Application of Broadband Signals to Increase Interference Immunity in Channels with Inter-Symbol Interference

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Abstract. Proposals for improving the noise immunity of receiving phase-shift keying signals in the conditions of inter-symbol interference caused by fading in the channel are presented. The use of Barker sequences for the expansion of modulating information pulses has been substantiated. The results of evaluating the noise immunity of Rice fading channels at various ratios of the effective voltages of the regular and diffuse signal components are presented. Proposals for the practical application of the results obtained are formulated.

1. Introduction

Wireless communication technologies are widely used in the interests of developing a single info communication space. Wireless communication technologies are based on the spatial propagation of radio waves.

However, in cities and towns, it is difficult to provide line-of-sight conditions, so radio waves arrive at the receiving point in different ways. As a result, inter-symbol interference occurs at the input of the receiving path, leading to weakening and distortion of the useful signal. Such channels are called fading channels [1–4].

In the interests of improving the quality of signal reception in fading channels, various technical methods are widely used [5]. In particular, diversity radio reception in frequency [6, 7], in which one message is transmitted at different operating frequencies. Time diversity, where the same message is transmitted at different times. Space diversity, when the same message is transmitted to several antennas, spaced apart [8, 9].

In the range of ultrahigh waves, MIMO technology is successfully used to combat inter-symbol interference [10]. Recently, the RAKE receiver technology has been widely used in CDMA systems [11, 12].
An interesting enough technical solution aimed at increasing the noise immunity of reception in channels with inter-symbol interference seems to be the use of transmissions based on OFDM technology [13, 14].

Thus, the above facts indicate the high relevance of the topic aimed at improving the quality of radio reception of signals in channels with fading.

Note that the above methods for increasing the noise immunity of reception under fading conditions are either quite complicated from a technical point of view, or lead to a significant decrease in the transmission rate. At the same time, it was substantiated in [15] that one can also use technologies of direct expansion of the spectrum of DS/SS signals to combat inter-symbol interference [15, 16].

Taking into account these circumstances, the purpose of this article is to develop proposals for increasing the noise immunity of reception in channels with Rice fading, through the use of phase-shift keying signals, additionally extended by seven Barker element sequences.

2. Features of signal transmission in fading channels

The peculiarity of digital communication is that the signal is transmitted symbolically. Therefore, if the signal propagates in a multipath channel, then at the input of the receiving path at each time instant there will be several symbols of the same denomination of duration $T_s$. But these symbols will be shifted in time relative to each other due to the different delays they experience in the channel. These delays are caused by the different propagation paths of copies of the original signal.

This phenomenon is called inter-symbol interference [15].

In accordance with the central limit theorem, the probability distribution, the sum of statistically independent random variables, should tend to the normal distribution in the case when the number of terms increases. This corresponds to the condition for the existence of a fading channel. Indeed, all copies of the original signal will, in principle, have the same amplitudes, but different phase values, evenly distributed in the interval from zero to $2\pi$.

Therefore, copies of the signal $s$, as realizations of the original signal $s(t)$ at different times $t$, within the interval on the duration of the symbol $T_s$, can be considered from the standpoint of the probability density distribution of a random variable $p(s)$. The specified copies of the signal $s$ will be used as a random variable.

Since within the framework of the target setting only one of the received copies of the original signal will be subjected to final processing, in [11, 15] it is proposed to use the characteristic function $\chi(v)$ of some argument of the value $s$, which is introduced as the Fourier transform of the probability density $p(s)$, that is

$$\chi(v) = \int_{-\infty}^{\infty} p(s) \exp(jvs) ds. \quad (1)$$

The solution for expression (1) was obtained in [17].

$$\chi(v) = \left[J_0\left(\frac{A}{\sqrt{n}}v\right)\right]^n, \quad (2)$$

where $J_0(\cdot)$ – Is the zero-order Bessel function of the first kind; $A$ – signal amplitude; $n$ is the order number of the Bessel function.

Since function (2) already at $n = 4$ gives a function close to the characteristic function of the normal distribution [18], it is sufficient to have about 6 terms for the total signal to be considered as a two-dimensional normal random process

$$p(A, \psi) = \frac{1}{2\pi \sigma^2} \exp\left(-\frac{A^2}{2\sigma^2}\right), \quad (3)$$

depending on the parameter amplitude $A$ and phase $\psi$. 

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In (3), $\sigma^2$ – the variance of signal realizations $s$.

In the case when all copies of the original signal at the reception are equivalent, i.e. obtained as a result of reflections, then the probability density of the amplitude values can be obtained by integrating over all possible values of the phase

$$p(A) = \frac{\sigma}{\pi} \int_0^{\frac{\pi}{2}} p(A, \psi) \, d\psi = \frac{A}{\sigma^2} \exp \left( -\frac{A^2}{2\sigma^2} \right), \quad (4)$$

The amplitude distribution (4) in [15, 17] is defined as the Rayleigh distribution, and the channel in which the signal undergoes such changes is called the Rayleigh channel.

In a Rayleigh channel, the signal experiences strong fading, since its amplitude can take on small values. And the resulting value depends only on one parameter $s$, therefore, it is rather difficult to solve the problem of increasing the noise immunity of reception only due to spectrum spreading technologies.

If there is a deterministic signal in the channel (assuming one direct unreflected ray), the resulting signal will be the additive sum of the deterministic signal $\bar{s}(t)$ and a random Rayleigh signal $\epsilon(t)$.

In this case, the distribution of the amplitude of the received signal will be determined by the Rice distribution law [18]

$$p(A) = \frac{A}{\sigma^2} \exp \left( -\frac{A^2 + \bar{A}^2}{2\sigma^2} \right) J_0 \left( \frac{\bar{A} A}{\sigma^2} \right) \text{ provided } A > 0 \quad (5)$$

where $\bar{A}$ – Is the amplitude value of the determining component of the resulting signal.

Since the probability density of the Rice distribution is determined by two parameters: the variance $2\sigma^2$ of the fading and the deterministic component $\bar{A}$, other indicators are used in the estimation of the channel with fading described by the Rice distribution. Namely, the so-called $K$-factor, equal to the ratio of the deterministic and fluctuating components of the signal power $K = \bar{A}^2 / 2\sigma^2$, and the average total signal power. Transition formulas have the form [18]:

$$\bar{A}^2 = \frac{K}{K + 1} P, \quad 2\sigma^2 = \frac{1}{K + 1} P. \quad (6)$$

Then the Rice distribution (5) can be rewritten as

$$p(A) = \frac{2(K + 1) \exp(-K)}{P} \exp \left( -\frac{\bar{A}^2 (K + 1)}{P} \right) J_0 \left( 2\bar{A} \sqrt{\frac{K(K + 1)}{P}} \right). \quad (7)$$

Distribution (7) can be considered as generalizing, since at $K = 0$ we obtain the Rayleigh distribution. At the same time, the presence of a constant component in the Rice distribution makes it possible to apply spread spectrum technologies to the signal to increase the resulting noise immunity of reception.

3. Evaluation of noise immunity of channels with intersymbol interference

Various technologies are used to combat with inter-symbol interference (ISI). In particular, [15] considered:

- a decision feedback equalizer (DFE) approach;
- based on an equalizer working according to the maximum-likelihood sequence estimation (MLSE);
- based on the direct-sequence spread spectrum (DS/SS) method;
- based on orthogonal frequency-division multiplexing (OFDM) and others.

From the whole set of approaches, consider the DS/SS method based on Barker sequences.

Since it is the Barker sequences that provide the best ratio between the maximum of the correlation function and the level of its side lobes [17].
At present, Barker sequences with a duration of 3, 4, 5, 7, 11 and 13 elements are known, which are successfully used in solving various problems of radio engineering.

Further, as an example, consider the seven-element sequence of the Barker code \{1, 1, 1, 0, 0, 1, 0\}, presented in the form of a pulse sequence \(C(t)\) in Fig. 1.

\[ C(t) \]

**Figure 1.** Temporary representation of the seven-element Barker sequence.

In the general case, the technology of spreading the spectrum leads to an increase in the base of the signal \(B\), and, consequently, to an increase in the noise immunity of the reception as a whole [17]. Indeed, the signal base \(B\) is the product of its spectrum \(F\) width by its duration \(T_s\):

\[ B = F \times T_s. \]  

(8)

According to (8), the sought-for base value \(B\), which characterizes the broadbandness of the generated signal, can be provided by expanding the occupied frequency band, or increasing the duration of the symbol message.

Moreover, both of these parameters are interrelated. According to [15], the broadening of the signal spectrum will allow covering a large number of periods of the frequency-selective attenuation characteristic in the processing band.

Thus, the ability of a broadband signal to cover a large number of periods of the transfer function of a frequency selective channel will help to reduce the negative consequences of the influence of a multipath environment. In this case, the manifestation of this effect is possible only if the dispersion of the spectrum of the extended signal is greater than the transmission rate of the signal element.

As a result of the correlation processing of the input implementation containing the broadband signal, the energy of the useful radiation will be localized in the reception band seven times narrower than the original one, within the main lobe of the correlation function.

In fig. 2 shows the autocorrelation function \(R(\tau)\) of a seven-chip Barker extended signal symbol.

\[ R(\tau) \]

**Figure 2.** Autocorrelation function of the seven-element Barker sequence.

Measurements have shown that 89% of the total energy is concentrated within the main lobe of the autocorrelation function.

To estimate the noise immunity of receiving wideband signals in a fading channel, consider the approach proposed in [18], where it is substantiated that to calculate the bit error in a fading channel, it is necessary to calculate the integral of the product of the channel distribution function by the
probability of receiving error in a Gaussian channel, in particular, consider the reception of a phase-shift keying (PM) signal:

\[ \rho_R = \frac{1}{\pi a} \int p(A) \rho_C(A) \, dA . \]  

(9)

In (9) \( p(A) \) is the probability distribution density of the channel transfer function; \( \rho_C(A) = Q\left(\sqrt{2a}\right) \) - probability of reception error in a Gaussian channel where

\[ Q(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} \exp\left(-t^2/2\right) \, dt . \]

For the value \( p(A) \) described by expression (7), the probability of a bit error in receiving a PM signal will be determined by the following formula [18]:

\[ \rho_R = \frac{1}{\pi a} \int_{0}^{\infty} \frac{1}{(x^2 + 1)} \exp\left[-\frac{K h_0^2 (x^2 + 1)}{(K + 1) + h_0^2 (x^2 + 1)}\right] \frac{(K + 1)}{(K + 1) + h_0^2 (x^2 + 1)} \, dx . \]  

(10)

Then, taking into account the implementation of the DS/SS technology, based on the seven-element Barker code, we get

\[ \rho_{Ba} = \frac{1}{\pi a} \int_{0}^{\infty} \frac{1}{(x^2 + 1)} \exp\left[-\frac{K h_0^2 G (x^2 + 1)}{(K + 1) + h_0^2 G (x^2 + 1)G}\right] \frac{(K + 1)}{(K + 1) + h_0^2 G (x^2 + 1)G} \, dx . \]  

(11)

In (11) \( G = 7 \times 0.89 \) is a coefficient that takes into account the factor of correlation processing of a wideband signal for a seven-element sequence of the Barker code; \( h_0^2 = E_s / N_0 \) is the average ratio of the signal energy \( E_s \) to the power spectral density of the noise \( N_0 \) per symbol (SNR).

The resulting expression (11) makes it possible to carry out mathematical modeling for a comparative assessment of the noise immunity of reception in a channel with Rice fading using a conventional signal and an extended one using DS/SS technology.

\[ \text{Figure 3. Results of evaluating the noise immunity of receiving PM signals in a channel with multipath} \]

In fig. 3, the following designations are introduced: \( \rho_R \) - the function of the dependence of the bit error probability on SNR when receiving PM signals in a channel with Rice fading without additional measures to increase noise immunity. \( \rho_{Ba} \) - the function of the dependence of the bit error probability on SNR when receiving PM signals in a channel with Rice fading, provided that the PM signal was previously extended by additional manipulation of each of its symbols with a seven-element Barker sequence.

In both cases, it was assumed that the value of \( K = 10 \) dB.
The analysis of the obtained results shows that for the conditions under consideration, the bit error probability equal in the channel with multipath at $K = 10$ dB without additional measures can be provided only with SNR at the dB level. The use of DS/SS technology makes it possible to reduce the specified SNR requirements to 9 dB.

Thus, we can conclude that in inter-symbol interference, the use of wideband signals under the conditions of expanding bit bursts with a seven-element Barker sequence makes it possible to increase the noise immunity of reception with a value of $K$ equal to 10 dB.

4. Conclusion

DS/SS technology provides an increase in the noise immunity of receiving PM signals with a sufficiently pronounced constant component, i.e. at $K = 10$ dB.

The application of these measures is quite sufficient for a channel described by Rice's law. The authors associate the direction of further research with the modification of Barker codes.

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