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Evaluation of the Impact of Doppler Effect on Quality of HSR Radiocommunications

Lyubov M. ZHURAVLEVA **Mikhail A. NILOV** **Vladimir L. LOSHKAREV** **Vladislav V. LEVSHUNOV**

Zhuravleva, Lyubov M., *Russian University of Transport, Moscow, Russia.*
Nilov, Mikhail A., *PJSC Megafon, Moscow, Russia.*
Loshkarev, Vladimir L., *PJSC Megafon, Moscow, Russia.*
Levshunov, Vladislav V., *PJSC MAXIM, Moscow, Russia*.*

ABSTRACT

The article proposes a methodology for evaluating radio signal distortions caused by Doppler effect (DE; also, Doppler shift) under the conditions of high-speed train traffic (HSR, high-speed rail). The objective of the work is to develop criteria for assessing quality of radiocommunications with moving objects in HSR environment. For this, a technique is proposed for calculating the probability of an error arising from Doppler effect. A rationale for relevance of the topic is that radiocommunications are used on railways for controlling train traffic and ensuring safety and achieving required quality of radio signals is a major challenge. Quality assessment is especially important for organization of broadband communication channels with locomotive drivers using mobile networks. To solve this problem, a model for assessing quality of radiocommunication influenced by DE is considered. Distortions of signals in a radio channel due to DE are proposed to be estimated using the reduced dispersion of the total error, which consists of two components: dynamic and interference. Calculations of the total reduced signal error and the error probability for speeds above 100 km/h are described. Estimates of the effect of DE on a coherent receiver, in which errors may occur due to changes in duration of radio pulses, are suggested. Effectiveness of the receiver's automatic frequency control (AFC) system is analysed as a means of challenging DE. For this, the concept of an instantaneous spectrum of parasitic frequency modulation due to DE was introduced and quality of radio communication was calculated using the reduced dispersion of the total error. The efficiency of using AFC has been proven after comparing the evaluations of reception quality with and without AFC in the form of the ratio of error probabilities. The features of the use of mobile communications on railways under the conditions of DE are formulated.

Keywords: *railway, high-speed traffic, Doppler effect, distortions, train speed, automatic frequency control, radio signal, radio communication quality.*

*Information about the authors:
Zhuravleva, Lyubov M. – D.Sc. (Eng), Professor at the Department of Rail Automatics, Telemechanics and Communication of Russian University of Transport, Moscow, Russia, zhlubov@mail.ru.
Nilov, Mikhail A. – Engineer of the Package Network Development Department of PJSC Megafon, Moscow, Russia, asp-nil@bk.ru.
Loshkarev, Vladimir L. – Engineer of the Overlay Networks Unit of PJSC Megafon, Moscow, Russia, bartok890@mail.ru.
Levshunov, Vladislav V. – Engineer of the Innovation Introduction Unit of PJSC MAXIM, Moscow, Russia, Levshynov1122@mail.ru.

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1. Relevance.

Train traffic control and safety provision on railways are possible only with the use of radiocommunication systems. The performance indicators of the transportation process and of train traffic safety depend on quality of radio channels operations. Achieving the required quality of radio signals is the main task when organizing broadband communication channels with locomotive drivers. The solution to this problem is especially important for transmission of alarm information to moving rolling stock. Such signals are generated in video surveillance systems when dangerous situations are detected at railway transport facilities (crossings, bridges, tunnels) and are transmitted using a mobile network. Assessment of quality of radiocommunication should consider not only the effects of external interference from the overhead contact network, operating motors, and other sources of noise, but also interference distortions arising from the multibeam nature of propagation of signals reflected from obstacles, as well as from Doppler effect (DE). Doppler effect is a shift in carrier frequency caused by movement of a signal source or a receiver [1].

The *objective* of this work is to assess the influence of Doppler effect on quality of radiocommunication and evaluate ways to counter the consequences of DE. Probability of a digital signal error arising from Doppler scattering of carrier frequency was assumed as a criterion and rate of quality of radiocommunication. The methodology for calculating the error probability is based on calculation of reduced dispersion of the error of the useful signal due to the action of parasitic frequency modulation caused by DE.

The method proposed in the article for calculating reduced dispersion of the error made it possible to evaluate efficiency of reducing distortions using the circuit of automatic frequency control of the carrier signal. This task acquires particular importance with introduction of high-speed train traffic (HSR) and Wi-Fi systems to improve passenger service and safety. To achieve this objective, methods for assessing distortions from DE and analysis of effectiveness of methods of reducing it are required. The results of similar studies on the influence of Doppler effect on quality of radiocommunication in HSR environment can be found, e.g., in [1; 2]. The problems associated with Doppler effect are especially acute in the countries with developed HSR, particularly, in China, where HS train speeds can exceed 400 km/h. Two methods of countering DE distortions proposed in [1; 2], are based on the principle of automatic carrier frequency control (AFC), which tracks changes in the carrier frequency f0 and adjusts it. In the first method, automatic frequency control in the receiver is carried out by predicting the carrier shift Δf_o in time depending on changes in train speed. For this, a special software is used, which is based on the calculation of higher order finite differences ($N \geq 2$), which is typical for non-Markov random processes. The resulting increment value ($\pm\Delta f_o$) adjusts the receiver local oscillator frequency. This method requires a large computational resource and high response speed of the element base. The implementation of this «algorithm of compensation» for DE based on processing a large amount of data is possible with the help of a new generation of electronics. In the simplest version, AFC circuit generates a control signal which is the difference between the current and previous values of Markov ($N = 1$) random process (changes in frequency of the carrier signal), which corresponds to a finite difference of the first order. The use of the process history in case of representing the carrier frequency oscillations in the form of a non-Markov process makes it possible to more accurately estimate the value of $\pm\Delta f_o$ and to adjust the receiver's local oscillator signal.

The second method is to control frequency of the local oscillator of the receiver using pilot signals added to the digital sequences (data frames) on the transmitting side. The purpose of the pilot signal is to track the propagation conditions of the radio signal, including the carrier frequency shift due to DE. After being detected at the receiving side, information about changes in carrier frequency is used to adjust the oscillator. Unlike the first method, the use of pilot signals does not require computing devices, but additional channel resources, for example, regarding frequency band. In HSR environment, a more effective way to counter the DE is the method of predicting carrier frequency changes Δf_o, which allows more accurately predicting the carrier deviation from the nominal value.

The shift of carrier frequencies due to the DE entails a violation of the principle of orthogonality and inter-frequency interference.

Currently, most radio systems (for example, in mobile communications) are focused on using signals with orthogonal frequency division multiplexing (OFDM) [3]. The principle of orthogonality is based on the coefficient of the correlation function, which allows choosing a system of orthogonal functions that provide the best transmission quality. If the input and reference signals in the receiver channel coincide, the correlation coefficient is equal to the maximum value, otherwise it is equal to zero. This method of forming a group signal allows to increase its spectral density by superimposing the spectra of adjacent subcarrier frequencies (subcarriers). In this case, adjacent subcarriers of the spectra do not interfere. Violation of the orthogonality condition of subcarriers leads to inter-frequency interference. The DE is among the causes of violation of the principle of orthogonality which occurs because of changes in the speed of movement of an object with installed transceiver. Emergence of Doppler effect consequently results in the Doppler shift of subcarrier frequency and signal distortion [3; 4].

Thus, when the train passengers use a mobile communication network (MN), the signal quality can be affected by the speed mode of traffic. To assess the influence of the train speed on quality of radiocommunication, it is necessary to develop a method for calculating signal distortions due to the DE.

2. Evaluation of signal distortions in a radio channel due to the Doppler effect

Distortions of the signal in a radio channel due to the Doppler effect occur because of the parasitic frequency modulation (PFM). This is manifested as follows:

1) loss of a part of the power of the useful signal that did not pass through the amplifier (filter) of the intermediate frequency (AIF) of the receiver when the carrier frequency f_0 is shifted by the amount of parasitic deviation f_d (dynamic component of the error), and an increase in f_0 occurs, for example, when MN receiver is approaching a base station (BS), a decrease in f_0 occurs in case when it is moving away from BS.

2) penetration of the spectra of adjacent channels (adjacent subcarriers) into AIF band (interference component of the error).

Distortions can be estimated using the dispersion of the total error σ^2_ε at the output of the receiver, which consists of two components (respectively, dynamic σ^2_{dyn} and interference σ^2_{int} components). Given the rectangular shape of the normalized spectral power density of the radio pulse envelope $S_\lambda(\omega)$, which has a cosine shape of the amplitude versus time [5], and an ideal intermediate frequency amplifier (AIF), the following relations can be written (Pic. 1):

$$\sigma^2_{dyn} = \sigma^2_{int};\ \sigma^2_\varepsilon = \sigma^2_{dyn} + \sigma^2_{int} = 2\sigma^2_{de}.$$

Hence, the reduced dispersion of the total error due to the DE, equal to the ratio of the power σ^2_ε to the power of the useful signal, will have the form:

$$\delta^2_{\varepsilon \mathrm{DE}} = \frac{2\sigma^2_{\mathrm{DE}}}{\sigma^2_{\mathrm{FM}}}, \qquad (1)$$

where σ^2_{fm} is dispersion (power) of a frequency-modulated signal (a radio impulse with duration τ_{imp}).

Formula (1) is true for the both cases of movement: when the receiver is approaching the BS (the frequency increases) or when it is moving away from the BS (the frequency decreases). For the above conditions (Pic. 1), it is possible to write the expression for the dispersion σ^2_{de} [5]:

$$\sigma^2_{\mathrm{DE}} = \frac{1}{2\pi} \int\limits_{\omega_0 + (\Delta\omega_{\mathrm{ef}})/2}^{\omega_0 + [(\Delta\omega_{\mathrm{ef}})/2] + \Delta\omega_{\mathrm{PFM}}} S_\lambda(\omega)\, d\omega, \qquad (2)$$

where $\Delta(\omega)_{ef} = 2\pi\{2\Delta F_\lambda(M_{fm} + 1)\}$ (2a) is the effective frequency band of the signal with frequency modulation (FM) (effective bandwidth of AIF) [6];

$\Delta F_\lambda \cong \frac{1}{\tau_{\mathrm{imp}}}$ is the effective bandwidth of a digital signal [5];

M_{fm} is the index of frequency modulation;

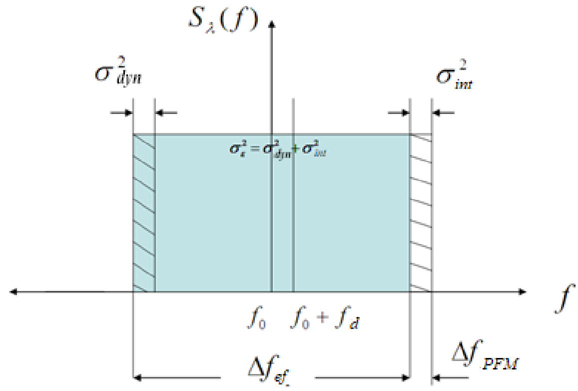
$\Delta(\omega)_{pfm} = 2\pi\{2M[f_{pfm}](M_{fm} + 1)\}$ (2b) is the effective frequency band of parasitic frequency modulation (PFM) arising from DE;

$M[f_{pfm}]$ is an average value of the modulating frequency f_{pfm} of parasitic FM from the action of DE with modulation index M_{pfm} (Pic. 2);

$(\omega)_0$ is carrier circular frequency of the signal;

$S_\lambda(\omega) = \frac{A_\lambda}{2\pi}$ is spectral power density of the signal [5].

$$\sigma_{\varepsilon}^{2} = \sigma_{dyn}^{2} + \sigma_{int}^{2}$$



Pic. 1. On the calculation of the reduced dispersion of total error occurred due to the Doppler effect (authors' picture).

Hence, the values of the dispersions σ^2_{de}, σ^2_{fm} and the reduced total error $\sigma^2_{\varepsilon de}$ are equal to:

$$\sigma_{\mathrm{DE}}^{2} = \frac{1}{2\pi} \int\limits_{\omega_0 + (\Delta\omega_{ef})/2}^{\omega_0 + [(\Delta\omega_{ef})/2] + \Delta\omega_{\mathrm{PFM}}} (A_\lambda / 2\pi) d\omega = \left(A_\lambda / (^2\right) \bullet \Delta\omega_{\mathrm{PFM}};$$

$$\sigma_{FM}^{2} = 2\left[\frac{1}{2\pi} \int\limits_{\omega_0}^{\omega_0 + (\Delta\omega_{ef})/2} (A_\lambda / 2\pi \Bigg) d\omega\right] = (^{A_\lambda} \bullet \Delta\omega_{ef};$$

$$\delta_{\varepsilon DE}^{2} = 2\left(\Delta\omega_{PFM} / \Delta\omega_{ef}\right) = 2\left(\Delta f_{PFM} / \Delta f_{AIF}\right), \quad (3)$$

where $\Delta f_{ef} = \Delta f_{AIF}$ is effective bandwidth of AIF.

Thus, to calculate distortions (errors) occurred due to the DE, it is necessary to determine the value of the effective frequency band PFM Δf_{pfm}. To do this, it is required to calculate the mathematical expectation of a random variable f_d and PFM index $M_{PFM} = \frac{M[f_{PFM}]}{M[f_d]}$, which is equal to the ratio of the average values of PFM modulating frequency and parasitic deviation.

3. Estimates of frequency of PFM deviation due to the action of the Doppler effect

Due to parasitic frequency modulation occurred following the DE (Doppler frequency scattering), the carrier frequency f_0 is shifted by $\pm f_d$. The random variable f_d changes in time (depends on the frequency f_0, the conditions of signal propagation, including the route topography, the parameters of movement of the moving object within the mobile communication network) [5].

As noted above, Doppler effect makes the spectrum of the useful signal randomly «move» along the frequency axis (Pic. 1). In this case, a part of useful data is lost (it does not pass through the AIF band). At the same time, extraneous signals from adjacent channels get into AIF, and those extraneous signals are interference for the AIF.

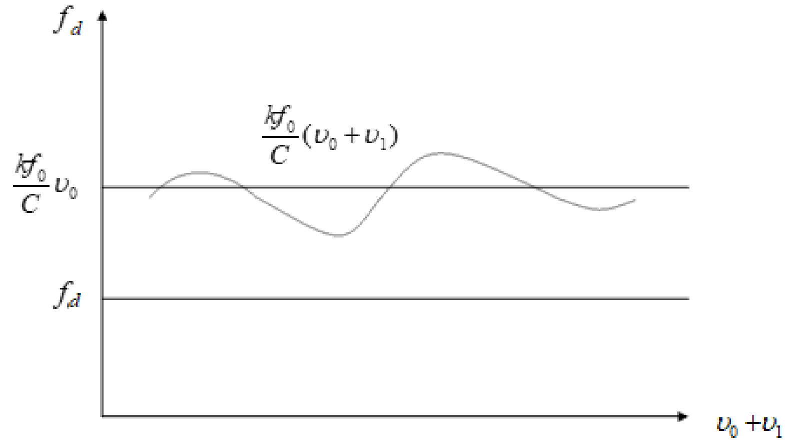
The deviation frequency f_d can be represented as the following product: coefficient κ (taking into account the propagation conditions of the radio signal, for example, rain or fog), speed (velocity) of the object moving υ, the carrier frequency f_0, cos*ą* (*ą* is the angle between the location of the transmitter and the direction of signal propagation), the speed of light *C*. The expression for calculating the frequency of deviation f_d has the following form [5]:

Fd = κ • ʋ • f0 • cos*ą* / C.

In the case of railways, all objects (BS towers, rolling stock) are located along the railway track. Therefore, the angle ą between the receiver located on BS (or in the driver's cab, or in the train wagon or coach) and the transmitter located at the same facilities approaches zero (which corresponds to the worst case, i.e., the greatest influence of DE). If we take *κ = 1*, cos*ą* = *1*, then the expression for the deviation frequency can be transformed as follows:

$$f_d = \frac{f_0}{C}\upsilon, \quad (4)$$

where ʋ is speed of movement of the object which is a function of random variables: acceleration *a* and time of movement of the



Pic. 2. Graph of change in frequency deviation f_d (for the case of uneven movement of an object) according to the sinusoidal law with frequency $M[f_{pfm}]$ (authors' picture).

object t in the mode of deceleration or acceleration (Pic. 2).

To calculate the bandwidth of PFM and the parasitic frequency modulation index, estimates of $M[f_d]$ and $M[f_{PFM}]$ are required, and they are determined by the average train speed υ_0 and the average time of changes in the train speed t_d.

Then, according to formula (4), the values $M[f_d]$ and $M[f_{PFM}]$, respectively, are equal to:

$$M[f_d]=\frac{f_0}{C}\upsilon_0=\frac{f_0}{C}M[(\pm a\cdot t_d)], \quad (5)$$

where $\upsilon_0 = M[\pm(a\cdot t_d)]$ is average value of train speed in case of uneven movement;

$$M\left[f_{PFM}\right]=M\left[\frac{1}{T_d}\right], \quad (6a)$$

where $T_d = 2t_d$ (6b) is period of change in speed of movement (by analogy with the sinusoidal dependence (Pic. 2)).

The value υ_0 is the product of two independent random variables, namely, acceleration a and time t_d. Hence, the mathematical expectation of the product of random variables (a and t_d) is the product of their mathematical expectations [6], i.e.: $M[\upsilon_0] = M[a]\cdot M[t_d]$.

For equiprobable distribution laws of probability density of random variables $\phi(a) = 1/A$ and $\Psi(t_d) = 1/T$, where A, T are, respectively, the limiting values of acceleration a and time t_d (starting from zero), after the averaging operation we obtain $M[a]$ and $M[t_d]$:

$M[a] = A/2$, $M[t_d] = T/2$.

The average value of frequency of speed changing modes (6a) is equal to:

$$M[f_{pfm}] = 1/T. \quad (7)$$

Example: if A = 2 m/s², T = 60 s, υ_0 = 108 km/h = 30 m/s, f_0 = 2,4 GHz, then based on formulas (5), (6a), (6b), (7) we get:

$$M[f_d]=\frac{2,4\cdot10^9\,\text{Hz}\cdot30\,\text{m/s}}{3\cdot10^8\,\text{m/s}}=240\ \text{Hz};$$

$$M[f_{PFM}]=\frac{1}{60\ s}=0,0167\ \text{Hz};$$

$$\Delta f_{PFM}\cong2\cdot M[f_d]=480\ \text{Hz}.$$

The calculated value of $M[f_d]$ according to published data [4] will have a negative impact on the quality of radiocommunications, i.e. will cause errors when receiving radio impulses.

Thus, the magnitude of the error (distortion of the useful signal) due to the action of the DE $\delta^2_{\varepsilon de}$ for the band $\Delta f_{AIF} = 2\cdot10^9\cdot1,3 = 2,6\cdot10^9$ Hz (calculated by formula (2a), where $\Delta F_\lambda = 10^9$ Hz, M = 0,3 [8]), according to formula (3) is equal to:

$$\delta^2_{\varepsilon DE}=\frac{2\cdot480\ \text{Hz}}{2,6\cdot10^9\ \text{Hz}}=369,23\cdot10^{-9}\cong0,37\cdot10^{-6}.$$

The magnitude of the error $\delta^2_{\varepsilon de}$ is commensurate with distortions from external interference and other sources of distortion [9].

To reduce distortion due to the DE in receivers, it is envisaged to install systems for automatic frequency control (AFC) of the carrier signal.

In addition to shifting the frequency band of the received signal, the action of DE can lead to distortions resulted from synchronization errors in coherent reception. As an example, we can consider the case of a radio signal receiver moving towards the transmitter at a speed of 120 km/h, operating at a frequency of 2,5 GHz with a period of 400 ps. The shift (increase) of frequency due to the DE will be 275 Hz and will cause a decrease in the signal duration by about 11 ps due to a decrease in the period of the carrier frequency [4]. The radio impulse is, as it were, compressed in time. In this case, the number of periods of the carrier signal during the impulse duration and the number of impulses per time unit (signal transmission rate) will not change. However, a reduction in the impulse duration by 11 ps can lead to a time shift τ of the input radio impulse relative to the reference signal in a coherent receiver. As a result, the final decision about the value of a received digit against the background of interference may be wrong. The error $\varepsilon(\tau)$ due to incoherence of signals will affect the value of marks of the multichannel receiver at the input of the solver, which, after selecting the maximum mark, determines the value of the transmitted digit.

The duration τ at a fixed value of the carrier frequency is a variable value that depends on speed and direction of the object. At the output of the receiver channels, each mark is the sum of the signal $g(\lambda)$ and interference $n(\lambda)$ components of the value of the correlation coefficient $R(\lambda)$, where λ means the transmitted signal (digit). In its «own channel» the signal component is maximum since the input signal corresponds to the reference one. In the «alien channel» $g(\lambda)$ is equal to zero based on the orthogonality principle [6]. In case of incoherent reception, the signal component in its «own channel» is equal to the value of the autocorrelation function $R_{ac}(\tau)$, which is less than the value of the function at $\tau = 0$ $R_{ac}(0)$. In an alien channel $g(\lambda)$ is equal to the value of the cross-correlation function $R_{cc}(\tau)$. Hence, the error in «own channel» after dividing it by the value of the signal power $\sigma^2_{\lambda} = \sigma^2_{fm}$ can be estimated as:

$\varepsilon(\tau) = [1 - r_{ac}(\tau)]$,

where $r_{ac}(\tau)$ is normalized autocorrelation function of the transmitted signal.

The normalized autocorrelation function for a radio impulse has the form $r(\tau) = \frac{\sin \omega\tau}{\omega\tau}$ [5]. In this case, ω as circular frequency corresponds to the frequency of the carrier signal. Considering that the carrier frequency and time shift (a decrease in the impulse duration due to the DE) differ in the example considered above by three orders of magnitude, the magnitude of the distortions $g(\tau)$ (deviations from the maximum value) is $\varepsilon(\tau) = (3 \cdot 10^{-5})\%$. However, with an increase in speed of movement of objects, the error due to incoherence of signals at the input of the receiver will increase.

If we fix speed of movement (for example, $\upsilon_0 = 30$ m/s) and change only the carrier frequency f_0, then for $f_0 = 2{,}4$ GHz the frequency shift in percent based on formula (4) will be $(4{,}7 \cdot 10^{-2})\%$. As the carrier frequency increases, the shift decreases as a percentage. So, for the infrared range of 400 THz, for example, in case of atmospheric (laser) communication, the frequency shift is 10^{-5} %. This indicates that Doppler effect is the most dangerous for the radio range.

4. Evaluation of the effectiveness of the automatic frequency control system

The automatic frequency control system (AFC) is installed in the intermediate frequency amplifier of AIF of the receiver. As noted above, AFC system monitors changes in the carrier frequency f_0 and adjusts it [5].

The efficiency assessment is based on comparison of the value of the reduced total dispersion of the error due to the DE with the use of AFC $\delta^2_{\varepsilon AFC}$ and without AFC system $\delta^2_{\varepsilon de}$.

The analysis of the reduced total dispersion of the error $\delta^2_{\varepsilon de}$ and the corresponding calculation formulas are discussed in the previous sections.

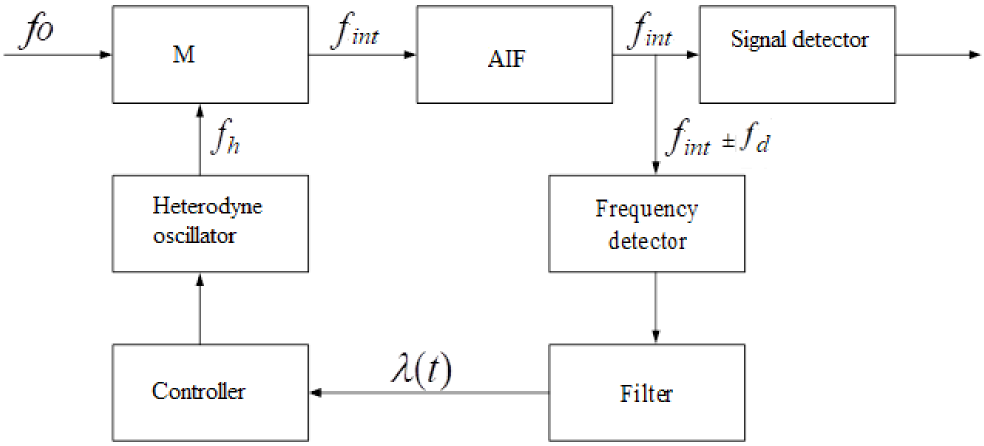
As noted above, to analyse the operation of AFC, Doppler effect can be represented as a parasitic frequency modulation PFM, modulating the useful signal according to the law of change in train speed. Therefore, it is necessary to estimate the bandwidth of PFM frequency Δf_{pfm} by the formula (2b) [6].

The value of Δf_{pfm} shows the possible range of changes in frequency of deviation f_d (Pic. 2). Along with the band Δf_{pfm}, it is advisable to introduce the concept of the instantaneous spectrum Δf_{inst} [6], which characterizes the dynamics of the change in frequency f_d. This will allow formulating AFC task in a different way.

The purpose of AFC system is to track changes in the carrier frequency f_0 in the band of the instantaneous spectrum of the parasitic frequency modulation, equal to:

$$\Delta f_{inst} = 2 \cdot M[f_{pfm}]. \quad (8)$$

The principle of AFC operation can be described as follows. The control signal $\lambda(t)$ from the output of the frequency detector



Pic. 3. Scheme of automatic frequency adjustment (automatic fine tuning) ($f_{int} \pm f_d$) through creating control voltage λ(t) and FMO [5], where: M – mixer; AIF – intermediate frequency amplifier; f_h – frequency of heterodyne oscillator (FMO); f_{int} – intermediate frequency; f_d – frequency deviation.

(Pic. 3) is fed to a control element, for example, to a variable-capacitance diode (varicap diode) in the load circuit of a local oscillator or a frequency-modulated oscillator (FMO) and changes the frequency of the output sinusoidal signal of FMO in accordance with changes in the input signal occurring due to DE. The mixer compares the frequencies of two signals. The error $\delta^2_{\varepsilon AFC}$ when using AFC system will be determined by the value of Δf_{inst} (locking range) [5]. The main element in AFC system is a control element (reactance control circuit), namely, a semiconductor diode, in which the barrier capacity of *p-n* junction depends on the applied reverse voltage. The speed of response of this element (the rate of change in the capacitance of the closed junction of the varicap following the blocking voltage λ(t) applied to it) directly affects the quality of the input signal frequency adjustment.

Thus, the efficiency of AFC system is determined by the speed of tracking changes in the amplitude of the control signal, which depends on the values of acceleration *a* and the frequency of changing the speed modes (or duration t_d). The speed of response of the control element is determined by the electronic characteristics of the material (for example, the effective mass of the electron, purity of the original chemical element, the size of the semiconductor crystal) [9].

The value of the effective bandwidth of the signal, equal to the value of Δf_{aif}, is calculated by the formula (2a) presented above.

The value of the reduced total dispersion of the error due to the DE for receivers with AFC system according to expressions (1), (3) is determined as follows:

$$\delta^2_{\varepsilon AFC} = \frac{2 \cdot \Delta f_{inst}}{\Delta f_{AIF}}. \qquad (9)$$

Based on the values already adopted above $M[f_{PFM}] = \frac{1}{60s} = 0{,}0167$ Hz (7) и $\Delta f_{aif} = 2{,}6 \cdot 10^9$ Hz (2a) it is possible to estimate the width of the instantaneous spectrum Δf_{inst} and the reduced total error $\delta^2_{\varepsilon AFC}$.

So, on the basis of formula (8) the width of the instantaneous spectrum PFM is equal to $\Delta f_{inst} = 2 \cdot (1/60\ s)$ (8), which means a change in the modes of movement on average after 60 s.

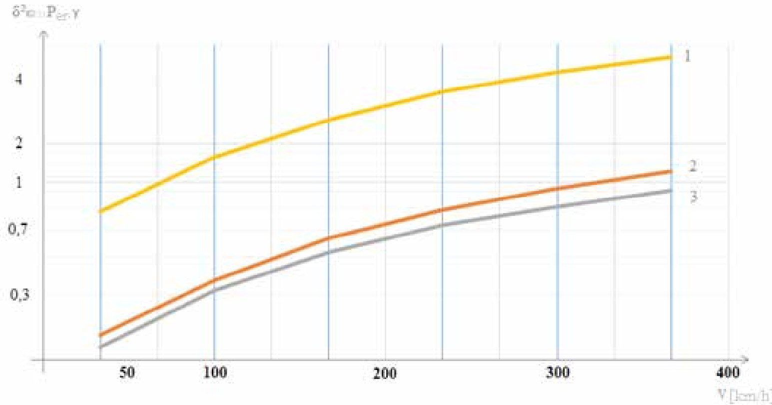
The value of the error $\delta^2_{\varepsilon AFC}$ considering the action of the AFC system is equal to:

$$\delta^2_{\varepsilon AFC} = \frac{2 \cdot 2 \cdot 0{,}0167}{2{,}6 \cdot 10^9} = 0{,}257 \cdot 10^{-10}.$$

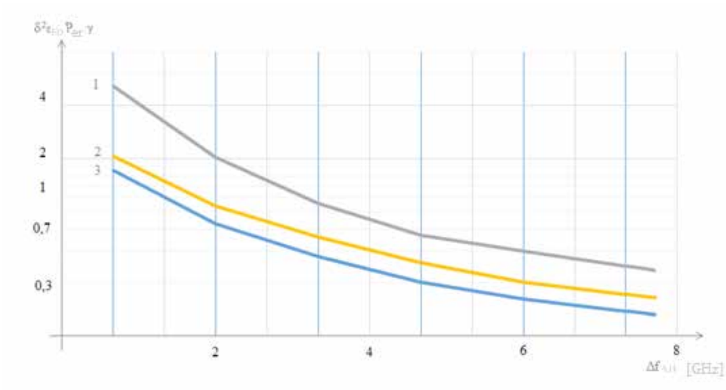
The value of the reduced total dispersion of the error without AFC system (calculated in the previous paragraph) is equal to $\delta^2_{\varepsilon DE} = 0{,}37 \cdot 10^{-6}$.

Hence, AFC system makes it possible to reduce the error from DE action by four orders of magnitude. Comparison of calculations made with formulas (3) and (9) shows that improvement in signal quality occurs due to a significantly smaller bandwidth of the instantaneous spectrum compared to the bandwidth of PFM, namely: $\Delta f_{inst} << \Delta f_{pfm}$.

The DE can also be estimated using the error probability when receiving an elementary



Pic. 4. Dependence of the error $\delta^2_{\varepsilon DE}$ ($\times 10^{-6}$), probability of the error P_{er} ($\times 10^{-7}$), efficiency of AIF γ ($\times 10^{4}$) on train speed V [1 – γ, 2 – $\delta^2_{\varepsilon DE}$, 3 – P_{er}].



Pic. 5. Dependences of errors $\delta^2_{\varepsilon DE}$ ($\times 10^{-6}$), $\delta^2_{\varepsilon AIF}$ ($\times 10^{-10}$) and probability of the error P_{erAIF} ($\times 10^{-11}$) on the width of the band Δf_{aif} [1 – $\delta^2_{\varepsilon DE}$, 2 – $\delta^2_{\varepsilon AIF}$, 3 – P_{erAIF}].

impulse P_{er} due to the shift of the channel frequency band. For digitized primary signals with a normal probability density distribution (for example, voice, video), the probability P_{er} can be calculated as follows [6]:

$$P_{er} \cong \delta^2\varepsilon DE/12. \quad (10)$$

Hence, the gain in quality of the connection γ due to the use of AFC will be:

$$\gamma = \frac{P_{er}}{P_{erAFC}} = \frac{0,37 \cdot 10^{-6}}{0,257 \cdot 10^{-10}} = 1,44 \cdot 10^{4}.$$

A decrease in probability of error by four orders of magnitude indicates the high efficiency of AFC system in countering the Doppler effect.

The nature of influence of train speed V and the frequency band of the signal Δf_{aif} on the value of the reduced dispersion of the total error, error probability and the efficiency of AFC is shown in Pic. 4, 5.

As seen from Pic. 4, with an increase in train speed, the distortion from Doppler effect increases, and the efficiency of using AFC increases.

As seen from Pic. 5, an increase in the signal transmission speed (widening the frequency band Δf_{aif}) reduces the magnitude of errors $\delta^2_{\varepsilon DE}$ and $\delta^2_{\varepsilon AIF}$, as well as probability of the error P_{erAIF}. According to formulas (3) and (9), an increase in Δf_{aif} does not affect the efficiency of automatic frequency control. The efficiency of AFC does not change and at the train speed of $V = 108$ km/h is $\gamma = 1,44 \cdot 10^4$. However, the presented calculations do not consider the delay time in AFC feedback loop, which should be significantly less than the elementary impulse duration, which in turn depends on the signal transmission rate. The calculated values of P_{er} probabilities using analytical formulas (Pic. 1, 2) give results that are an order of magnitude better than those obtained experimentally [1; 2]. This can be explained by the fact that in the original expressions (1)–(3); (9); (10) the complex electromagnetic environment prevailing at railways is not taken into account. So, in real conditions, in addition to Doppler effect, intermodulation interference of various origins affects the quality of signals.

It is known that establishing the mode of capturing the frequency band Δf_{inst} and ensuring that this band is held are core elements of the implementation of AFC system. This largely depends on the inertia and speed of the electronic component base, with which AFC system is realized, namely, on the use of new generation semiconductor materials based on nanostructures [9].

5. Conclusions. Features of the operation of mobile communications at railways under the conditions of the Doppler effect action

Analysis of the features of the Doppler effect impact on the quality of radiocommunications in HSR environment allows us to draw the following conclusions:

1. Doppler effect has a negative impact on the quality of communications at train speeds over 100 km/h. In this case, the value of the reduced total dispersion of the signal error due to the Doppler effect is comparable in magnitude with the action of external interference.

2. For railways, the effectiveness of countering the Doppler effect determines the quality of communication of moving objects within mobile networks and Wi-Fi. This is especially true for the process of handing over a subscriber during a call from a base station (BS) to another.

3. The speed of switching from a base station to another («soft handover» mode) depends on speed of data transfer and speed of the element base of microelectronics, which also determines the effectiveness of countering the Doppler effect.

4. The higher is the mobile communication standard, the higher is the data transfer rate, the stricter are the requirements for speed of system units, controllers, access switches of mobile networks, as well as receiver's AFC systems.

5. In HSR environment, the transmission of data to the train driver can be carried out using 4G mobile communication, which has more advanced technology for exchanging data between users and the base station, network protocols, algorithms for managing mobility of subscribers in the network, methods of combating interference arising, including those occurring due to the Doppler effect.

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