Estimation of energy secrecy of low-frequency satellite communication system with arbitrary number of spatial diversity reception of signals

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Abstract. The imitational model for the low-frequency satellite communication system has been developed using Simulink Ver. 8.2 (MATLAB) environment. The imitational modeling has been carried out for the signal reception with carrier frequencies in $f_0 \approx 30$ MHz...1 GHz range and with both single antenna ($n=1$) and diversified ($n=2, 4, 8$ antennas) signal reception. On this basis, the dependency of energetic concealment coefficient on the carrier frequency selection has been determined. The analysis of the obtained dependencies shows that in the lowered frequency range ($f_0 \approx 30$ MHz ... 100 MHz) it is possible to increase the energetic concealment coefficient by $\gamma_{e(2)} \approx 24$ dB when using the dual antenna reception system and up to $\gamma_{e(8)} \approx 42$ dB when the signal is received by 8 antennas.

1. Introduction
There is a known method \cite{1, 2} to achieve a high energetic concealment coefficient ($\gamma_e \approx 22…34$ dB) for the satellite communication systems (SCS) with the radio intercepting receiver in close proximity to the ground-based SCS receiver. This method implies the application of lowered carrier frequency ($f_0 = 30 \ldots 100$ MHz) and diversified signal reception with several ($n = 2\ldots4$) antennas. However, such high energetic concealment coefficients (ECc) can only be achieved with the carrier frequency value of $f_0 = 30$ MHz under the conditions of the deepest (Rayleigh) fading of the received signals (when the Rice parameter $\gamma^2 = 0$) and when the fading is uncorrelated (when the correlation coefficient $R = 0$) on the outputs of the diversified antennas.

In works \cite{3, 4} for the case when diversified reception with dual antennas ($n = 2$) is applied in the low-frequency SCS, the analytical dependency $\gamma_{e(2)} = \Psi(P_{\text{er alwd}}, \gamma^2, R, n = 2)$ has been obtained based on the following dependencies for the ECc: on the allowed signal reception error rate ($P_{\text{er alwd}}$), on the Rician fading parameter of the received signal ($0 \leq \gamma^2 < \infty$) and on the fading correlation coefficient ($0 \leq R \leq \infty$) on the outputs of the diversified antennas. Aside from that, the dependencies of the Rice parameter $\gamma^2 = \Psi(f_0)$ and the fading correlation coefficient $R = \Psi(f_0)$ on the carrier frequency selection in the transionospheric (satellite) communication link has been obtained. Through these dependencies, another dependency $\gamma_{e(2)} = \Psi(f_0, P_{\text{er alwd}}, n = 2)$ has been determined. It is the dependency of the ECc on the carrier.
frequency selection with the determined $P_{er\ abd}$ value and the diversified signal reception with $n=2$ antennas.

It is obvious that the application of spatially diversified signal reception with an increased number $(n>2)$ of antennas allows to significantly boost the ECc ($\gamma_{(n)}$). However, when the multiplier of diversification is more than two $(n>2)$, it is impossible to obtain the analytical dependency $\gamma_{(n)} = \Psi(f_0, P_{er\ abd}, n > 2)$ due to the following reasons.

Known analytical dependencies $P_{er(n)} = \Psi(h^2, \gamma^2, R, n)$ are limited by the cases where only singular ($n=1$) or dual ($n=2$) reception is applied. There are no known analytical dependencies $P_{er(n)} = \Psi(h^2, \gamma^2, R, n)$ for the cases of increased diversification multiplicity $(n>2)$. Hence, a conclusion follows that it is useful to utilize the capabilities of imitational modeling to compose the dependencies $P_{er(n)} = \Psi(h^2, \gamma^2, R, n)$ that can lead to the obtainment of the desired dependency $\gamma_{(n)} = \Psi(f_0, P_{er\ abd}, n > 2)$.

The purpose of this research is to develop the imitational model for the low-frequency SCS to obtain the dependencies $P_{er(n)} = \Psi(h^2, \gamma^2, R, n\geq1)$ of the erroneous reception of the signals with the Rician $(0 \leq \gamma^2 < \infty)$ correlated $(0 \leq R \leq \infty)$ fading with an arbitrary number $(n \geq 2)$ of the receiving antennas, and, based on the dependency $\gamma_{(n)} = \Psi(f_0, P_{er\ abd}, n > 2)$, to calculate of the SCS’ energetic concealment coefficient on the carrier frequency selection $f_0$ when the antenna diversification multiplicity is more than two $(n > 2)$.

2. The imitational model for the low-frequency satellite communication system with the spatially diversified signal reception system

The energetic gain when utilizing the spatially diverse reception system depends on the addition scheme of the diversification branches. Judging by the efficiency and the simplicity of realization, the average position is taken by the scheme of coherent addition of the diversification branches with incoherent processing of the resulting signal [5]. The imitational model for the low-frequency SCS with diversified signal reception with two $(n=2)$ diversified antennas with specified addition scheme can be realized in Simulink Ver 8.2 (MATLAB) environment, as shown on figure 1 [6, 7]. The imitational model for the low-frequency SCS consists of the transmitter, transionospheric communication link, branch addition scheme and the receiver with the error rate calculator (ER).

In the transmitter, the pseudorandom sequence generator (The Random Integer block) forms the initial sequence of the information symbols $x(t)$ with the alphabet volume (code base) $M = 2$, which is transformed into the orthogonal binary frequency-manipulated signal $s(t)$ by the modulator (the 2-FSK block).

Further, the signal $s(t)$ passes through the communication link, where the Rayleigh SISO subsystem (Rayleigh Single Input Single Output) models the Rayleigh fading (when the Rice parameter $\gamma^2 = 0$) and where the signal splits to two $(n=2)$ channel signals $s_i(t)$ $(i = 1, 2)$ without considering the fading correlation $(R = 0)$ [8]. Then AWGN blocks add an additive white Gaussian noise (AWGN) with adjustable spectral density of the power $N_0$ to the signals $s_i(t)$.

Afterwards, the fluctuations $y_i(t) = s_i(t) + \xi_i(t)$ proceed to the branch coherent addition scheme. In the given scheme, the process of “weighting” (multiplying) of the received fluctuations $y_i(t)$ proportionally to the expected signal amplitude $s_i(t)$, which is taken into account by the transmission coefficient (TC) $\mu_i(t) = s_i(t)/s(t)$, takes place [5]. Further, the signals formed on the outputs of the multipliers $v_i(t) = y_i(t) \cdot \mu_i(t)$ are transmitted to the adder and the received result $\sum_{i=1}^{n} v_i(t)$ arrives to the input of the demodulator (the 2-FSK block).
Figure 1. The imitational model for the low-frequency SCS with the diversified reception system utilizing two \((n = 2)\) antennas, Rayleigh \((\gamma^2 = 0)\) uncorrelated \((R = 0)\) fading, coherent branch addition and incoherent processing of the resulting signal.

In the receiver the demodulator produces an incoherent detection of the signal sum \(\sum_{i=1}^{n} v_i(t)\) and forms the information symbol sequence \(x'(t)\) on the output. The error rate calculator (the Error Rate Calculation block) calculates the number of erroneously transmitted symbols based on the comparison of the received \(x'(t)\) and the transmitted \(x(t)\) data flow and outputs the error rate value \(P_{er}\).

The imitational modeling is carried out using the built-in MATLAB application – BER Error Rate Analysis Tool, which allows to obtain dependencies \(P_{er} = \psi(h^2, n = 2)\) with Rayleigh \((\gamma^2 = 0)\) uncorrelated \((R = 0)\) fading.

However, specified imitational model for the low-frequency SCS does not allow to obtain a dependency \(P_{er} = \psi(h^2, \gamma^2, R, n \geq 2)\) of the erroneous reception of the signals with the Rician \((0 \leq \gamma^2 < \infty)\) correlated \((0 \leq R \leq 1)\) fading as the model uses two Rayleigh SISO Blocks representing communication links with one input and one output, where Rayleigh \((\gamma^2 = 0)\) uncorrelated \((R = 0)\) fading takes place [8].

To overcome this limitation, the authors propose to use the approach [10, 11], which is applied in the imitational model (figure 2) for the SCS with using adaptive coding method called OSTBC (Orthogonal Space-Time Block Coding).

Specified imitational model includes the transmitter and the receiver with the ER calculator, which operate similarly to figure 1. The difference is the use of another type of digital modulation – QPSK (Quadrature Phase Shift Keying).

The transmitter and receiver include the OSTBC Encoder and OSTBC Decoder blocks, which simulate the OSTBC encoding algorithms. This encoding is intended for the SCS using MIMO (Multiple Input Multiple Output). Principle of OSTBC [12] is to divide the sequence of information symbols into blocks and transmit each block at set time intervals over spatially diversified antennas in accordance with the coding matrix. Reception is performed on spatially diversified antennas, followed by the addition of all signals. Decoding is provided through the use of a special structure of the transmitted units. The simplest and most common example is the OSTBC Alamouti circuit which is intended for using two transmitting and one receiving antennas.
Figure 2. The imitational model for the SCS with using OSTBC.

In the communication channel segment the Rician MIMO block is used (figure 2), which is included in the class of MIMO Fading Channel (Multiple Input Multiple Output Fading Channel) blocks, which allows modeling the communication channel with the required Rician ($0 \leq \gamma^2 < \infty$) correlated ($0 \leq R \leq 1$) fading and with diversity for arbitrary number of transmitting and receiving antennas ($N_t \geq 2$, $N_r = n \geq 2$) [13].

Figure 3 shows the imitational model for the low-frequency SCS, which includes the transmitter, communication link, branch addition scheme and the receiver with the ER calculator. Specified model has been developed using Simulink Ver. 8.2 (MATLAB) environment.

Figure 3. The imitational model for the low-frequency SCS with the diversified reception system utilizing an arbitrary number ($n \geq 2$) of the antennas, Rician ($0 \leq \gamma^2 < \infty$) correlated ($0 \leq R \leq 1$) fading, coherent branch addition scheme and incoherent processing of the resulting signal.

The segments of the transmitter, the scheme of addition of branches and of the receiver with the with the ER calculator are similar to figure 1. The novelty of the imitational model is the algorithm of the communication link segment functioning in conjunction with the other segments, which is described below.
Thus, combining the approach in the modeling of communication channels with fading and diversity (figure 2) with coherent branch addition scheme and incoherent processing of the resulting signal (figure 1), it becomes possible to get a dependency $P_{\text{err}} = \Psi(h^2, \gamma^2, R, n \geq 2)$ of the erroneous reception of the signals with the Rician $(0 \leq \gamma^2 < \infty)$ correlated $(0 \leq R \leq 1)$ fading.

To confirm the functioning authenticity of the SCS imitational model, the error rate calculation $P_{\text{err}}$ has been carried out with the spatially diversified reception based on one $(n = 1)$ and four $(n = 4)$ receiving antennas without the correlative fading $(R = 0)$ for the two values of the Rice parameter: $\gamma^2 = 0$ and $\gamma^2 = 2$.

For statistically homogenous parallel communication links with the Rician $(0 \leq \gamma^2 < \infty)$ uncorrelated $(R = 0)$ fading with the singular $(n = 1)$ and the spatially diversified $(n \geq 2)$ reception of the binary equiprobable orthogonal signals and the diversification branch coherent addition scheme with incoherent processing of the resulting signal, the equation for the error rate $P_{\text{err}}$ is determined as [5].

$$P_{\text{err}}(h^2, \gamma^2, n) = \frac{1}{2^n} \sum_{i=1}^{n} \left[ \frac{2(1 + \gamma^2_i)}{2(1 + \gamma_i^2 + h^2)} \exp \left( -\frac{\gamma^2_i h^2}{2(1 + \gamma_i^2 + h^2)} \right) \right].$$

The results of theoretical calculation (solid lines) and imitational modeling (dots) based on the formulas (1) with the Rayleigh $(\gamma^2 = 0)$ and the Rician $(\gamma^2 = 2)$ fading are presented on figures 4a and 4b respectively.

Figure 4. The results of theoretical calculation (solid lines) and imitational modeling (dots).

As observed on figure 4, it is evident that the results of imitational modeling match the theoretical calculation results fairly accurately, which tells about the reliability of the developed imitational model for the low-frequency SCS (figure 3).

According to figure 4a, to achieve the desired error rate $P_{\text{err,ald}} = 10^{-5}$ with the Rayleigh fading $(\gamma^2 = 0)$, it is required to provide the acceptable S/N ratio: $h_{\text{ald,1}}^2 \approx 50$ dB for the singular $(n = 1)$ reception and just $h_{\text{ald,4}}^2 \approx 14$ dB for the quadruple $(n = 4)$ reception without the correlation of fading in the antennas $(R = 0)$. According to figure 4b, to achieve $P_{\text{err,ald}} = 10^{-5}$, it is required to provide the acceptable S/N ratio of $h_{\text{ald,1}}^2 \approx 46$ dB and $h_{\text{ald,4}}^2 \approx 12$ dB respectively.

3. The baseline parameters of imitational modeling for the low-frequency satellite communication system

Using the developed imitational model (figure 3), it is possible to build the graphs for desired dependencies $P_{\text{err}} = \Psi(h^2, \gamma^2, R, n \geq 1)$. Based on these graphs, it is possible to find the acceptable
achieve $P_r = P_{er.alwd} = 10^{-10}$ S/N ratio on the receiver’s input with the singular ($n = 1$) reception $h_{alwd}^2 (1)$ and with the diversified reception $h_{alwd}^2 (n)$ of the signal with an arbitrary number ($n \geq 2$) of the antennas. These S/N ratios are the baseline to obtain the energetic concealment coefficient $\gamma_e = h_{alwd}^2 (1)/h_{alwd}^2 (n)$.

However, to obtain the desired dependency $\gamma_e = \Psi(f_0, P_{er.alwd}, n > 2)$ of the SCS’ ECc on the carrier frequency $f_0$ selection with the antenna diversification multiplicity $n > 2$, it is required to consider the known [14–16] frequency dependencies of the Rice parameter $\gamma^2 = \Psi(f_0)$ and of the fading spatial correlation coefficient $R = \Psi(f_0)$ in the transionospheric communication link (CL).

It is known [14] that the Rician fading parameter, which characterizes the ratio of the regular component $P_r$ of the received signal’s power to the fluctuating $P_{fl}$ component’s power, depends only on the dispersion of phasic wave front’s fluctuations $\sigma^2$ on the exit of the ionosphere in the transionospheric CL as

$$\gamma^2 = P_r/P_{fl} = \left[\exp(\sigma^2) - 1\right]^{-1}.$$  \hspace{1cm} (2)

The standard deviation (SD) of phasic wave front’s fluctuations for the emerging wave is described by the expression

$$\sigma^2 = \sqrt{2(80.8 \pi/c)\sqrt{l_zz_c \sec}\alpha}(\sigma_{\Delta\lambda}/f_0) \text{ [rad]},$$

where $80.8$ is a coefficient with the dimension $[m^3/s^2]$; $l_z \approx 390 \text{ m}$ is a characteristic (average) size of the small-scale ionospheric inhomogeneities; $z_c = 5 \cdot 10^3 \text{ m}$ is an equivalent depth of the homogenous ionospheric layer with the electron concentration (EC) equal to its average value on the height $h_n$ of maximum ionospheric ionization $\overline{N}(h_n) = \overline{N}_m$; $f_0$ is a carrier frequency in [Hz]; $\alpha$ is a zenith angle.

In accordance with the typical parameters for mid-latitude ionosphere ($\sigma_{\Delta\lambda} \approx 2 \cdot 10^9 \text{ el/m}^3$; $l_z \approx 390 \text{ m}; z_c = 5 \cdot 10^3 \text{ m}$) and with the analytical dependencies (2–4) with transionospheric propagation of the radiowaves with the carrier frequency $f_0 = 30 \ldots 1000 \text{ MHz}$ and the zenith angle
$\alpha = 65^\circ$, values presented in table 1 are the values for the SD of phasic wave front fluctuations $\sigma_\psi$ on the exit of the inhomogenous ionosphere, the values for the Rice parameter $\gamma^2$, the values for the fading spatial correlation interval $\Delta \rho_a$ and for the fading correlation coefficient $R_{\psi}$ on the outputs $n = 1, \ldots, 8$ of the receiving antennas with $\Delta \rho_a = 300 \text{ m}$.

**Table 1.** The dependency of SCS' fading parameters on the carrier frequency selection.

| $f_0$, MHz | $\sigma_\psi$, rad | $\gamma^2$ | $\Delta \rho_a$, m | $R_{\psi}(\Delta \rho_a)$ | $R_{\psi}(2\Delta \rho_a)$ | $R_{\psi}(3\Delta \rho_a)$ | $R_{\psi}(4\Delta \rho_a)$ | $R_{\psi}(5\Delta \rho_a)$ | $R_{\psi}(6\Delta \rho_a)$ | $R_{\psi}(7\Delta \rho_a)$ |
|------------|-------------------|------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| 30         | 1.71              | 0.056      | 227              | 0.18             | 0.08             | 0.003            | 0.0 0            | 0.0              | 0.0              | 0.0              |
| 50         | 1.03              | 0.53       | 379              | 0.53             | 0.38             | 0.011            | 0.0 0            | 0.0              | 0.0              | 0.0              |
| 80         | 0.64              | 1.96       | 607              | 0.78             | 0.353            | 0.25             | 0.02             | 0.0              | 0.0              | 0.0              |
| 100        | 0.51              | 3.3        | 758              | 0.85             | 0.76             | 0.25             | 0.08             | 0.0              | 0.0              | 0.0              |
| 150        | 0.34              | 8.02       | 1138             | 0.93             | 0.85             | 0.54             | 0.33             | 0.0              | 0.0              | 0.0              |
| 200        | 0.26              | 14.64      | 1517             | 0.96             | 0.85             | 0.76             | 0.54             | 0.0              | 0.0              | 0.0              |
| 300        | 0.17              | 33.56      | 2276             | 0.99             | 0.98             | 0.95             | 0.76             | 0.0              | 0.0              | 0.0              |
| 500        | 0.1               | 94.1       | 3793             | 0.99             | 0.99             | 0.98             | 0.95             | 0.0              | 0.0              | 0.0              |
| 1000       | 0.05              | 378        | 7586             | 0.99             | 0.99             | 0.98             | 0.97             | 0.0              | 0.0              | 0.0              |

The analysis of the obtained values (table 1) for the Rice parameter $\gamma^2 = \psi(f_0)$ and for the fading correlation coefficient $R = \psi(f_0)$ in the transionospheric CL indicates that as the carrier frequency in the SCS decreases from the traditional values $f_0 = 1$ GHz to the smallest $f_0 = 30$ MHz, the Rice parameter decreases from $\gamma^2 = P_\psi/P_\beta \approx 380$ (i.e. there is practically no fading) to $\gamma^2 = P_\psi/P_\beta \approx 0.05$ (the regular component of the fading is practically absent, i.e. the fading is nearly Rayleigh), the fading spatial correlation coefficient decreases from $R \approx 1$ (almost total correlation) to $R \approx 0$ (decorrelation).

4. The imitational modeling and the evaluation of energetic concealment coefficient for the low-frequency satellite communication system

Based on the imitational model (figure 3) and the data from table 1 ($\gamma^2, n, R_{\psi}$), the imitational modeling has been carried out for the low-frequency SCS’ functioning with the transmission of signals via the transionospheric CL with statically homogenous correlated ($0 \leq R \leq 1$) Rician ($0 \leq \gamma^2 < \infty$) fading and with the singular ($n = 1$) and the diversified signal reception with $n = 2, 4, 8$ antennas, the dependency curves have been obtained $P_{\psi(n)} = \psi(h^2, \gamma^2, R, n \geq 1)$.

As an example, on figure 5 there are dependency graphs $P_{\psi(n)} = \psi(h^2, \gamma^2, R, n = 8)$ for the evaluation of SCS’ noise immunity with the diversified signal reception with $n = 8$ antennas. These graphs are built with various carrier frequencies $f_0 = 30 \ldots 1000$ MHz according to the data from table 1.
Figure 5. The dependency graphs $P_{er} = \psi(h^2, \gamma^2, R, n = 8)$ for the evaluation of SCS’ noise immunity with various carrier frequency values $f_o$: 1) 30 MHz; 2) 50 MHz; 3) 80 MHz; 4) 100 MHz; 5) 150 MHz; 6) 200 MHz; 7) 300 MHz; 8) 500 MHz; 9) 1000 MHz.

The analysis of figure 5 indicates that with $f_o = 30$ MHz, the value to achieve the desired $P_{er} = P_{er\,alwd} = 10^{-5}$ S/N ratio is $h_{alwd(8)}^2 = 7.7$ dB. As the carrier frequency increases, the noise immunity curves initially shift towards the right up to the maximum value $h_{alwd(8)\,max}^2 = 11.7$ dB at $f_o = 100$ MHz, but afterwards shift towards the left until the minimum value $h_{alwd(8)\,min}^2 = 4.5$ dB at the carrier frequency $f_o = 1000$ MHz. These changes are described by the fact that, according to table 1, at the frequency of $f_o = 30$ MHz the fading of received signals in the SCS has a nearly Rayleigh character ($\gamma^2 = P_r/P_\beta \approx 0.056$) and is weakly correlated ($R_{12} \approx 0.18$). At the frequency of $f_o = 100$ MHz the fading of received signals shall have lesser depth (Rician character ($\gamma^2 = P_r/P_\beta \approx 3.3$) and is strongly correlated ($R_{12} \approx 0.85$)). At the frequency of $f_o = 1000$ MHz the fading of received signals is nearly absent ($\gamma^2 = P_r/P_\beta \approx 378$) and is totally correlated ($R_{12} \approx 0.998$).

Based on these curves (figure 5) the formulation (figure 6) has been found that describes the dependency of acceptable S/N ratio $h_{alwd(8)}^2$ on the SCS receiver’s input with the application of $n = 8$ diversified antennas on the Rice parameter $\gamma^2$ and the carrier frequency $f_o$ selection. Similarly, on figure 4 there are functional dependencies built $h_{alwd(n)\,alwd(4)}^2 = \psi(\gamma^2, f_o)$ for the cases when signals are received using $n = 1$ antenna and when the reception is diversified with $n = 2$ and $n = 4$ antennas. The acceptable S/N values $h_{alwd(n)\,alwd(4)}^2$ depending on the selection of carrier frequency $f_o$ in the SCS and on the Rice parameter $\gamma^2$ of received signals are provided in table 2.

The analysis of figure 6 and of the data from tables 1 and 2 indicates that in the lowered carrier frequency range $f_o = 80 \ldots 100$ MHz the acceptable S/N values $h_{alwd(n)\,alwd(4)}^2$ on the receiver’s input are maximized with the application of diversified reception with $n = 2, 4, 8$ antennas. It is described by the fact that in this range a fairly deep fading of the received signals ($\gamma^2 \approx 2 \ldots 3$) is observed with a relatively insignificant spatial correlation ($R_{12} \approx 0.8$).
Figure 6. The dependency graphs for the acceptable signal/noise ratios $h_{\text{alwd}(n)}^2$ on the SCS receiver’s input with the reception based on $n = 1$ antenna and $n = 2, 4, 8$ antennas on the carrier frequency $f_0$ selection.

Table 2. The dependencies of acceptable S/N ratios on the SCS’ carrier frequency selection.

| $f_0$, MHz | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  |
|------------|----|----|----|----|----|----|----|----|----|
| $\gamma^2$ | 0.056 | 0.53 | 1.96 | 3.3 | 8  | 14.6 | 33.6 | 94.1 | 378 |
| $h_{\text{alwd}(1)}^2$, dB | 49.99 | 49.5 | 46.2 | 42  | 26 | 18  | 15  | 13.9 | 13.5 |
| $h_{\text{alwd}(2)}^2$, dB | 26.2 | 27.5 | 28.4 | 27.7 | 21 | 14.7 | 11.9 | 10.8 | 10.4 |
| $h_{\text{alwd}(4)}^2$, dB | 14.5 | 16.5 | 18.8 | 18.3 | 13 | 11.2 | 8.7  | 7.9  | 7.5  |
| $h_{\text{alwd}(8)}^2$, dB | 7.7  | 8.9  | 11.2 | 11.7 | 7.5 | 6.6  | 5.6  | 4.8  | 4.5  |
| $\gamma_{(2)}$, dB | 23.8 | 22  | 17.8 | 14.3 | 5  | 3.3  | 3.05 | 3.07 | 3.08 |
| $\gamma_{(4)}$, dB | 35.5 | 33  | 27.4 | 23.7 | 13 | 6.8  | 6.3  | 5.97 | 5.98 |
| $\gamma_{(8)}$, dB | 42.3 | 40.6 | 35  | 30.3 | 18.5 | 11.4 | 9.4  | 9.1  | 9   |

As the carrier frequency of SCS grows up to the traditional values $f_0 = 1000$ MHz, it is possible to observe the decrease in acceptable S/N ratios on the receiver’s input down to $h_{\text{alwd}(n)}^2 \approx 10 \ldots 4$ dB with $n = 2 \ldots 8$ due to the practical absence of fading ($\gamma^2 \approx 378$) and its correlation ($R_{12} \approx 1$) in the diversified antennas. This corresponds to the known [5] conclusion stating that the gain from diversified reception grows with the increase of received signal’s fading depth and with the decrease of their spatial correlation, as well as conforms with the conclusion about the unpracticality of applying spatially diversified reception in the communication channels without fading.
Thereby, the obtained (figure 6, table 1) dependencies $P_{er(n)} = \psi(h^2, \gamma^2, R, n)$ allow to calculate (table 2) the ECc $\gamma_{er(n)}$, expressed in decibels, as the difference of acceptable S/N ratios:

$$\gamma_{er(n)}(\gamma^2)_{db} = h_{alwd(1)}(\gamma^2)_{db} - h_{alwd(8)}(\gamma^2)_{db}$$

Based on the results in table 2, presented on figure 7 are the dependency graphs for ECc $\gamma_{er(n)} = \psi(\gamma^2, f_0)$ in the SCS with diversified reception based on $n = 2, 4, 8$ antennas on the Rice parameter $\gamma^2$ and on the carrier frequency $f_0$ selection.

![Figure 7](image)

**Figure 7.** The dependency of SCS’ energetic concealment coefficient on the carrier frequency $f_0$ selection with the diversified signal reception based on $n = 2, 4, 8$ antennas.

5. Conclusion
The imitational model for the low-frequency SCS (fig. 3) with spatially diversified signal reception system with the general Rician fading has been developed in Simulink Ver. 8.2 (MATLAB) graphical modeling environment.

This imitational model allows to obtain the dependency graphs $P_{er(n)} = \psi(h^2, \gamma^2, R, n \geq 1)$ of erroneous signal reception rate with Rician ($0 \leq \gamma^2 < \infty$) correlated ($0 \leq R \leq 1$) fading with an arbitrary number ($n \geq 1$) of the receiving antennas. As an example, presented on figure 5 is a dependency graph $P_{er(n)} = \psi(h^8, \gamma^2, R, n = 8)$ with $n = 8$ receiving antennas.

Based on the dependencies $P_{er(n)} = \psi(h^2, \gamma^2, R, n)$ and the expressions (2–4), provided on figure 6 are the graphs for the dependency of acceptable signal/noise ratios $h_{alwd(n)}$ on the SCS receiver’s input with the singular ($n=1$) and the diversified signal reception based on $n = 2, 4, 8$ antennas on the carrier frequency $f_0$ selection.

Based on the results of figure 6 and table 2, the desired dependencies $\gamma_{er(n)} = \psi(f_0, P_{er alwd}, n)$ are obtained $\gamma_{er} = \psi(f_0, P_{er alwd}, n)$ and presented on figure 7. Specified dependencies show the dependency of SCS’ energetic concealment coefficient on the carrier frequency $f_0$ selection with the diversified reception based on $n = 2, 4, 8$ antennas.
The analysis of these graphs indicates about the possibility of increasing the energetic concealment coefficient in the low-frequency SCS from $\gamma_{(2)} \approx 24$ dB when the dual antenna signal reception is applied to $\gamma_{(4)} \approx 35$ dB with the quad antenna signal reception system and up to $\gamma_{(8)} \approx 42$ dB with the reception system based on 8 antennas.

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