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ABOUT THE POSSIBILITY OF ONE TYPE BROADBAND CHANNEL SIGNAL APPLICATION WITH LINEAR FREQUENCY MODULATION IN MULTI-CHANNEL SYSTEMS OF SATELLITE COMMUNICATION

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ABSTRACT

They consider the expediency of one class of broadband channel signal application created on the basis of intrapulse phase modulation according to the pseudo-random sequence (PRS) of a linear-frequency-modulated (LFM) radio pulse in multi-channel satellite communication systems with the code division of the frequency-time resources of a communication channel. In the framework of this paper, the uncertainty functions (UF) and the mutual uncertainty functions (MUF) of the proposed class of signals are studied in order to evaluate the effect of the Doppler frequency shift on its noise immunity and the dimension of an ensemble volume concerning weakly correlated forms of this signal. It was shown that the developed class of broadband channel signals (LFM-FM signals) can be used effectively in multi-channel satellite communication systems with code division of the frequency-time resources of a communication channel, since it has a large ensemble of slightly correlated forms in comparison with pseudo-random sequences and its noise immunity with Doppler frequency shift is comparable with the noise immunity of LFM radio pulse in the real limits of its change

Key words: multichannel satellite communication systems, code division method of frequency-time resources of a communication channel, broadband channel signals, pseudo-random sequences, linear frequency-modulated radio impulse, uncertainty functions.

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INTRODUCTION

During the development of modern multi-channel satellite communication systems, the method of a communication channel code division is widely used concerning frequency-time resources [1-4]. The main requirements for signals during their use in such systems are resistant to Doppler frequency mismatch and a large volume of slightly correlated form ensemble.

As is known [5-11], LFM signals have the property of invariance to the Doppler frequency mismatch, but they have a small ensemble of slightly correlated forms, while the signals formed by phase modulation of the harmonic carrier oscillation according to the law of pseudo-random sequence change (FM PSP) [1,3,4], have sufficient volumes of slightly correlated form ensemble, but they are not invariant to the Doppler frequency shift.

In this regard, the paper studies the possibility of FM PSP and LFM signal positive property combination to create broadband channel signals that would satisfy both requirements.

According to [12], LFM FM signals have the following mathematical form

$$S(t)=\begin{cases} S_0\cdot\sum\limits_{l=1}^{N}\nu_l\cdot rect\left\{\dfrac{t-(l-1)\cdot\tau_э-\dfrac{T}{2}-\dfrac{\tau_э}{2}}{\tau_э}\right\}\cdot\exp\left(j\mu\dfrac{t^2}{2}\right); & при\ \ |t|\le\dfrac{T}{2}\\ 0;\ \ при\ \ других\ \ t \end{cases} \tag{1}$$

where S_0 – is the amplitude of the enveloped signal, henceforth a constant value equal to 1, μ is the slope of LFM radio pulse modulation characteristic (frequency change rate), related to the frequency deviation ΔF and the signal duration T by the ratio $\mu = 2\cdot\pi\cdot\Delta F / T$, $\tau_э$ – the duration of PSP element; N is the number of elements in PSP; - the coefficient characterizing the state of PSP takes the values +1 or -1, $rect(x)$ – the rectangular "cut-off" function, $rect(x)=1,\ \ при\ \ |x|\le\frac{1}{2};0,\ \ при\ \ |x|>\frac{1}{2}$.

During the estimation of the simultaneous effect of mismatch by frequency and delay FN is used for the reception of channel signal quality, which according to [5] can be written as follows:

$$\dot{\chi}(\tau,F_д)=\frac{1}{2E}\int\limits_{-\infty}^{\infty}\dot{S}(t)\cdot\dot{S}^*(t-\tau)\cdot\exp(j2\pi F_д t)dt \tag{2}$$

where: τ – time shift between signals; $F_д$ – the additional frequency shift;

E – signal energy; $\dot{S}^{*}(t-\tau)$ – complex conjugated signal envelope.

In order to use the effect of Doppler frequency shift on the noise immunity of LFM-FM signals, we will study the envelope of their uncertainty functions (FN), since an incoherent processing method is used in non-frequency-frequency radio channels. In mathematical form, the expression for the enveloping FN (2) after a series of transformations can be written as follows:

$$\left|\dot{\chi}(\tau,F_{\text{д}})\right| = \frac{1}{N}\cdot\left\{\left[\left[\frac{\sin\left(\frac{2\pi F_{\text{д}}+\mu(|p|\tau_{\text{э}}+|\theta|)}{2}(\tau_{\text{э}}-|\theta|)\right)}{\frac{2\pi F_{\text{д}}+\mu(|p|\tau_{\text{э}}+|\theta|)}{2}(\tau_{\text{э}}-|\theta|)}\cdot\left(1-\frac{|\theta|}{\tau_{\text{э}}}\right)\cdot\sum_{l=1}^{N-|p|}\nu_l\cdot\nu_{l+p}\cdot\cos\left(\frac{2\pi F_{\text{д}}+\mu(|p|\tau_{\text{э}}+|\theta|)}{2}\times\right.\right.\right.\right.$$

$$\left.\times(2l-1)\cdot\tau_{\text{э}}\right)+\frac{\sin\left(\frac{2\pi F_{\text{д}}+\mu(|p|\tau_{\text{э}}+|\theta|)}{2}\cdot|\theta|\right)}{\frac{2\pi F_{\text{д}}+\mu(|p|\tau_{\text{э}}+|\theta|)}{2}\cdot|\theta|}\cdot\frac{|\theta|}{\tau_{\text{э}}}\cdot\sum_{l=1}^{N-|p|-1}\nu_l\cdot\nu_{l+p+1}\cdot\cos\left(\left(2\pi F_{\text{д}}+\mu(|p|\tau_{\text{э}}+|\theta|)\right)\cdot l\tau_{\text{э}}\right)\Bigg]^2+$$

$$+\frac{\sin\left(\frac{2\pi F_{\text{д}}+\mu(|p|\tau_{\text{э}}+|\theta|)}{2}(\tau_{\text{э}}-|\theta|)\right)}{\frac{2\pi F_{\text{д}}+\mu(|p|\tau_{\text{э}}+|\theta|)}{2}(\tau_{\text{э}}-|\theta|)}\cdot\left(1-\frac{|\theta|}{\tau_{\text{э}}}\right)\cdot\sum_{l=1}^{N-|p|}\nu_l\cdot\nu_{l+p}\cdot\sin\left(\frac{2\pi F_{\text{д}}+\mu(|p|\tau_{\text{э}}+|\theta|)}{2}\cdot(2l-1)\cdot\tau_{\text{э}}\right)+$$

$$\left.\left.+\frac{\sin\left(\frac{2\pi F_{\text{д}}+\mu(|p|\tau_{\text{э}}+|\theta|)}{2}\cdot|\theta|\right)}{\frac{2\pi F_{\text{д}}+\mu(|p|\tau_{\text{э}}+|\theta|)}{2}\cdot|\theta|}\cdot\frac{|\theta|}{\tau_{\text{э}}}\cdot\sum_{l=1}^{N-|p|-1}\nu_l\cdot\nu_{l+p+1}\cdot\sin\left(\left(2\pi F_{\text{д}}+\mu(|p|\tau_{\text{э}}+|\theta|)\right)\cdot l\tau_{\text{э}}\right)\right]^2\right]^{1/2}\right\}$$

(3)

where: $\tau = p\tau_{\text{э}}+\theta, p=\pm(0,\ 1,\ 2,\ \ldots,\ N-1,\ N), 0\le|\theta|\le\tau_{\text{э}}$.

The result of the performed computational experiments is the obtaining of the enveloping FN LFM-FM signals with the changes in the values of the Doppler frequency shift within the real limits of its variation ($F_{\text{д}}$ from 0 to 50 kHz) the typical examples of which for different LFM base ratios of a radio pulse ($\Delta F \bullet T$) to the base of the pseudo-random sequence (N) are presented on Figures 1, 2.

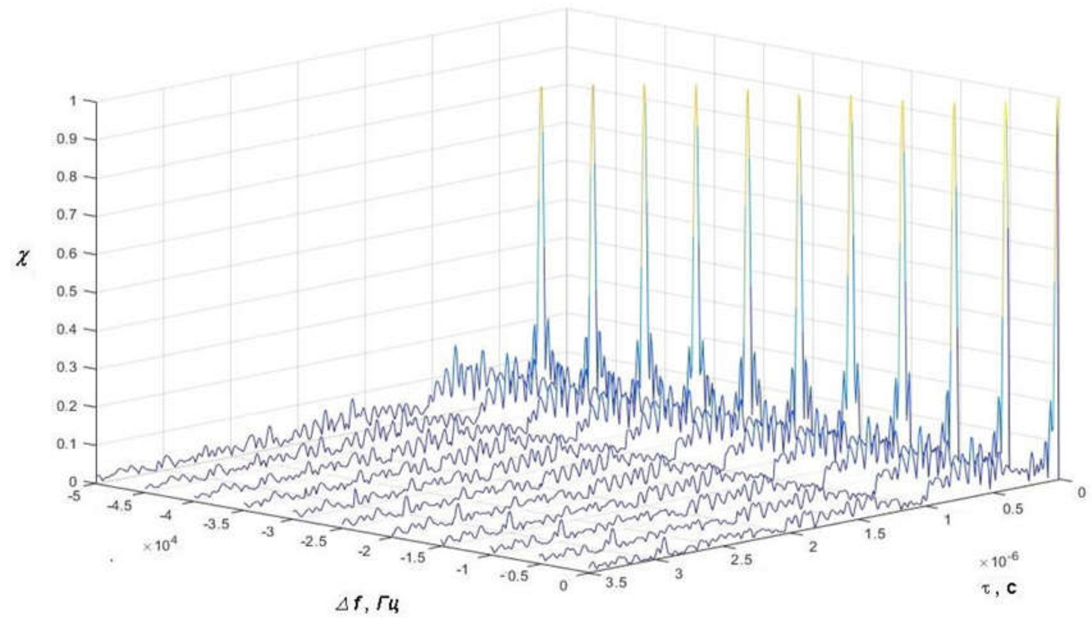

Fig.1. The values of the envelope of the uncertainty function of the LFM-FM signal at $\Delta F \bullet T = 1000$, N = 31

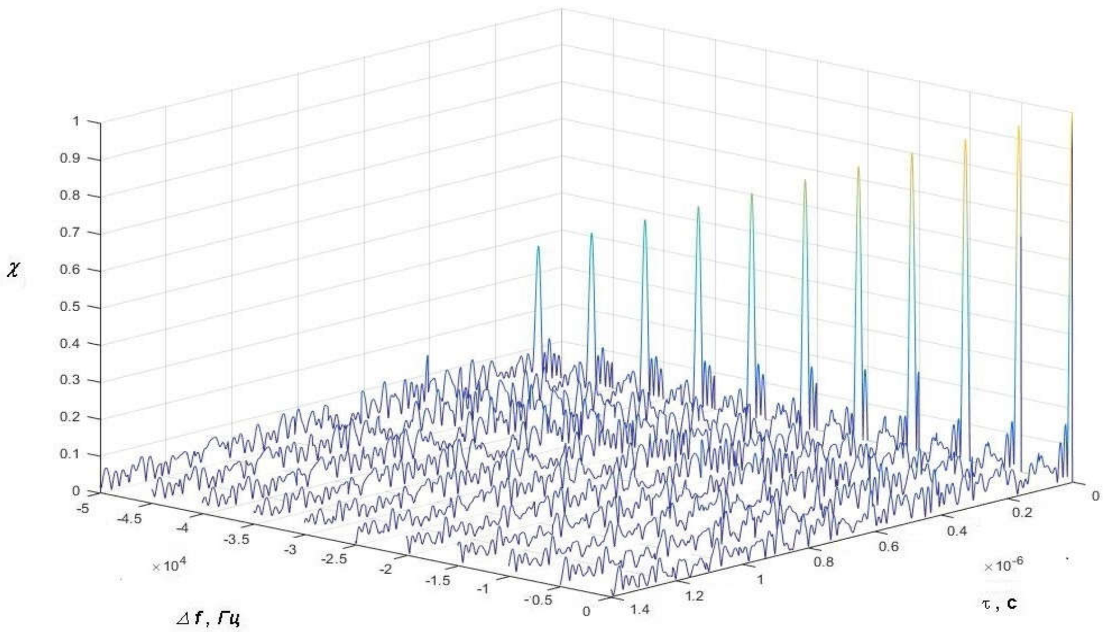

Fig.2. The values of the envelope of the uncertainty function of the LFM-FM signal at $\Delta F \bullet T = 1000$, N = 127

On the basis of the obtained numerical data about the change of the maximum values of enveloping FN LFM-FM signals, the graphs of their noise immunity were plotted, depending on the signal/noise ratio in the communication channel, the values of the ratio

$\Delta F \bullet T$ /N and the Doppler frequency shift within its real variation (Fd from 0 to 50 kHz), which are presented on Figures 3, 4.

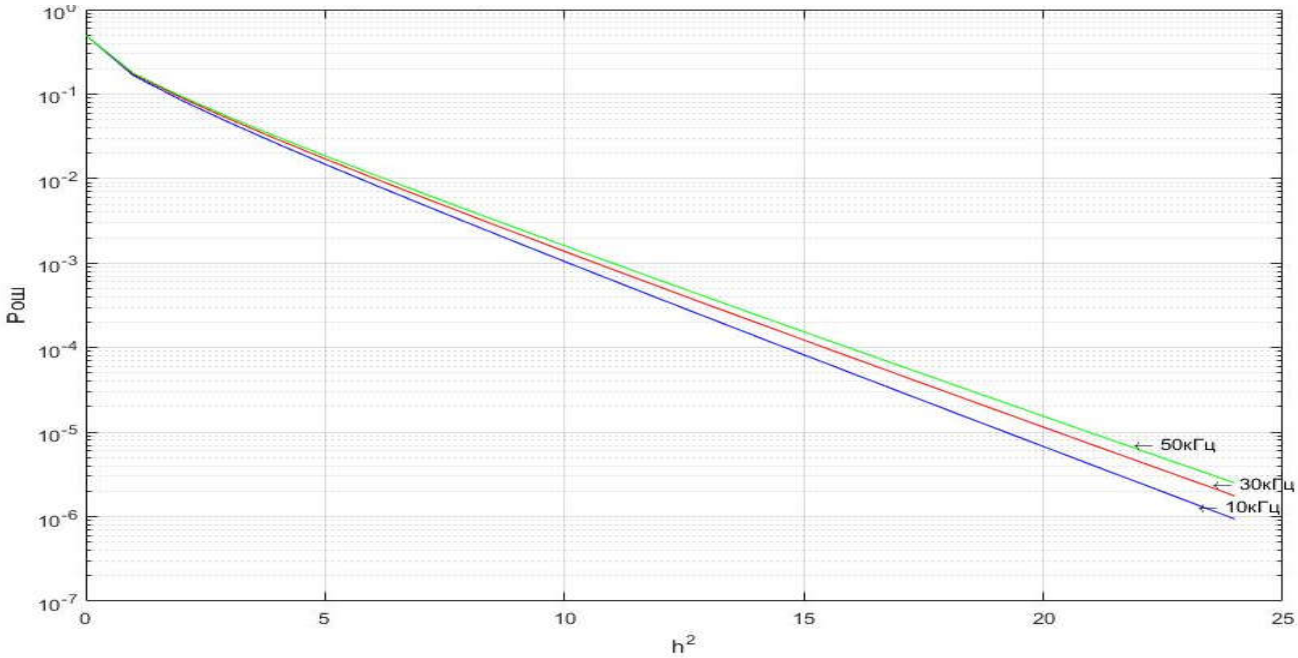

Fig.3. The graph of the probability of the error of the LFM-FM signal with $\Delta F \bullet T$ = 1000,N = 31 depending on the value of the signal-to-noise ratio, at F_d = 10,30 and 50 kHz

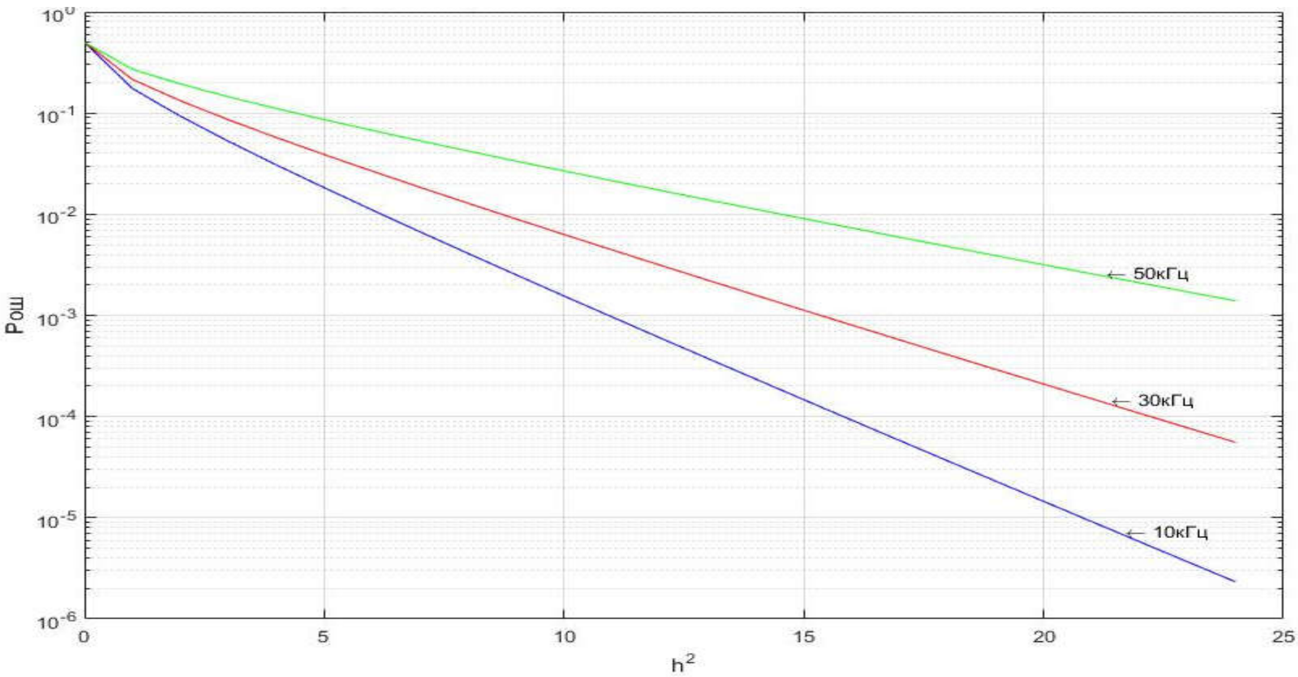

Fig.4. The graph of the probability of the error of the LFM-FM signal with $\Delta F \bullet T$ = 1000,N = 127 depending on the value of the signal-to-noise ratio, at F_d =10,30and 50 kHz

For a comparative evaluation of LFM-FM, FM PSP and LFM signal noise immunity with the same parameters figures 5.6 show the probability curves for the error of FM PSP and LFM signals, depending on the magnitude of the signal-to-noise ratio in a communication channel at different F_∂ values.

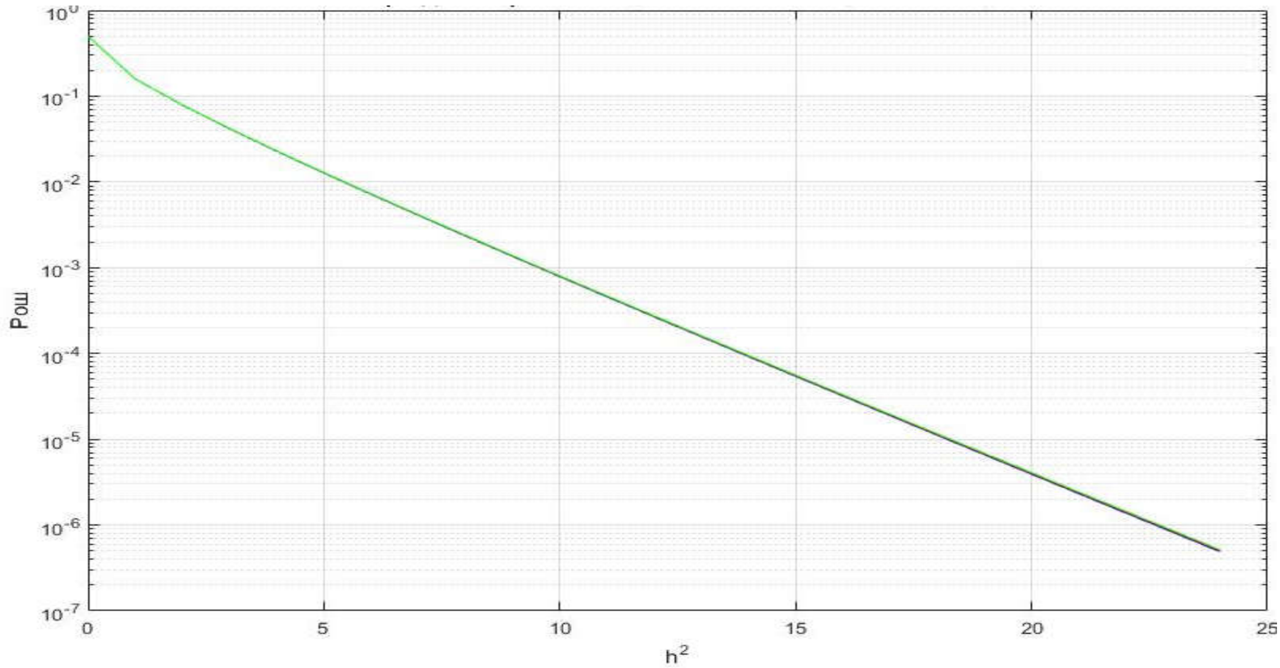

Fig.5. The graph of the probability of the error of the LFM signal with $\Delta F \bullet T$ = 1000 depending on the value of the signal-to-noise ratio, at F_d =10, 30 and 50 kHz

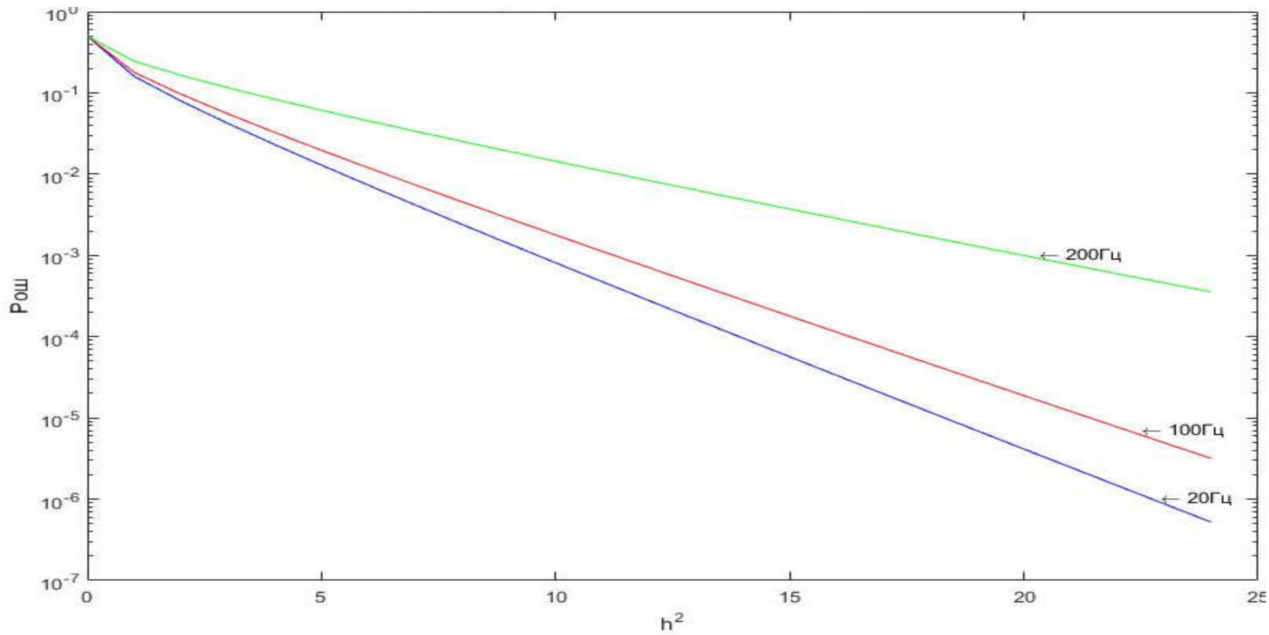

Fig.6. Graph of the probability of error FM PSP signal with N = 31 depending on the value of the signal-to-noise ratio at F_d = 20, 100 and 200 Hz

Broadband channel signals with LFM, like most other classes of broadband channel signals, are not orthogonal with an arbitrary time and frequency shift, in this case one can speak only of the quasi orthogonality of these signals, that is, about the transition of such a class of signals from a LFM to an orthogonal class.

In order to estimate the degree of signal orthogonality with their time and frequency offset they use the function of mutual uncertainty (FMU), which according to [5] can be written as follows in mathematical form:

$$\dot{\chi}_{ij}(\tau, F_\partial) = \frac{1}{2E}\int_{-\infty}^{\infty} \dot{S}_i(t)\cdot \dot{S}_j^{\,*}(t-\tau)\cdot \exp(j2\pi F_\partial t)\,dt \tag{4}$$

where: $\dot{S}_i(t)$ the enveloping element of the i-th signal, $\dot{S}_j^{\,*}(t-\tau)$ – the complex conjugate enveloping element of the j-th signal.

For LFM-FM signals, the expression for the enveloping element of FMU after a series of transformations can be represented as follows:

$$\begin{aligned}\left|\dot{\chi}_{ij}(\tau,F_\partial)\right| = \frac{1}{N}\cdot\Bigg\{\Bigg[\Bigg[& \frac{\sin\left(\frac{2\pi F_\partial+\mu(|p|\tau_Э+|\theta|)}{2}(\tau_Э-|\theta|)\right)}{\frac{2\pi F_\partial+\mu(|p|\tau_Э+|\theta|)}{2}(\tau_Э-|\theta|)}\cdot\left(1-\frac{|\theta|}{\tau_Э}\right)\cdot\sum_{l=1}^{N-|p|}\nu_l^i\cdot\nu_{l+p}^j\cdot\cos\Bigg(\frac{2\pi F_\partial+\mu(|p|\tau_Э+|\theta|)}{2}\times \\ & \times(2l-1)\cdot\tau_Э\Bigg)+\frac{\sin\left(\frac{2\pi F_\partial+\mu(|p|\tau_Э+|\theta|)}{2}\cdot|\theta|\right)}{\frac{2\pi F_\partial+\mu(|p|\tau_Э+|\theta|)}{2}\cdot|\theta|}\cdot\frac{|\theta|}{\tau_Э}\cdot\sum_{l=1}^{N-|p|-1}\nu_l^i\cdot\nu_{l+p+1}^j\cdot\cos\left(\left(2\pi F_\partial+\mu(|p|\tau_Э+|\theta|)\right)\cdot l\tau_Э\right)\Bigg]^2+ \\ & +\Bigg[\frac{\sin\left(\frac{2\pi F_\partial+\mu(|p|\tau_Э+|\theta|)}{2}(\tau_Э-|\theta|)\right)}{\frac{2\pi F_\partial+\mu(|p|\tau_Э+|\theta|)}{2}(\tau_Э-|\theta|)}\cdot\left(1-\frac{|\theta|}{\tau_Э}\right)\cdot\sum_{l=1}^{N-|p|}\nu_l^i\cdot\nu_{l+p}^j\cdot\sin\left(\frac{2\pi F_\partial+\mu(|p|\tau_Э+|\theta|)}{2}\cdot(2l-1)\cdot\tau_Э\right)+ \\ & +\frac{\sin\left(\frac{2\pi F_\partial+\mu(|p|\tau_Э+|\theta|)}{2}\cdot|\theta|\right)}{\frac{2\pi F_\partial+\mu(|p|\tau_Э+|\theta|)}{2}\cdot|\theta|}\cdot\frac{|\theta|}{\tau_Э}\cdot\sum_{l=1}^{N-|p|-1}\nu_l^i\cdot\nu_{l+p+1}^j\cdot\sin\left(\left(2\pi F_\partial+\mu(|p|\tau_Э+|\theta|)\right)\cdot l\tau_Э\right)\Bigg]^2\Bigg\}^{1/2}\end{aligned} \tag{5}$$

where ν^i and ν^j are the coefficients describing the PSP state of the i-th and the j-th signals.

The analysis of the cross sections concerning the enveloping FVN LFM-FM signals obtained during phase modulation by pseudo-random sequences of LFM radio pulses with the same steepness of the modulation characteristic, the plane F_∂=0, made it possible to establish that the maximum level of lateral ejection is practically independent of LFM radio pulse base

($\Delta F \bullet T$), and is determined mainly by PSP length and type. The values of the maximum levels of lateral emissions are within $\frac{(1.0-4.0)}{\sqrt{N}}$. At arbitrary time ($\tau$) and frequency ($F_\partial$) mismatches, the maximum values of the lateral emission levels are within $\frac{(1.5-4.3)}{\sqrt{N}}$.

The consideration of LFM FM signal properties, in which the difference in the structure is both the structure of PSP and the slope of the LFM radio pulse modulation characteristic is of particular interest. For these signals FVN in mathematical form can be represented by the following relation:

$$\left|\dot{\chi}_{ij}(\tau,F_\partial)\right| = \frac{1}{\sqrt{2\bullet(\Delta F_1-\Delta F_2)\bullet T}} \bullet \{[\sum_{l=1}^{N-|p|} v_l^i \cdot v_{l+p}^j \bullet ((C(x_2)-C(x_1)) + \sum_{l=1}^{N-|p|-1} v_l^i \cdot v_{l+p+1}^j \bullet ((C(x_4)-C(x_3))]^2 +$$
$$+[\sum_{l=1}^{N-|p|} v_l^i \cdot v_{l+p}^j \bullet ((S(x_2)-S(x_1)) + \sum_{l=1}^{N-|p|-1} v_l^i \cdot v_{l+p+1}^j \bullet ((S(x_4)-S(x_3))]^2\}^{1/2} \tag{6}$$

where $C(x)=\int_0^x Cos(\frac{\pi y^2}{2})dy$ is the cosine of the Fresnel integral, $S(x)=\int_0^x Sin(\frac{\pi y^2}{2})dy$ is the sine of the Fresnel integral, and $x_1 - x_4$ are the arguments of the Fresnel integrals, which are written as follows in mathematical form:

$$x_4 = \frac{2}{\sqrt{2\bullet(\Delta F_1-\Delta F_2)\bullet T}} \bullet ((l\bullet\tau_э - \frac{T}{2})\bullet(\Delta F_1-\Delta F_2) + (p\bullet\tau_э+\theta)\bullet\Delta F_1 + F_\partial\bullet T),$$

$$x_3 = \frac{2}{\sqrt{2\bullet(\Delta F_1-\Delta F_2)\bullet T}} \bullet ((l\bullet\tau_э - \frac{T}{2})\bullet(\Delta F_1-\Delta F_2) + p\bullet\tau_э\bullet\Delta F_1 + F_\partial\bullet T + \theta\bullet\Delta F_2),$$

$$x_2 = \frac{2}{\sqrt{2\bullet(\Delta F_1-\Delta F_2)\bullet T}} \bullet ((l\bullet\tau_э - \frac{T}{2})\bullet(\Delta F_1-\Delta F_2) + p\bullet\tau_э\bullet\Delta F_1 + F_\partial\bullet T + \theta\bullet\Delta F_2)$$

$$x_1 = \frac{2}{\sqrt{2\bullet(\Delta F_1-\Delta F_2)\bullet T}} \bullet (((l-)\bullet\tau_э - \frac{T}{2})\bullet(\Delta F_1-\Delta F_2) + (p\bullet\tau_э+\theta)\bullet\Delta F_1 + F_\partial\bullet T).$$

During the evaluation of the lateral enveloping FVN emissions of this class of signals, it was found that their largest values are within $\frac{(1.5-2)}{\sqrt{(\Delta F_1-\Delta F_2)\bullet T}}$ at the ratios of $\frac{\Delta F\bullet T}{N} >> 1$ and are practically independent of PSP type and length. Besides, it should be noted that at $(\Delta F_1-\Delta F_2)\bullet T >> 100$ the level of lateral emissions is almost independent of the shift magnitude between the signals.

The analysis of side section emission levels of enveloping FVN LFM FM signals at $\frac{\Delta F \bullet T}{N} << 1$ shows that the maximum lateral emission levels of enveloping FVN are determined mainly by the length and the type of PSP and are within $\frac{(1.0-4.0)}{\sqrt{N}}$.

It is easy to see that if τ = 0 and with the same PSP structures the expression (6) can be represented by the following relation after a series of transformations:

$$\left|\dot{\chi}_{ij}\left(\tau, F_{\partial}\right)\right| = \frac{2}{\sqrt{2 \bullet (\Delta F_1 - \Delta F_2) \bullet T}} \sqrt{C^2(x_2) + S^2(x_2)}\,, \tag{7}$$

i.e. the expression coincides with the expression for the enveloping FVN of "ordinary" radio pulses with different parameters of the modulation characteristics.

In order to use LFM FM signals in the multichannel systems of satellite communication with the code division of time-frequency resources of a communication channel, as was noted above, much attention is paid to their ensemble performance. It should be noted that the signs of the differences among the designed classes of signals are either PSP structure or a PSP structure and the slope of the LFM modulation characteristic for a radio pulse. In this regard, one can use the following relation to quantify the ensemble characteristics:

$$N = N_{ПСП} \bullet N_{ЛЧМ} \tag{8}$$

where $N_{ПСП}$ is the number of different forms in the ensemble of used PSP,

$N_{ЛЧМ}$ - the number of different forms in the ensemble of LFM radio impulses.

Both linear and nonlinear sequences can be used, as well as PSP with varying durations can be used as pseudo-random sequences.

According to (8) it is clear that the scope of LFM FM signals with the same steepness of LFM radio pulse modulation characteristic is equal to the ensemble of PSP and the amount of LFM FM signals with a varying slope of the modulation characteristic for LFM radio pulses is equal to the product of PSP and LFM ensembles of radio pulses.

Thus, the developed signal classes, with different steepness of LFM radio pulse modulation characteristic, have a much larger volume for the ensemble of weakly correlated forms, in comparison with pseudorandom sequences, and with the same steepness of the modulation characteristic equal to the volume of the ensemble possessed by PSP.

SUMMARY

The work studied the enveloping elements of uncertainty functions and the functions of mutual uncertainty of one of the classes of complex signals with LFM. It is concluded that this class of signals has a much larger volume of slightly correlated form ensemble, as compared to PSP volume, if LFM radio pulses with different steepness of modulation characteristics are used as a main oscillation. In addition to this, the noise immunity values of LFM FM signals, when the ratio of LFM radio pulse base to the base of PSP is more than ten, are comparable with the noise immunity of a radio pulse LFM in the case of Doppler frequency shifts within its actual variation (Fd from 0 to 50 kHz).

CONCLUSIONS

The developed class of broadband channel signals (LFM-FM signals) is advisable to use in multi-channel satellite communication systems with code division of the frequency-time resources within a communication channel, especially when a retransmitter is in a highly elliptical orbit, since this class of signals has much larger sequences as compared to pseudorandom ones, the volume of weakly correlated forms ensemble, and its noise immunity is comparable with the noise immunity of LFM radio pulse at the Doppler frequency shift, within the real limits of its variation

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