectral structure containing all transmitted information. We consider the spectral method of processing ultra-wideband noise signals in receiver and propose the technique of allocating the digital information maintained in them.

## Terahertz channel of noise radio communication

Fig. 1 demonstrates the functional diagram of communication link. In the transmitter, the continuous signal $n(t)$ from the noise source NS is supplied to the input of modulator M in which it is delayed on the time $T_1 = 10$ ns at receiving the symbol “1” or on the time $T_0 = 18$ ns at receiving the symbol “0”. We suppose that transmission coefficients $H_{1,0} = h_{1,0}\ \exp(i\theta_{1,0})$ and delays $T_{1,0}$ for both delayed signals do not depend from frequency $f$ in the range $\Delta f$ of noise signal $n(t)$. According to information bit stream, the delayed signals $H_1 n(t - T_1)$ or $H_0 n(t - T_0)$ are summarized in the modulator with the reference noise signal $n(t)$.

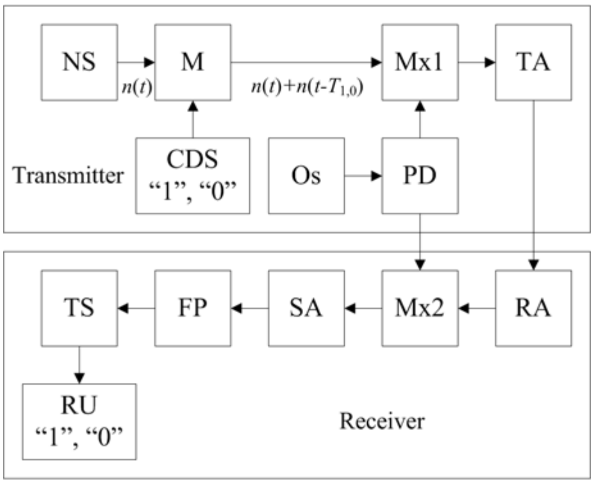


Fig. 1. Block diagram of the transmitter with code spectral modulation and the receiver with double spectral processing.

The total noise signal carrying the binary information is formed in the frequency range of 3.1—4.1 GHz. This summarized signal feeds the input of heterodyne detector Mx1. The reference signal of the generator Os feeds another input of the detector from the output of the power divider PD. The oscillations frequency of the reference generator is 130 GHz. The noise signal with coded spectral modulation is transmitted by the converter into the terahertz frequency range 133.1—134.1 GHz with retaining its thin spectral structure. By employing the narrow-beam antenna, the transformed signal is wirelessly transmitted to one or several subscribers. The radiated power is about 70 microwatt. To reach this level, the initial ultra-wideband signal is amplified by 12 decibels in order to compensate the signal losses at the up-conversion.

The reverse conversion of the terahertz signal into the ultra-wideband noise signal is exercised in the range of 3.1—4.1 GHz in the user’s receiver by mixer Mx2 completely retaining the information containing in it. Heterodyne mixers Mx1 and Mx2 are implemented as the same device performing various functions of the frequency increase in the transmitter and the frequency decrease in the receiver [2].

In the modulator M of the transmitter, the reference signal $n(t)$ is summarized with one of the signals delayed on time $T_1$ either on time $T_0$ according to received bit symbols “1” or “0”.

$$u(t) = n(t) + H_{1,0} n(t - T_{1,0})\,. \tag{1}$$

After heterodyning with up-converting the frequency into terahertz range, the total signal is radiated by the transmitter antenna TA and through radio propagation link is fed on input of the receiving antenna TR. The signal received by antenna TR feeds the input of the heterodyning down-converter Mx2 into initial frequency range. On the output of this converter in linear tract of the receiver, there is the additive composite of transmitted signal and receiver’s non-coherent intrinsic noises which can be written as follows:

$$z_{1,0}(t) = ku(t - t_k) + s(t)\,, \tag{2}$$

where the values $k$, $t_k$ present the total attenuation and delay of the carrier signal (1) in transmitting channel comprising the wireless propagation link, transmitting and receiving tracts with heterodynes.

The power spectrum of the received sum signal $z_{1,0}(t)$ calculated for the running time $T_b$ of one information signal is modulated by the periodic function:

$$\hat{S}_z(f) = \hat{S}_n(f)(1 + h_{1,0}^2 + 2h_{1,0}\xi) + \hat{S}_s(f)\,; \tag{3}$$
$$\xi = \cos(2\pi f T_{1,0} + \theta_{1,0})\,,$$

where $\hat{S}_s(f)$ denotes the additive spectrum component of the receiver’s non-coherent intrinsic noises.

The coded spectral modulation is fulfilled under summation of completely non-coherent signals when delays $T_1$ and $T_0$ of information signals $H_{1,0} n(t - T_{1,0})$ with respect to the reference signal $n(t)$ significantly exceed the coherency time $\tau_c \approx 1/(\Delta f)$ of the carrier ultra-wideband signal.

$$T_{1,0} >> \tau_c \text{ or } T_{1,0}\Delta f >> 1 \quad (4)$$

When completely non-coherent noise signals are summarized [5, 6] under the condition (4), the spectral density (2) is modulated by the harmonic function depending on the frequency $f$ with the periodicity scale $\delta f_{1,0} = 1/T_{1,0}$.

The broad band of frequencies $\Delta f >> \delta f_{1,0}$ of the carrier signal is a necessary condition for implementation of the proposed technique of the digital information transmission [7—8]. In this case, many periodicity scales $\delta f_{1,0}$ are packed in the band $\Delta f$ of the carrier signal.

Fig. 2 shows the power spectrum of received ultra-wideband noise signal under transmission of the binary signal "1" and the spectrum of receiver's intrinsic noises after heterodyning with frequency decrease in the receiver by the converter. The frequency band $\Delta f$ of the carrier noise signals is 1,000 MHz and the coherence time approximately equals $\tau_c \approx 1/(\Delta f) = 1$ ns. When the binary signal "1" is transmitted, the spectral modulation of the carrier noise signal is conducted with the period $\delta f_1 = 100$ MHz. If the binary signal "0" is transmitted, the spectral modulation is carried out with the period $\delta f_0 = 55.56$ MHz. As shown in Fig. 2, the depth of spectral modulation versus the current frequency is non-uniform that is a result of frequency and dispersive distortions of ultra-wideband signals in the transmission channel.

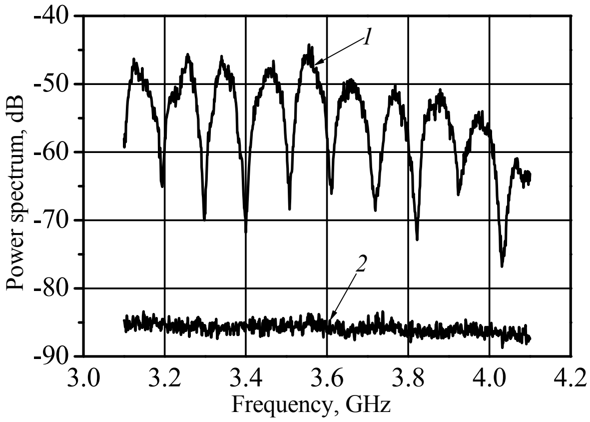


Fig. 2. Power spectrums of received ultra-wideband noise signal (*1*) with code spectrum modulation and receiver fluctuation noise (*2*).

After frequency down-heterodyning in the receiver, ultra-wideband noise signals are compressed into a band of the information message via dual spectral processing. In accordance with known formulas Wiener — Khintchine [10]

$$S_z(\omega) = \int_{-\infty}^{\infty} R_z(\tau) e^{-j\omega\tau} d\tau;$$
$$R_z(\tau) = \frac{1}{2\pi} \int_{-\infty}^{\infty} S_z(\omega) e^{j\omega\tau} d\omega, \quad (5)$$

the correlation $R_z(\tau)$ can be defined via inverse Fourier transform from power spectrum $S_z(\omega)$ of initial signal $z(t)$. Carrying out the inverse Fourier transform for power spectrum (4), we can find the correlation function of the received signal correlation function $z(t)$. Supposing $h_1 = h_0 = 1$ and taking into account (5), we obtain

$$\hat{R}_z(\tau) = 4\pi k^2 [\hat{R}_n(\tau) + \hat{R}_n(\tau - T_{1,0}) + \hat{R}_n(\tau + T_{1,0})] + \hat{R}_s(\tau), \quad (6)$$

where $k$ is the total attenuation coefficient of the signal in transmission link; $R_n(\tau), R_s(\tau)$ are autocorrelation functions of initial noise signal $n(t)$ and receiver intrinsic noises $s(t)$, respectively.

The correlation function (6) of the signal $z(t)$ contains information peaks $4\pi k^2[R_n(\tau - T_{1,0}) + R_n(\tau + T_{1,0})]$ with delay shift $\tau$ on the time $T_1$ or on the time $T_0$ according to transmitted bit stream, as well as the total correlation peak $4\pi k^2 R_n(\tau) + R_s(\tau)$ around the zero shift for both non-coherent the initial signal $n(t)$ and the receiver's intrinsic noise signal $s(t)$. The dual spectral analysis results in evaluation of the correlation function (6) of received noise signals $z(t)$ during the follow time $T_b$ of each information bit [10]:

$$\hat{R}_z(\tau) = \frac{1}{T_b} \int_{t}^{t+T_b} z(t) z^*(t+\tau) d\tau. \quad (7)$$

Evaluation of the correlation (6) and (7) during the finite follow time of each information bit transmitted by noise signals $n(t)$ is a random value with average mathematical expectation and dispersion. Even in the absence of receiver's intrinsic noises, the energy of each received information bit is randomly changed near its average value. This degrades probability characteristics of the communication system based on the noise signal applications. The final dispersion of random evaluation of correlation function (6) over shift times $T_1$ and $T_0$ defines probability characteristics of the communication system.

The recovery of transmitted binary information can be carried out by the following procedure. By employing the SA harmonic analyzer, the signal power spectrum is measured during the bit receiving time. The measured spectrum is presented as a sum of the received signal with coded spectral modulation and the receiver intrinsic noises. The digital Fourier processor FP calculates the autocorrelation function (Fig. 3) by fast reverse Fourier transform from the measured power spectrum. The calculated autocorrelation function comprises the information peak on the delay times $T_1$ or $T_0$ versus the current symbol "1" or "0". Quadrature sinusoidal (*2*) and cosine (*3*) spectral components have the beating in the range of correlation peak with crossing the zero level because of noise signal broadbandness. The complex correlation function of received ultra-wideband noise signal at transmission of bit "1" contains the information peak with the shift of 10 ns. The correlation peak length for quadrature components is determined by the correlation time and constitutes $\tau_c \approx 1/(\Delta f) = 1$ ns that correspond to $\Delta f = 1{,}000$ MHz frequency band of carrier noise signals. With the purpose of transmitted bit identification, the correlation peak assignment is performed by using the information about the form of envelope (*1*) for correlation function shown in Fig. 3.

The digital detector TS at the output of Fourier processor FP allocates the largest peak for the autocorrelation function. The resolver unit RU detects one of the binary symbols. In this way, the transmitted binary information is uniquely recovered.

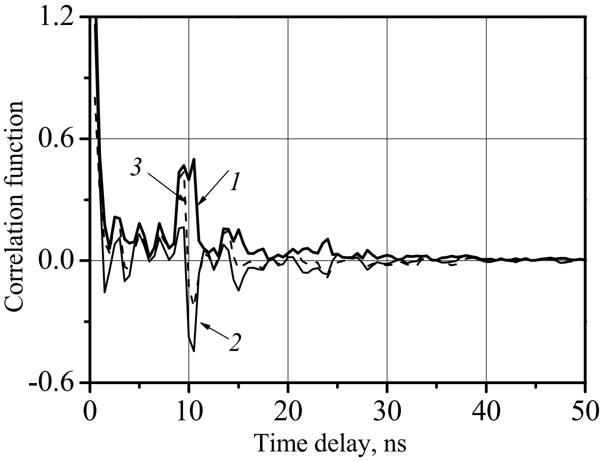


Fig. 3. Complex correlation function of received ultra-wideband noise signal at transmission of bit "1": (*1*) envelope; (*2*) sinusoidal and (*3*) cosine quadrature components.

## Theoretical analysis

According to Spread Spectrum Technology [3, 4], the receiver must perform the coherent compression of received ultra-wideband signals into the frequency band of transmitted information due to correlation [4, 5] or dual spectral [8] processing.

By using the reverse Fourier transform (5) from the power spectrum (3), the computer calculates the complex correlation function $R_z(\tau)$ which comprises the information peak with the shift on time $T_1$ or $T_0$ according to the stream of bits "1" or "0". The detector of maximal level defines modules $|R_z(T_0;T_{10})|$ and $|R_z(T_1;T_{10})|$ of correlation peaks $R_z(\tau;T_{10})$. The difference of correlation peak modules at $\tau = T_1$ and $\tau = T_0$ is compared with zero threshold $U_t = 0$ to determine the transmitted bit value. Correlation peak modules $r_0$ and $r_1$ for hypotheses $H_0$ and $H_1$ can be respectively expressed as

$$r_0(T_0) = |R_z(T_0;T_0)|,\ r_1(T_0) = |R_z(T_1;T_0)|; \tag{8}$$

$$r_0(T_1) = |R_z(T_0;T_1)|,\ r_1(T_1) = |R_z(T_1;T_1)|. \tag{9}$$

The demodulator compares these modules to each other ($r_0 > r_1$ or $r_0 < r_1$) that is equivalent to comparison of their differences $r_0 - r_1$ with zero threshold $U_t = 0$. To determine the error probability at the binary symbol transmission, it is necessary to previously define two-dimensional probability densities of random amplitudes $r_0$ and $r_1$ of complex correlation functions for two hypotheses $H_0$ and $H_1$. Denoting these probability densities via $w(r_0, r_1/H_0)$, $w(r_0, r_1/H_1)$ and applying the decision rule based on comparison of modules, we define conditional error probabilities at the transmission of bits "0" or "1" in the form [5]:

$$P(r_0 < r_1/H_0) = \int_0^\infty [\int_{r_0}^\infty w(r_0, r_1/H_0) dr_1] dr_0;$$
$$P(r_0 > r_1/H_1) = \int_0^\infty [\int_0^{r_0} w(r_0, r_1/H_1) dr_1] dr_0. \tag{10}$$

Supposing in (10) that the carrier noise signal $n(t)$ and receiver intrinsic noises $s(t)$ are stationary Gaussian random processes, we obtain final expressions for conditional error probabilities:

$$P(r_0 < r_1/H_0) = \int_0^\infty y \exp[-\frac{1}{2}(y^2 + \alpha_{00}^2)] I_0(\alpha_{00} y) Q(\alpha_{10}, y\gamma_0)\, dy; \tag{11a}$$

$$P(r_0 > r_1/H_1) = 1 - \int_0^\infty y \exp[-\frac{1}{2}(y^2 + \alpha_{01}^2)] I_0(\alpha_{01} y) Q(\alpha_{11}, y\gamma_1)\, dy, \tag{11b}$$

$$\alpha_{k\nu} = \frac{m_k(T_\nu)}{\sqrt{N_{kk}(T_\nu)}};\ \gamma_\nu = \sqrt{\frac{N_{00}(T_\nu)}{N_{11}(T_\nu)}}; \tag{12}$$

$$k = 0,1;\ \nu = 0,1$$

where $m_k(T_\nu)$, $N_{kk}(T_\nu)$ denote average values and dispersions for evaluation of the correlation function $R_z(\tau;T_{10})$; $Q(\alpha,\beta)$ is Marcum $Q$-function.

When priori probabilities of hypotheses are equal $P_a(H_0)=P_a(H_1)=0.5$, the total error probability is [5]:

$$P_{err}=0.5[P(r_0<r_1/H_0)+P(r_0>r_1/H_1)]. \quad (14)$$

Formulas (11)—(13) allow calculating the total error probability (14) of binary information transmission in wireless noise communication system using the spectral interference of carrier and delayed noise signals for bit coding under condition of appropriate choice of encoding delay values $T_0$ and $T_1$ which ratio should not be a multiple 2. The choice of delays must ensure small mutual correlation between fluctuation components of the function evaluation $R_z(\tau;T_{10})$ on times $\tau=T_0$ and $\tau=T_1$ for each of hypotheses $H_0$ or $H_1$.

## Characteristics of terahertz system of radio communication

The signal to noise ratio $q_b=E_b/N_s$ at signal detection with the bit energy $E_b$ against the background of noises with spectral power density $N_s$ is the important parameter of the radio communication system. Taking into account the expression (1), the traditional signal to noise ratio is transformed to $q_b=E_b/N_s=$ $=2\sigma_n^2 T_b/N_s$, where $\sigma_n^2$ denotes the dispersion of continuous noise signals $n(t)$; $T_b$ is the bit duration. The channel signal to noise ratio $q=2\sigma_n^2/\sigma_s^2$ is widely used to assess the system characteristics in practice [5, 6]. The energy signal to noise ratio $q_b$ and the channel signal to noise ratio $q$ are interconnected by a simple formula $q_b=\Delta f T_b q=Bq$, where the coefficient $B=\Delta f T_b=\Delta f/C_b$ is the base of carrier noise signal with the frequency band $\Delta f$ at the data transmission rate $C_b=1/T_b$.

The performed analysis shows that the information transmission with the low error probability per bit about $\mathrm{BER}=10^{-5}$—$10^{-6}$ should be carried out by ultra-wideband signals with a large base $B=500$—1,000. The bit transmission rate $C_b=1$—2 Mb/s is estimated from the expression for the signal base $B=\Delta f/C_b$ at the specified band $\Delta f=1{,}000$ MHz. The channel signal to noise ratio $q$ required for the terahertz system of radio communication constitutes the value from $-3$ dB to $-7$ dB at the transmission rate $C_b=1$—2 Mb/s with the error probability per bit $\mathrm{BER}=10^{-5}$—$10^{-6}$. The reliable data transmission under the noises influence at the negative signal to noise ratio $q$ from $-3$ dB to $-7$ dB when the desired signal at the receiving antenna output is several times less than the intrinsic noises or external interferences characterizes the high interference immunity and electromagnetic compatibility of the proposed terahertz system of radio communication.

The operating range of terahertz radio communication at the low radiation power of the transmitter 70 microwatt in the frequency band 133.1—134.1 GHz reaches 2,000 meters when beam antennas with the diameter of circular aperture 40 mm are used. However when mini-antennas with circular aperture 10 mm are utilized, the operating distance constitutes 150 meters.

## Conclusion

The performed research proves the possibility of terahertz radio communication systems creation for wireless data transmission with the rate 1—2 Mb/s at the error probability per bit less than $10^{-5}$ relying on ultra-wideband continuous noise signals with low radiation power about 70 microwatt in the frequency range 133.1—134.1 GHz.

The proposed system of terahertz noise radio communication with coded spectral modulation provides the reliable data transmission under existence of strong interference. It has high interference immunity, electromagnetic compatibility and environmental safety. The considered ultra-wideband system of noise communication can be applied in the wireless personal local WPAN networks of terahertz frequency range.

## References

1. Federici J., Moeller L. Review of terahertz and sub-terahertz wireless communications // Journal of Applied Physics. — 2010. — Vol. 107, 111101. — 22 p.

2. Sub-terahertz low power UWB communication link for WPAN / T. Narytnik, A. Amro, M. Ilchenko, V. Kalinin, O. Turabi // Network and Complex Systems. — 2012. — Vol. 2, N. 4. — P. 45—49.

3. Rushforth C. K. Transmitted-reference techniques for random or unknown channels // IEEE Transactions on Information Theory. — 1964. — Vol. 10, N. 1. — P. 39—42

4. Holmes J. K. Coherent spread spectrum systems. — New York: John Wiley & Sons, 1982. — 624 p.

5. Sklar B. Digital communications: Fundamentals and applications, 2nd edition. — Prentice Hall, 2001. — 1104 p.

6. Narayanan R. M., Chuang J. Covert communications using heterodyne correlation random noise signals // Electronics Letters. — 2007. — Vol. 43, N. 22. — P. 1211—1212.

7. Kalinin V. I. Spectral modulation of wideband noise signals // Journal of Communication Technology and Electronics. — 1996. — Vol. 41, N. 5. — P. 452—457.

8. Kalinin V. I. Ultra-wideband data transmission with double spectral processing of noise signals // Technical Physics Letters. — 2005. — Vol. 31, N. 11. — 2005. — P. 929—931.

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